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Performance results and analysis of 3 kW grid-connected PV systems

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Abstract

Four 3 kW grid-connected photovoltaic (PV) generation systems have been installed and monitored at the Field Demonstration Test Center in Korea since October 2002. To observe the overall effect of meteorological conditions on their operation characteristics by field test, the monitoring system has been constructed for measuring and analyzing the performance of PV systems and components in November 2002. In this paper, the performance of PV systems is evaluated and analyzed not only for component perspective but also for global perspective by reviewing one year of monitoring results and loss factors of PV systems. On the basis of these monitoring results, the performance of PV systems is compared to the measured performance of PV systems with the estimated performance by simulation. These results will indicate that it is highly imperative to develop evaluation, analysis and application technology for PV systems.
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1. Introduction

As a solution for the depletion of conventional fossil fuel energy sources and serious environmental problems, focus on the photovoltaic (PV) system has been increasing around the world. Especially, PV systems have been becoming widespread in Korea as a result of active government polices for renewable energy sources including 100,000 PV house dissemination project by 2012 [1,2]. In the future, the establishment of utilization technology for stability and reliability of PV systems will take on more significance in this area as high-density grid-connected PV systems will be interconnected with distribution networks [3]. Therefore, total four units of 3 kW grid-connected PV systems have been installed at Field Demonstration Test Center (FDTC) in Korea since Oct. 2002. The monitoring system has been constructed for measuring and analyzing the performance of PV systems to observe the overall effect of meteorological conditions on their operation characteristics by field test. During one year of monitoring period, the performance of PV systems has been evaluated and analyzed not only for component perspective (PV array, power conditioning unit (PCU)) but also for global perspective (system efficiency, capacity factor, electrical energy) [4]. The loss factors of PV systems and components such as a PCU and PV have been also reviewed. On the basis of these investigation results, the performance of PV systems has been simulated with PVSYST program and compared with the measured performance of PV systems [5]. This research aims at not only evaluating and analyzing the performance of PV system through field test but also developing optimum technologies for stability and reliability of PV systems.

2. System description

Four 3 kW grid-connected PV systems installed in the FDTC to analyze performance characteristics by field test are shown in Fig. 1. The nominal power of both PV arrays range from 3 to 3.3 kW. Both PV arrays are set in a fixed tilt of 18° with azimuth of 0° (south). Each PV array is composed of two multi-crystal and two mono-crystal PV modules, which are provided by different domestic manufacturers. The specifications of PV module and PCU installed at the FDTC are summarized in Tables 1 and 2.

The installed PV systems have been fully monitored and supervised to evaluate the performance of PV systems on meteorological conditions with meteorological and electrical sensors [6,7]. The monitored results of PV systems were collected in a 1 s sampling period so that the operational characteristics of PV systems could be analyzed by field test. The PV systems have been monitored from November 2002 to present. The measured data are recorded averaged every 5 min and stored on a disk for analyzing and evaluating. The installed on-line monitoring system could be remotely supervised through a wide area network (WAN). A schematic of the whole system is shown in Fig. 2. In this monitoring system, the following items are measured to evaluate and analyze the performance of PV systems.

Electrical measurement items

- Direct current (DC) voltages and currents
- Alternating current (AC) voltages and currents
- PCU and utility grid power
- PCU and utility grid frequency

Fig. 1. PV systems installed in the FDTC.

Table 1
PV module specifications (under standard test conditions)

PV module	A	B	C	D
Cell type (crystalline silicon)	Multi	Mono	Mono	Multi
Nominal power (W)	78	53	75	75
Short-circuit current (A)	4.88	3.35	4.7	4.75
Open-circuit voltage (V)	21.5	21.7	21.2	21.8
Maximum power point current (A)	4.46	3.05	4.30	4.35
Maximum power point voltage (V)	17.2	17.4	17.2	17.3

