Photovoltaic Plant Metering Monitoring Model and its Calibration and Parameter Assessment

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Abstract—**Photovoltaic plants are more and more widespread in the world, which should be monitored by their connected bulk power grid company. By using PV module manufacture non-confidential datasheet, a practical PV plant model based on so called "2C PV Module Model" for the power grid company's metering system is provided. A comprehensive parameter K is introduced into the model, which can be calibrated by trial or optimization method by using historical operation data, with no need of collection of topographic connection data as well as the detailed efficient coefficient parameters of energy transmission and converting of the plant, therefore greatly decreasing the modeling expenditure. Two useful models, in names of, minimum power calculation model, and maximum possible power prediction model with MPPT algorithm, have been explored for the power generation prediction, metering error or plant improper operation means prevention. The parameter sensitivity of model is also discussed for parameter assessment. Such model is validated by two operated PV plants.**

Index Terms—**photovoltaic plant, monitoring, metering system, simple model with less parameters, parameter sensitivity analysis, minimum power calculation model, maximum possible power prediction model, MPPT**

I. INTRODUCTION

PHOTOVOLTAIC power has a good correlation with peak load for a power system in sunshine day and summer peak apart from its basic role as a renewable and sustainable energy and low carbon electricity [1, 2], so PV plants have been widespread all over the world. As per connected power grid company is concerned, those PV plants should be monitored in order to operate the power grid more safe, reliable, and economical.

PV array or plant monitoring are used for different purpose: PV efficiency and performance measurement and evaluation [3,4], PV plant operation monitoring [5,6], PV integrated power system operation monitoring [7-8], etc.

As per a power grid company's concern, apart from a general requirement, the monitoring of connected PV plant has a special consideration: because PV is a sort of renewable power source, the electricity it sells to power grid shares a high price, such priority is only applicable for the electricity which should be strictly generated from corresponding nature resource, not from other forms [10], so the primary nature source of PV, like solar irradiance, temperature, the real PV generation process, etc. It is necessary to have a PV plant simulation model which can predict the possible power generation from the PV array up to all the related facilities like energy convert, process, transfer, etc., which very complicated and costly. So an accurate enough, but simple model becomes very important, that is what we have done. Due to approximation, we put forward a PV plant generation model to predict the maximum possible generation from the measured site solar irradiance and PV temperature, and a model to predict the minimum generation; with these two models' prediction value, to compare with the measured power generation curve, we can see whether the PV plant is working on a proper operation mode. If the real measured generation curve is greatly higher than the maximum generation prediction curve, or lower than the minimum generation prediction curve, there must be some wrong thing happening, which should have a investigation and fault detection[11].

As references [4-10] point out, for the power grid monitoring and operation use purpose, the dynamic power plant model must be simple and practical, by using the electrical characteristics data sheet provided by the manufacturer. More than that, the parameters of the model and the measurements to run the model should be as less as possible under certain accuracy, and the sensitivity of parameters and measurements should also be aware and the accuracy requirements for them should be studied for the reliability of the model.

II. GENERAL SCHEME OF PV PLANT DATA COLLECTION

Based on the china specification [12], medium-size PV plant who connects the power grid at voltage above 10kV is considered as a necessary dispatching object, needs a real-time remote communication with the dispatching center; however, small PV plant who connects the power grid at low voltage as 400V has been taken as a special customer, needs to store its operation records prepared for the inquiring by the power grid in a regular time or on-time callings.

In practice, there are two categories monitoring systems. The first one is real time SCADA system which has real time communication between dispatching center and power plants to carry out the real time control and regulation, keeping the power grid safely and economically. The second one is quasi-real time data acquisition system which is generally used for energy settlement purpose, normally being called metering

system which is what we focus in this paper.

Normally, metering system of medium-size PV plant uses existed high speed communication, but for the small PV plants, GPRS/CDMA public communication is used. A remote terminal PVTU is developed to collect all the necessary data from meters at grid connected point as well as inside the control or energy management system （EMS）of plant, like in Fig.1.
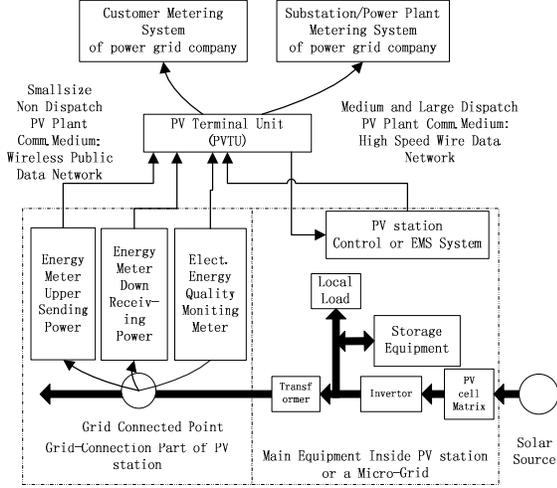

Fig.1 Structure of PV metering system

III. PV MODULE MANUFACTURE DATASHEETS

PV manufactures normally provide the datasheets including following items related with PV model in data tables and/or in curves:

A. Nominal or STC data table

Including (a) Maximum Power (P_m);(b) Current at Maximum Power (I_m); (c) Voltage at Maximum Power (V_m); (d) Short Circuit Current(I_{sc});(e) Open Circuit Voltage(V_{oc}); at Nominal or standard test condition (STC, i.e., solar irradiance at 1kW/m2, solar cell temperature at 25℃, a standard air mass ratio AM 1.5).

B. Curves of parameter vs. temperature or data table in correlations

Some manufactures provide curves of (a) Short circuit current vs. temperature; (b) Short circuit current vs. temperature; (c) Maximum power vs. temperature.

Others may provide following data in table:(a)Short circuit current temperature correlation in %/℃ or in Amps/℃; (b) Open circuit voltage temperature correlation in %/℃ or in V/ ℃;(c) Maximum power temperature correlation in %/℃ or in W/ ℃.

C. I-V typical curves

Normally 5or less I-V curves with solar irradiance at 1 kW/m², 0.8kW/m², 0.6kW/m², 0.4kW/m², 0.2kW/m², will be provided. The STC curve, i.e., at kW/m², must be provided.

Some manufactures may provide I-V curves with typical cell temperatures.

D. P-V typical curves

Some manufactures may provide 5or less P-V curves at 1 kW/m², 0.8kW/m², 0.6kW/m², 0.4kW/m², 0.2kW/m² respectively.

IV. DIFFERENT MODEL PURPOSE COMPARISON

TABLE I
DIFFERENT PURPOSE OF PV MODULE RELATED MODELING WITH DIFFERENT SPECIFICATION

Model Items / Modeling Purpose	PV Cell	PV Module	PV Array	Convert	Power Plant	Goals to be addressed
PV Manufacture	+	+	−	−	−	Give a standarized and acurate parameter datasheets
Inverter Manufacture	+	+	+	+	−	The accuracy of PV module model is very important for MPPT to operate PV array in optimal point
Power Plant Control & Management	+	+	+	+	+	Active power & reactive power control at a safe (including pretection) and economic way in real time for plant
Power Grid Control & Management	+	+	+	+	+	Active power & reactive power control at a safe (including pretection) and economic way in real time for the grid
Power Grid Metering & Management	+	+	+	+	+	Elect.energy billing & settlement and energy efficieny monitoring in none real time

PV module related modeling will depend on the different users with their different goals to address, as shown in Tab. I.

We can see From Tab. I, PV manufactures should provide some standard data-sheet under some accuracy. Inverter manufacture needs a suitable and accurate PV module model to work out a MPPT algorithm together with other power quality control function.

As per PV plant control & management system is concerned, the PV module modeling mainly comes from the requirement of the economic operation with the other energy regulation facilities inside the power plant, like battery storage, local load, coordination with power grid, etc.

As per power grid control & management is concerned, the main areas to apply the PV module are as followings:

(1) Short term or long term PV power availability or intermittence prediction for the integrated power system planning, economic operation and dispatching.

(2) Real time PV power availability or intermittence prediction. With the increase of penetration of the intermittence renewable power source into the grid, such prediction becomes more and more important.

(3) Metering management. This will affect the billing between power grid and the connected PV plant. The record of the PV generation including the PV solar irradiance availability will help both sides.

This paper is concentrate to PV metering management, i.e., the supervisory and data collection of PV solar energy transformation to electricity stepped to the grid. In fact, the collected data are almost the same as above (1) required. The modeling should consist of all the energy transformation process, definitely the PV module model is the core.

V. PV MODULE MODEL

PV module is consisted of a number of pre-wired cells in series, all encased in tough, weather-resistant packages.