Table 2
PCU specifications (at rated conditions)

|	PCU Type	A Grid-connected	B Grid-connected	C Grid-connected
DC input	Input voltage (V)	200	340	245
	Operating voltage range (V)	145–350	280–480	200–300
	Rated output (kW)	3.0	3.0	3.0
AC output	Efficiency (%)	93.5 or more	91.0 or more	90.0 or more
	Power factor	0.95 or more	0.98 or more	0.95 or more
	Total harmonic distortion (%)	5 or less	5 or less	5 or less
	Maximum single harmonic (%)	3 or less	3 or less	3 or less
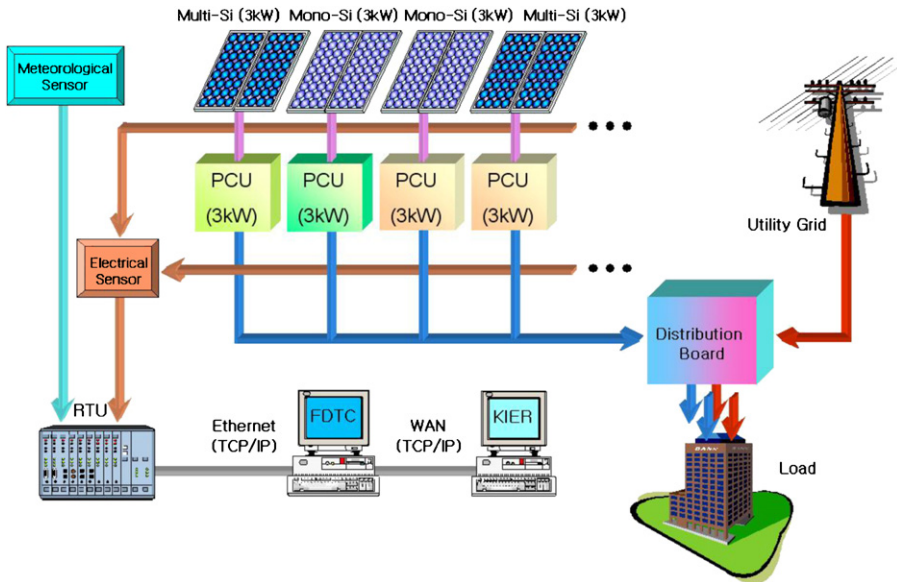
Fig. 2. System overview.

Meteorological measurement items

- Irradiance on horizontal plane (CM21)
- Irradiance on plane of PV array (CM21)
- PV module surface temperature (T-type)
- Ambient temperature (PT-100)

3. Performance results of PV system

3.1. Performance results of PV array

The performance results of installed PV systems at the FDTC had been monitored from November 2002 to October 2003 to investigate operational characteristics of PV systems and components. The monthly output energy and their efficiency of PV array for the monitoring period are shown in Figs. 3 and 4. The annual total DC output energy generated by PV array was respectively 4.13 MWh (system 1), 3.51 MWh (system 2), 3.98 MWh (system 3) and 3.68 MWh (system 4). The monthly conversion efficiency of PV array varied from 9.2% to 10.1%. As shown in figures below, especially in January 2003, the conversion efficiency and output energy of PV arrays dropped dramatically, which could be caused by worst meteorological conditions such as snow. In July 2003, the output energy of PV arrays dropped compared with the rest of the monitoring period. The cause was generated by total irradiation reduction due to bad meteorological conditions and PV array losses increase on temperature rise.