Normally manufacturer will provide the parameters of the module. Selected PV model should at first have a strong theoretical foundation, and its static parameters must be selected from the non-confidential datasheet of manufacturer.

A. Review of PV Module Model

A tremendous literature has been published so far. In fact, we want to have an accurate enough but simple PV module model, with which the characteristic data including the measured items and data should be as less as possible.

There are two types of analytic PV module model, one we call as implicit model in forms as { I=f(V,I),or V=g(V,I)}, other we call as explicit model in forms as {I=f(V), or V=g(I)}; Obviously the latter one is more easy for analysis and application. An explicit PV module model with C1, C2 coefficients [7,13-15], being suggested by us in name of "2C PV module Model", was selected by us for the project. That 2C model has been widely adopted or referred by 229 papers since its birth in 1996's after searching from Google. The detailed of 2C model's behavior and its performance, will be introduced by our another paper [18].

B. Selected 2C PV Module Model

The model is as followings:

$$I = I_{SC}(1 - C_1(\exp(\frac{V - \Delta V}{C_2 V_{OC}}) - 1)) + \Delta I \qquad (1)$$

$$C_1 = (1 - \frac{I_m}{I_{SC}})\exp(-\frac{V_m}{C_2 V_{OC}}) \qquad (2)$$

$$C_2 = (\frac{V_m}{V_{OC}} - 1) / In(1 - \frac{I_m}{I_{SC}}) \qquad (3)$$

$$\Delta V = -\beta \cdot \Delta T - R_s \cdot \Delta I \qquad (4)$$

$$\Delta I = \alpha \frac{R}{R_{ref}} \Delta T + (\frac{R}{R_{ref}} - 1)I_{SC} \qquad (5)$$

$$\Delta T = T_C - T_{ref} \qquad (6)$$

Where R is the total solar irradiance on the tilted PV module, Tc is the temperature of the PV cell, in ℃. R and Tc are two time changing variables, and are the dynamic driving force to change the output of PV cell or module. So above model is a dynamic model.

C_1, C_2, ΔI, ΔV, ΔT are intermediate variables;

I_{sc}, V_{oc}, I_m, V_m are data at STC, already mentioned in section II;

R_{ref}, T_{ref} are references of solar irradiance and ambient temperature respectively, and the typical values are 1000w/m² and 25℃ respectively;

α, β are current temperature correlation in Amps/℃ and voltage temperature correlation in V/ ℃; R_s is cell internal series resistance (Ohms).

Ambient temperature is T（℃）, PV cell temperature is T_c is as:

$$T_c = T + t_c R\cos \theta \qquad (7)$$

t_c （deg $w^{-2}m^2$） is the temperature coefficient of PV cell. θ is angle of solar radiation.

C. Angle of solar radiation θ

From （7） we know that output of PV cell has relationship with solar radiation angle. Because Rcos θ changes with the external environment is relatively smaller, that we can take:

$$T_c = T \qquad (8)$$

In the general case, when the temperature drops, the output of PV cells increases. Therefore, this approximation will slightly increase the power output.

D. Series resistance R_s

PV cell manufacturer does not provide the series resistance of PV cell, but it is a very important parameter in above model, and it has a significant impact on the performance of PV cell. Nowadays crystalline silicon PV cell is widely used, and literature [15] gives a calculation formula of series resistance, which use the same static parameters and measurement, but with more accuracy of Rs calculation.

VI. DYNAMIC BEHAVIOR OF 2C PV MODULE MODEL AND MPPT CALCULATION

A. Dynamic behavior of 2C PV module model

When in standard test condition (STC), ΔI, ΔV, ΔT in (4)-(6) are all zero, so (1)-(3) are the dynamic curve under STD condition, the I-V will following (9) in parameter with C_1,C_2.

$$I = I_{SC}(1 - C_1(\exp(\frac{V}{C_2 V_{OC}}) - 1)) \qquad (9)$$

When irradiance and Temperature change, we can calculate ΔI, ΔV accordingly. We just introduce two variables as:

$$I^* = I - \Delta I \qquad (10)$$

$$V^* = V - \Delta V \qquad (11)$$

So we will have:

$$I^* = I_{SC}(1 - C_1(\exp(\frac{V^*}{C_2 V_{OC}}) - 1)) \qquad (12)$$

This is similar with (9), we can consider the PV module is still working on that STC characteristic curve, only the variable space has changed from (I,V) plane to (I*, V*) plane.