DC output energy generated by PV array is linearly dependent on the irradiance except for the nonlinear characteristics range of lower irradiance. The conversion efficiency of PV
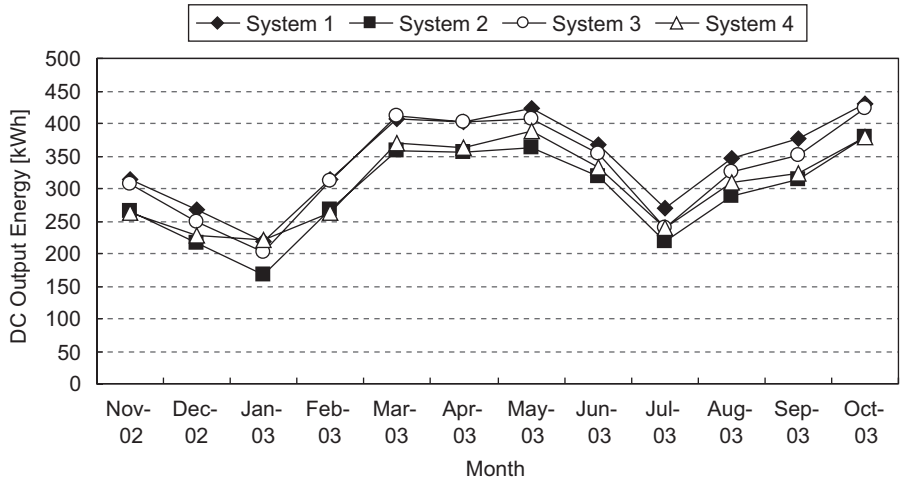
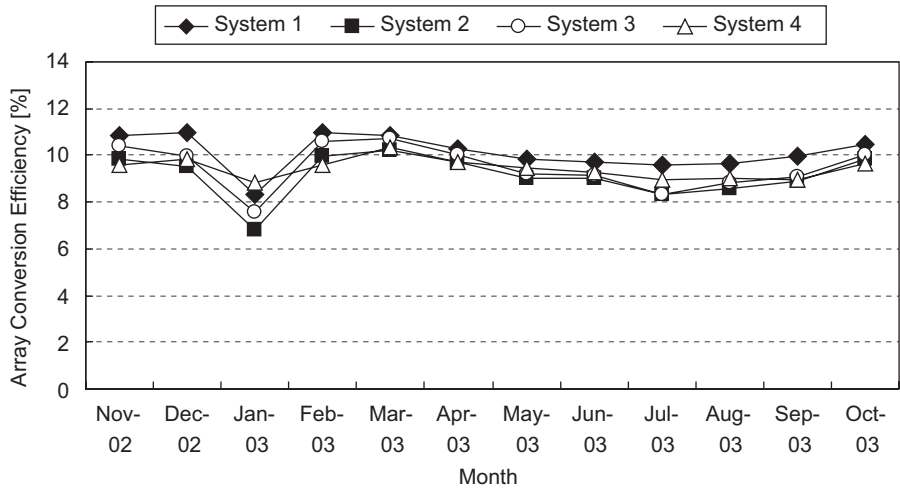Fig. 3. Monthly PV array output energy.

Fig. 4. Monthly PV array conversion efficiency.

array does not strongly depend on irradiance but rather on module surface temperature [4,6]. Therefore, there is a necessity for carrying out a detailed temperature correction of the PV module efficiency and for investigating this dependence on DC output power versus meteorological characteristics such as irradiance and PV module surface temperature.

3.2. Performance results of PCU

The monthly efficiency and operational performance of PCUs are shown in Figs. 5 and 6. The annual averaged efficiency of PCU was individually 89.1% (system 1), 86.1% (system 2), 83.5% (system 3) and 87.1% (system 4). The annual averaged availability of PCU ranged from 40.7% to 42.9%. The availability of PCU defined as ratio of PCU