So using 2C PV module model, we can only take care of the STC characteristics curve only, that make us much easy.

B. MPPT Calculation of 2C PV module model

In (I*, V*) space, P(V*) is as :

$$P(V^*) = I(V^*)V^* = I_{SC}\left[1 - C_1 \exp\left(\frac{V^*}{C_2 V_{OC}}\right)\right]V^* \qquad (13)$$

Assuming at V*=V'_m, I*=I'_m, it reaches the maximum, we have:

$$(14)$$

$$\left.\frac{dP}{dV}\right|_{\substack{V^* = V'm \\ I^* = I'm}} = I_{SC}\left[1 - C_1 \exp\left(\frac{V'_m}{C_2 V_{OC}}\right)\right] - \frac{C_1}{C_2}\frac{I_{SC}}{V_{OC}}V'_m \exp\left(\frac{V'_m}{C_2 V_{OC}}\right) = 0$$

Look at above first item, it is just the I'_m, so we have:

$$I'_m - \frac{C_1}{C_2}\frac{I_{SC}}{V_{OC}}V'_m \exp\left(\frac{V'_m}{C_2 V_{OC}}\right) = 0 \qquad (15)$$

V'_m, I'_m also meet:

$$I_m^{'} = I_{SC}\left(1 - C_1 \exp\left(\frac{V_m^{'}}{C_2 V_{OC}}\right)\right) \tag{16}$$

Or

Multiple V'm to both side of (12), we get

$$V_m^{'} \exp\left(\frac{V_m^{'}}{C_2 V_{OC}}\right) = \frac{1}{C_1 I_{sc}}(I_{SC}V_m^{'} - I_m^{'}V_m^{'}) \tag{17}$$

Replace the second item of (15) with (17), we get:

$$I_m^{'} = \frac{1}{C_2 V_{oc}}(I_{SC} - I_m^{'})V_m^{'} \tag{18}$$

Let transfer (8) into a formula as V=g(I), V'm, I'm also meet that condition as:

$$V_m^{'} = C_2 V_{OC} \ln\left\{1 + \frac{1}{C_1}\left(1 - \frac{I_m^{'}}{I_{SC}}\right)\right\} \tag{19}$$

(18) and (19) together are the MPP solution equations, which are also very suitable to have a fast search iterative algorithm as following introduction.

We all know that the upper side of I-V curve has a more flat shape, and MPP is almost in that region, that means the $I_m^{'}$ from the 2C model calculation is very near to the I_m from the given sheet data, so the $I_m^{'}$ at right of (18) can be substituted directly with I_m, so we have:

$$I_m^{'} = \frac{1}{C_2 V_{oc}}(I_{SC} - I_m)V_m^{'} \tag{20}$$

The fast search iterative algorithm:

$$I_m^{'k+1} = \frac{1}{C_2 V_{oc}}(I_{SC} - I_m)V_m^{'k} \tag{21}$$

$$V_m^{'k+1} = C_2 V_{OC} \ln\left\{1 + \frac{1}{C_1}\left(1 - \frac{I_m^{'k}}{I_{SC}}\right)\right\} \tag{22}$$

VII. MAXIMUM AND MINIMUM POSSIBLE PV GENERATION MODEL OF PV PLANT

A. Minimum power calculation model (MinPM)

Assuming photovoltaic array consists of *m* string PV modules in parallel, each string consists of *n* PV modules in series which are with same type of cell, and the total output current is I_{tl}, terminal voltage is U_{tl}, total power is P_{tl}, so:

$$I_{tl} = mI \tag{23}$$

$$U_{tl} = nV \tag{24}$$

$$P = IV \tag{25}$$

$$P_{tl} = \eta_R I_{tl} U_{tl} = \eta_R mnIV = \eta_R mnP \tag{26}$$

η_R is overall transmission efficiency of the PV array. If we know the inverter efficiency is η_I, transformer efficiency is η_T, then grid output power:

$$P_g = \eta_I \eta_T P_{tl} = \eta_I \eta_T \eta_R mnIV \tag{27}$$

If a systems use different connection of PV array with multi-inverter, we can have a similar Pg formula accordingly. Inverter manufacturers usually provide η_I, η_T in non-linear curve, but η_R requires on-site measurement and it is not easy to obtain. Therefore, to reduce the amount of work and be easy for calculation, rated efficiency, i.e., $\bar{\eta}_T, \bar{\eta}_I$ are used.