operation time versus calendar time for monitoring period. Through the performance results of PCU availability, it was known that both PCUs continued operating for a long time without faults or troubles during monitoring period. In the PCU (system 3), the efficiency of PCU was low compared with the rest of the PCUs. The cause of lower efficiency is design faults of PCU since the measured performance of PCU was less efficient than the specified performance provided by manufacturer as described in Table 2. When irradiance was higher than $200 \, W/m^2$, it was known that both PCU performed
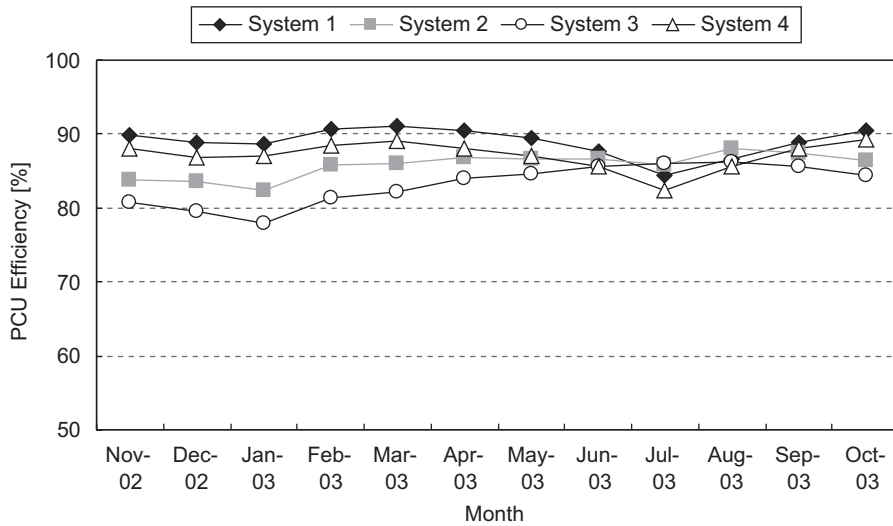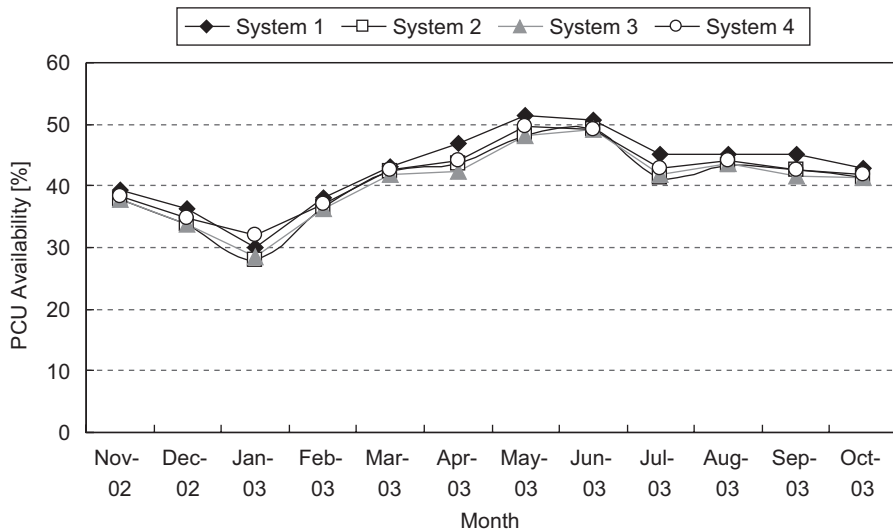
Fig. 5. Monthly PCU efficiency.

Fig. 6. Monthly PCU availability.

Table 3
Performance results of PV systems

PV system		System 1	System 2	System 3	System 4
PV array	Conversion efficiency (%)	10.1	9.2	9.5	9.5
	Output energy (kWh)	4135	3510	3980	3682
PCU	Efficiency (%)	89.1	86.1	83.5	87.1
	Output energy (kWh)	3686	3021	3322	3213
	Availability (%)	42.9	40.7	40.5	41.6
System	Capacity factor (%)	12.8	11.5	11.5	12.2
	System efficiency (%)	9.0	7.9	7.9	8.3

comparatively at maximum power point tracking (MPPT) control to track the MPP in accuracy.

3.3. Performance results of the whole system

The performance results of PV systems monitored from November 2002 to October 2003 are summarized in Table 3. During one year of monitoring period, the capacity factor and system efficiency of PV systems ranged from 11.5% to 12.8% and from 7.9% to 9.0%, respectively. As described in Table 3, in the PV array (system 2), when irradiance went down to about $300 \, W/m^2$, the conversion efficiency of PV array varied suddenly from 3% to 10% due to nonlinear $I–V$ characteristics of PV array for meteorological conditions. That means that it was difficult to track MPP due to PV module performance deterioration and mismatch of PV sub-arrays. Therefore, the performance of PV system dropped since the PV array losses were increased. The conversion efficiency of PV array (system 3) also varied suddenly from 4% to 10% due to nonlinear $I–V$ characteristics of PV array when irradiance fell below $300 \, W/m^2$. In the PV arrays (systems 1 and 4), the conversion efficiency was comparatively constant in the range of 8–11% for a wide variance of irradiance. But the performance of PV system (system 4) more or less declined due to the increased PV array losses by temperature rise compared with the rest of the PV systems. The performance of PCU (system 3) decreased due to lower PCU efficiency. When irradiance was under $300 \, W/m^2$, the variation of PCU efficiency became large because PCU losses increased due to MPPT failure and PCU faults.