Assuming there is L numbers of inverter PV groups in parallel to supply the power to the grid, then we have (28) by introducing a comprehensive efficiency factor K (where transmission efficiency of the PV array is considered into K):

$$Pg = \sum_{i=1}^{L} \eta_{Ti}\eta_{Ri}\eta_{Ii}m_i n_i I_i V_i = K\sum_{i=1}^{L}\bar{\eta}_{Ti}\bar{\eta}_{Ii}m_i n_i I_i V_i \tag{28}$$

By using measured data of PV array's voltage V (we use the terminal voltage measured to be divided by the n), solar irradiance R, ambient temperature T, and using equation (1)-(6), (21)-(25), we can calculate $P_g(t)$ as in (28).

Normally PV plant operates using maximum power tracking (MPPT), but the equations (1)-(6), (23)-(28) has not considered with the function of MPPT, so that P_g should be less than the measured real power sold to the grid, so we can call P_g as the ***minimum power calculation model (MinPM).***

B. Maximum possible power prediction model (MaxPM)

As MPPT is widely used, we can also using MPPT to predict the maximum possible power of the PV plant.

For a PV plant in its maximum power point, we have:

$$\frac{dP_{tl}}{dU_{tl}} = 0 \tag{29}$$

From (24), (26) we have:

$$dU_{tl} = ndV \tag{30}$$

$$dP_{tl} = \eta_R mndP \tag{31}$$

Put (30) (31) into (29), we have:

$$\frac{dP_{tl}}{dU_{tl}} = \eta_R m\frac{dP}{dV} = 0 \tag{32}$$

Which means that when PV modules are at maximum power point, the total PV array will be at the maximum power point; So we have:

$$P_{tl,max} = \eta_R mnP_{max} \tag{33}$$

For the entire plant:

$$P_{gmax} = \sum_{i=1}^{L}\eta_{Ti}\eta_{Ri}\eta_{Ii}m_i n_i P_{max,i} = K\sum_{i=1}^{L}\bar{\eta}_{Ti}\bar{\eta}_{Ii}m_i n_i P_{max,i} \tag{34}$$

According to the measured solar irradiance R, ambient temperature T, and using equation (1)-(6), (21)-(22) to get the maximum power, and use (33)-(34) to calculate P_{gmax} (t). Because that calculation is with a globe MPPT function and the selection of (8) is trending to have a greater power output, so that P_{gmax} should be great than the measured real power sold to the grid, so we can call P_{gmax} as the ***maximum possible power prediction model(MaxPM)***

If the measured power output is $P_m(t)$, it must meet :

$$P_{gmax}(t) \geq P_m(t) \geq P_g(t) \tag{35}$$

Above (35) only consider the net power generation from PV array. If plant has storage equipment or local load, then they should be measured separately, and the data should be also reported to master station of power grid company.

VIII. MODEL CALIBRATION

A. Evaluation of the model

Four criteria for model evaluation:
(1) coefficient of correlation：

$$R = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \sum(y_i - \bar{y})^2}} \quad (36)$$

(2) mean absolute error：

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|x_i - y_i| \quad (37)$$

(3) root mean square error：

$$RMSE = \sqrt{\frac{1}{n}\sum(x_i - y_i)^2} \quad (38)$$

(4) average error

$$EE = \sum_{i=1}^{n}x_i - \sum_{i=1}^{n}y_i \quad (39)$$

Above formula, x_i means the test samples data (measured value), y_i means model calculations or the maximum power predicted power data. $\bar{x}$ means test samples average power, $\bar{y}$ means model predicted average power.

B. Calibration calculation of K

The comprehensive efficiency parameter K has its ranges from 0.6 to 0.95. It can be got by trial method to make K selection to meet (35), other way is a optimization method as follows:

$$\min : c_1\{MAE(P_{g\max}, P_m) + MAE(P_m, P_g)\}$$
$$+ c_2\{RMSE(P_{g\max}, P_m) + RMSE(P_m, P_g)\} \quad (40)$$
$$sub\ to : EE(P_{g\max}, P_m) > 0$$
$$EE(P_m, P_g) < 0$$

IX. CASE STUDY

A. Case Description

Two case studies have been taken, here only one is introduced as for Hangzhou Dianzi University's photovoltaic power plant. SHARP ND-Q7L5H 175W PV cells have been installed, modeling and test data collection period is the entire months of Oct 2010, the time interval of 1 minute.

TABLE II
COMPARISON OF PREDICTION AND REAL MEASUREMENT

Choose 20-days data to calibrate K; a trial method as simple calculation in Table I, knowing *K* is 0.85. In Tab. II, $P_g(t)$、$P_{g\max}(t)$ both have a high correlation with $P_m(t)$.

B. Model validation

Choose the remaining 10 days data for model validation. Performance in Table III shows that the two models maintain the target consistency of calibrated model.

Fig.2 is curves of one day's Model validation. Real

	K	Model	R	MAE		RMSE		EE
1	0.95	MinPM	0.9998	1.94	2.43	2.47	3.05	46.59
		MaxPM	0.9996	2.92		3.62		70.061
2	0.90	MinPM	0.9998	0.78	1.25	1.11	1.65	18.736
		MaxPM	0.9996	1.71		2.19		40.975
3	0.85	MinPM	0.9998	0.41	0.48	0.45	0.64	-9.195
		MaxPM	0.9996	0.55		0.82		11.806
4	0.80	MinPM	0.9998	1.55	1.14	1.74	1.30	-37.127
		MaxPM	0.9996	0.73		0.85		-17.362
5	0.75	MinPM	0.9998	2.71	2.33	3.11	2.67	-64.981
		MaxPM	0.9996	1.94		2.22		-46.449

power generation curve generally caught in the between the

power calculation curve and maximum power predicted curve. It shows the two models can be well on the measured power curve for a supervisory role.

TABLE III
COMPARISON OF PREDICTION AND REAL MEASUREMENT

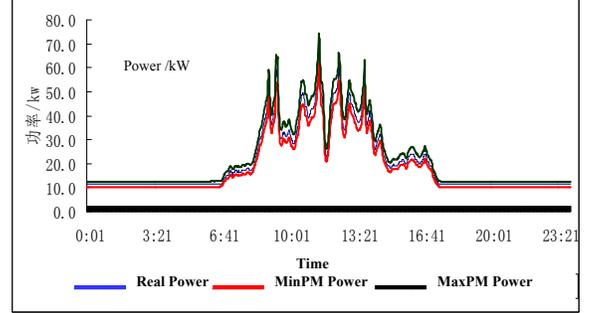| Model	R	MAE	RMSE	Day time energy Difference
MINPM	0.9997	0.442	0.533	-10.1009
MAXPM	0.9993	0.505	0.781	10.007

Fig.2 Comparing of MinPM Power, MaxPM Power and Real Power

X. PARAMETER ASSESSMENT

A. Model and sensitivity analysis

Sensitivity analysis can be used to analyze the importance of various model parameters to the model and the affection of its data deviation to model output values. The advantage of local sensitivity analysis is its operability, which is to calculate the changing rate of model output affected by the parameter changing in a small area near best estimated value when other parameters remain constant.

Assume the output power of power plant is y, it can be expressed as a function consist of n static parameters ($a1, a2, ..., a_n$), m measurements ($x1, x2, ., x_m$) and l calibrated parameters ($b1, b2, .., b_l$) as follows：

$$y = f(a1, .., a_n;\ x1, ., x_m;\ b1, .., b_l;\ ) \quad (41)$$

Revised Morse screening method is widely used in local sensitivity analysis. That is to let the variable changes by a fixed-step and take several average values as the sensitivity determine factor, as follows:

$$S_{ai} = \sum_{j=0}^{J-1}\frac{(y_{j+1,ai} - y_{j+1,ai})/y_0}{(p_{j+1,ai} - p_{j+1,ai})/100}/(J-1) \quad (42)$$

y0 is the best estimate parameter values corresponding to y; For a certain parameter ai, J times model operation will be done; for each operation, i.e., k-th(k=0~J-1), the model output is $y_{k,ai}$; $p_{k,ai}$ is a changing rate of that k-th model parameter ai value with its initial value.

Larger S means the parameter is more sensitive. In general, we can divide it to highly sensitive, sensitive, medium sensitive and insensitive parameters in accordance with $|S| \geq 1$, $0.2 \leq |S| < 1$, $0.05 \leq |S| < 0.2$, $0 \leq |S| < 0.05$.