4. Performance analysis of PV system

4.1. Analysis results of PV array performance

The performance of PV system is strongly dependant on meteorological conditions such as shading, irradiance, PV array surface temperature, etc. Therefore, the performance of PV arrays was analyzed using the measured performance results of PV systems for monitoring period and investigated by reviewing several problems such as performance deterioration and losses.
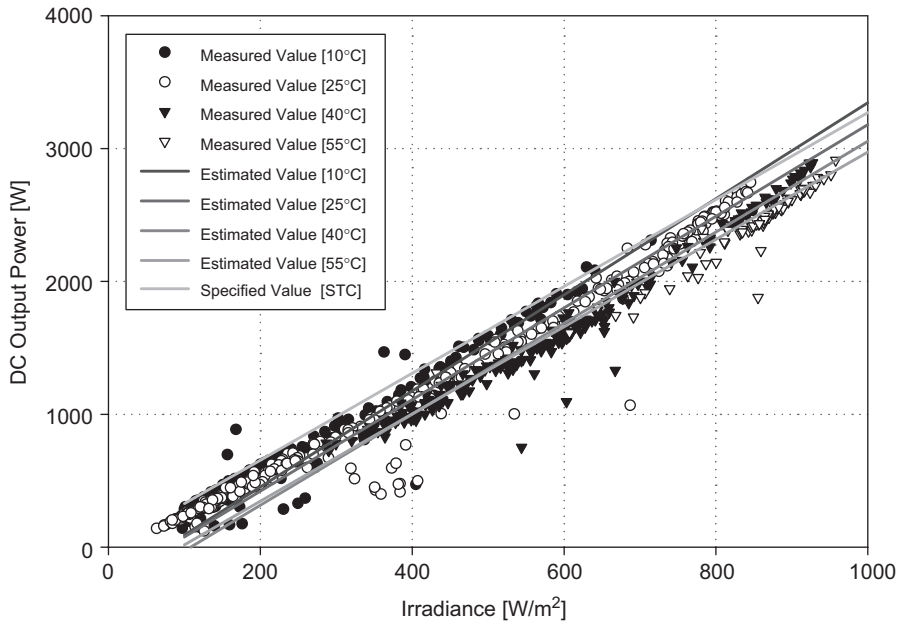
Fig. 7. PV array performance at surface temperature variation (system 1).

Figs. 7 and 8 show DC output power of the PV arrays (systems 1 and 3) according to PV array surface temperature variation for a full range of irradiance. DC output power generated by the PV array was linearly dependent on the irradiance except for lower irradiance due to the nonlinear characteristics. As shown in Fig. 7, the PV array (system 1) was comparatively constant for temperature variation with a wide range of irradiance. After comparing the estimated performance of PV array based on measured results at 25 °C of surface temperature with specified performance under STC, the residual between estimated and specified performance of PV array was low considering measurement accuracy error and loss factors, etc. In the PV array (system 2), DC output power of the PV array declined a little due to decreased PV array performance when irradiance fell below 300 W/m^2. When irradiance was higher than about 300 W/m^2, the conversion efficiency and performance of PV array became constant as shown in Fig. 8. When both the indoor and outdoor conditions were assumed under STC, compared with estimated value of the PV array (system 2), the big difference of PV array performance was caused by increased PV array losses due to PV module performance deterioration and mismatch of PV sub-arrays.

The measured results of each PV system are applied to analyze and evaluate loss factors of PV systems and components such as a PV array and PCU. As shown in Figs. 7 and 8, relationship between irradiance and DC output power of the PV array on PV array surface temperature can be approximated as the following linear regression:

$$P_{PV,Esti} = B_0 G_A + B_1, \tag{1}$$

where $P_{PV,Esti}$ is the estimated DC output power of PV array based on measured results (kW), G_A the measured irradiance on plane of PV array (W/m^2) and B_0, B_1 are regression coefficients of linear equation.
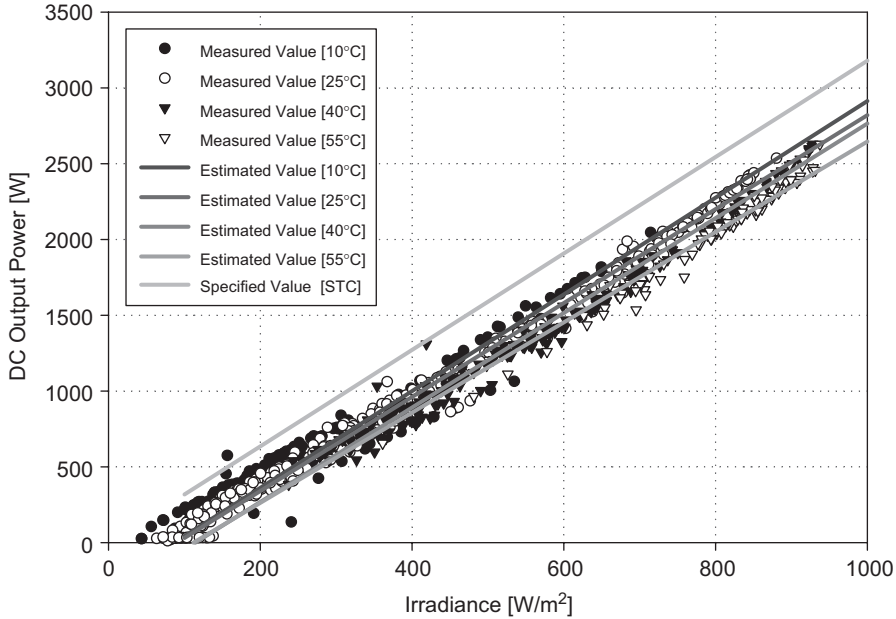
Fig. 8. PV array performance at surface temperature variation (system 2).

The residual between measured and estimated output power of each PV array can be calculated as follows:

$$R_{,PV} = \frac{(P_{PV,Meas} - P_{PV,Esti})}{P_{PV,Meas}}, \tag{2}$$

where $R_{,PV}$ is the residual between measured and estimated output power of PV array, $P_{PV,Meas}$, $P_{PV,Esti}$ are the measured and estimated output power (kW) of PV array, respectively.

With the definition in Eqs. (1) and (2), when the PV array surface temperature of each PV system which is measured by field test is $25\,°C \pm 2\%$ (range of $24.5–25.5\,°C$), the performance results of regression coefficient and residual output power of each PV array for irradiance on plane of PV array is summarized in Table 4.

As described in Table 4, the causes of big difference between measured and estimated output powers when irradiance goes down to about $200\,W/m^2$ is not only error of measurement accuracy but also nonlinear I–V characteristics of PV array. Therefore, there is difficulty in accurately estimating performance of PV array for lower irradiance. When irradiance is higher than $200\,W/m^2$, the residual between measured and estimated output power of the PV array ranges 0.3–3.3%. That is, the performance of the PV array can be comparatively accurately estimated in the region of higher irradiance compared to lower irradiance.

4.2. Analysis results of PCU performance

Figs. 9 and 10 show the efficiency characteristics of the PCUs (systems 1 and 3) installed in FDTC. Both PCU equipped with an MPP tracking function and carried out the auto

Table 4
Residual comparisons of the PV array output power

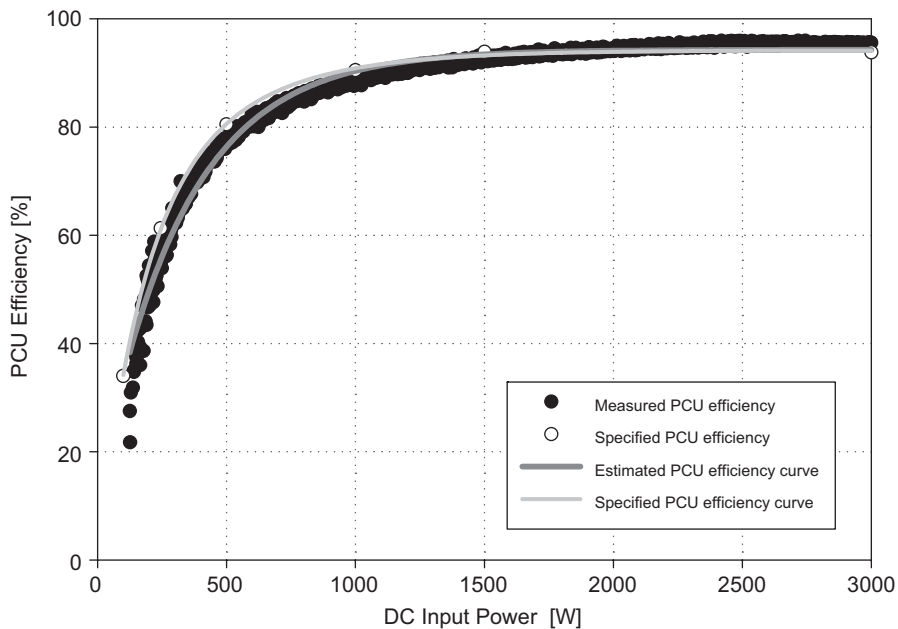| PV array (surface temp. 25 °C)		System 1	System 2	System 3	System 4
Regression coefficient	B0	3.45	3.1	3.65	3.07
	B1	−269	−279	−355	−229
Output power Irradiance (W/m^2)		Residual (%)	Residual (%)	Residual (%)	Residual (%)
	200	19.6	12.9	18.7	20.9
	400	0.8	0.4	7.2	0.5
	600	3.2	2.3	2.4	2.3
	800	0.3	1.8	1.8	0.4