The low sensitive static parameter can directly use standard technology constant provided by the manufacturer, otherwise we have to review it carefully and take necessary correction. Also for the low sensitive measurement, we can use the low precision and low prices one, otherwise we ought to take measures to ensure the accuracy of its acquisition.

B. Influence from static parameter and measurement to output power deviation

In power calculation model (1)-(6), I_{sc}, V_{oc}, I_m, V_m, a, b, R_s are static parameters; I is a function of V, so measuring power need to measure the R,T,V.

TABLE.IV
ANALYSIS OF STATIC PARAMETERS

static parameter	Relative deviation (%)	Datasheet	Value range	Sensitivity	Impact on the overall deviation (%)	proportion of total deviation (%)
I_{sc}	≤0.5	8.02	7.699~8.34	-0.171	±0.024	0.718
V_{oc}	≤0.5	29.04	27.88~30.20	0.046	±0.016	0.478
I_m	≤0.5	7.27	6.98~7.56	0.797	±0.615	18.39
V_m	≤0.5	22.98	22.06~23.90	0.647	±0.582	17.41
a	≤0.5	0.0032	0.0031~0.0033	0	0	0
b	≤0.5	0.1045	0.1003~0.1086	0	0	0
Rs	≤2	2	1.92~2.04	0	0	0

All the PV cell are the same manufacturer model, according to (11), we can get：

$$\gamma_{pg} = \gamma_p = \gamma_I + \gamma_V \qquad (43)$$

The relative deviation of total generation power Pg equals to that of PV cell power. It is determined by the relative error of direct measured voltage measurement and indirect measured current measurement. The former depends on the voltage meter, the latter need to be calculated according to (1)–(6),(21)-(26),that is determined by the relative error of measurement R,T. Table IV is the analysis.

The static parameters and the relative errors of measurement in table IV and table V are determined by the measurement standards of IEC 904 photovoltaic devices [16]. When carrying on the local sensitivity analysis, we can use 1% as a fixed step to the disturbance of the parameter value which range is [-4%, +4%], and the other parameters are fixed. According to the Table III for the output power under standard conditions, I_m and V_m belong to the sensitive parameters, I_{sc} belongs to the secondarily sensitive parameters, V_{oc},a,b,R_s belong to insensitive parameters whose affect to the errors of the output power is 0; So I_m and V_m has to be reviewed during the data collections.

TABLE V
ANALYSIS OF MEASUREMENT

measurement	Value range	Relative deviation (%)	Sensitivity	Impact on the overall deviation (%)	proportion of total deviation (%)
R	81~726	≤1	1.622	±0.9322	27.88
T	18~29.9	≤1.67	-0.269	±0.3687	11.03
U	25	≤0.5	1.385	±0.8046	24.07

According to the Table V, R and U belong to the highly sensitive parameters, T belongs to the sensitive parameters, the greatest affection to the errors of the output power is the solar radiation R.

C. Determine the accuracy demand of static parameters and measurements

Grid company has a certain precision measurements to the active power which fed into the grid, IEC 61724-1998[17] pointed out that the power of accuracy must be≤2%.Total component error is γ_p=3.3425% in Table VI and V, which

does not meet the standard; Therefore, in order to achieve the precision of power, we ought to allocate total measurement deviation, as R and V each takes 2 parts, I_m,V_m,T each takes 1 part. The allocation formula of each part is:

$$\Delta x_j = \frac{\Delta y / m}{\partial y / \partial x_j} \qquad (44)$$

m is the total number 7.

After calculation, we require the deviation range of I_m is in [-0.0363A, 0.0363A],the deviation range of V_m is in [-0.1149V, 0. 1149V],the measurement deviation range of solar radiation is in[-7.26, 7.26],the measurement deviation range of temperature sensor is in [-0.501 º C,0.501 º C] and the measurement deviation range of PV Operating voltage is in [-0.125V, 0.125V].

Therefore, in order to meet the prediction or review of minimum and maximum possible power generated from PV plant, we need collection static parameters as Table III, and increase the operation record or non real time data collection of solar irradiance R, ambient temperature T, and PV array terminal voltage V as in Table V.

Generally, R,T,V are all available in PV plant's control or energy management system, so a remote terminal PVTU can communicate with plant's corresponding system and collect the necessary non real time data to power grid company.

XI. CONCLUSION

The key issue of power grid oriented PV plant metering monitoring system is the modeling of those grid-connected PV plants:

(1) A minimum static parameter scheme is put forward, this is (a)Select a good theoretical based PV module model with the parameter accessible from the datasheet from its manufacturers;(b)Other critical equipments in power plant such as inverters, transformers can be taken as the rated efficiency values instead of efficiency curves;(c)only collect the PV cell string number n and the cell number m of each string number;(d)The energy transfer efficiency of array and confluence, the deviation caused by rated efficiency of inverter and transformer, are treated through model calibration by a comprehensive parameter K. That makes modeling in a simple but effective way.

(2) Two models, minimum power calculation model, and maximum possible power prediction model, have presented which can be used to check the validation of real measured power which PV plant generates to the power grid, to prevent metering error or other improper means.

(3). Based on the sensitivity calculation for the static parameters and dynamic data measurement parameters of the presented PV model, the accuracy requirement of those parameters have been worked out which can help for static parameter data verification from the datasheets of PV cell supplier or accurate allocation for the PV plant's corresponding system data measurement.
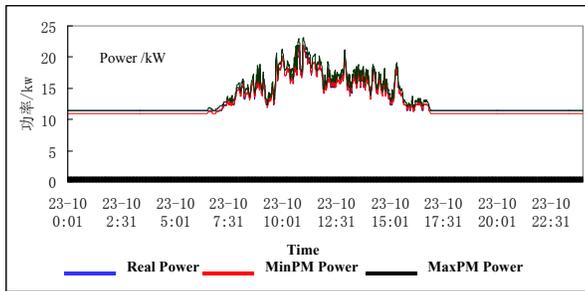
XII. Appendix

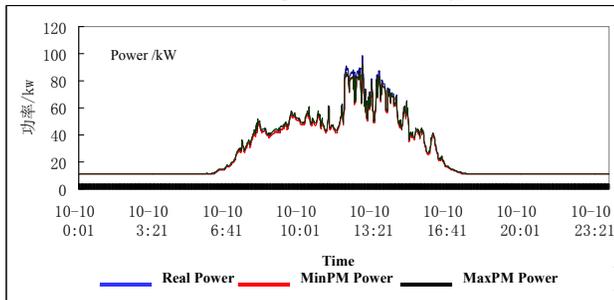
Fig. 3. Oct., 23 (cloudy)

Fig. 4. Oct., 10 data (sunny)

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XIV. Biographies

Qianzhi Zhang (Student M'11) will graduate and get B.Sc of Electrical Engineering from Shandong University of Technology in June, 2012. His research interests include the renewable energy integration with power system and their planning, control and operation. He has authored and coauthored 5 papers.

Jianmin Zhang (M'11) received B.S., M.S. from Huazhong Univ.of Sci.& Tech.,Wuhan, China, and M.E. from Indian Institute of Technology (IIT, Roorkee), all in electrical Engineering, in 1984, 1987, 1992 respectively. He joined Hangzhou Regional Center of Small Hydro Power (HRC) and National Institute of Rural Electrification, Hangzhou, China from 1987 to 1997.He is a full professor of Electrical Engineering and Automation at Hangzhou Dianzi University, a R&D consultant of Zhejiang Province Gov., chief engineer and director of institute of smart grid of Zhejiang Creaway Automation Ltd under Zhejiang Electrical Power Corporation. He has authored and coauthored more than 100 technical publications, including more than 60 journal papers, 10 conference papers and 2 books. His research interests include electric power and energy system modeling, optimal operation and dispatching, intelligence engineering and automation, information system integration

Chuangxin Guo was born in China in 1969. He obtained the B.Sc., M.Sc., and Ph.D. degrees in Electrical Engineering from Huazhong Univ.of Science and Technology, Wuhan, China, in 1992, 1994 and 1997,respectively. From 1997 to 2003, he worked as the Director of Beijing Dongfang Electronics Research Institute and the Deputy Chief Engineer of Dongfang Electronics Co., Ltd. During 2003 and 2005, he worked as a postdoctoral inElectrical Engineering in Zhejiang University (ZJU), Hangzhou, China. From 2005 to 2006, he was an associate professor in the College of Electrical Engineering (CEE), ZJU. Since September, 2006, he has been the professor in CEE, ZJU. He has authored and coauthored more than 100 technical publications, including 85 papers and one book. Dr. Guo is a Member of IEEE and a Committee Member of CIGRE China. His research interests include smart grid, distributed energy resources attaching to power grid, intelligent information processing technology and its application in power system.