Fig. 9. PCU efficiency (system 1).

start/stop procedures. When the irradiance was higher than about 100 W/m^2, PCU started supplying energy to the grid. PCU stopped supplying energy when the irradiance went down to about 70 W/m^2. When irradiance was higher than 200 W/m^2, the efficiency of PCU was approximately constant without large variation. However, when irradiance was under 200 W/m^2, the efficiency of PCU varied dramatically because it was difficult to track MPP of PCU due to nonlinear I–V characteristics of PV array. If PCU cannot perform to track accurately MPP, PCU losses will be increased largely by the effect of MPPT control failure.

As shown in Figs. 9 and 10, the PCU (system 1) operated with stability accurately for the full range of DC input power. But in the PCU (system 3), when PCU input power was
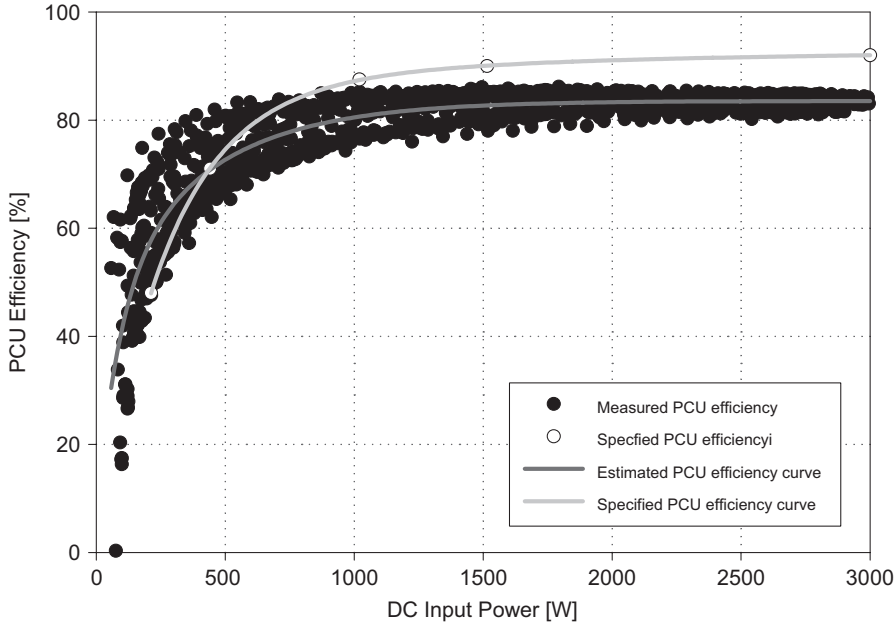
Fig. 10. PCU efficiency (system 3).

under 500 W, the efficiency of PCU showed comparatively large variation due to several troubles such as a MPPT control failure and PCU faults.

To evaluate and analyze performance of the PCUs, as shown in the above figures, relationship between DC input power and efficiency of the PCU is approximated by the following nonlinear regression:

$$\eta_{,\text{PCU}} = Y_0 + A\left(1 - e^{-BP_{\text{IN}}}\right) + C\left(1 - e^{-DP_{\text{IN}}}\right), \tag{3}$$

where $\eta_{,\text{PCU}}$ is the estimated PCU efficiency, P_{IN} the measured input power of PCU (kW) and Y_0, A, B, C, D, are the regression coefficients of the nonlinear equation.

The residual between measured and estimated efficiency of each PCU is described as follows:

$$R_{\eta,\text{PCU}} = \frac{(\eta_{\text{PCU,Meas}} - \eta_{\text{PCU,Esti}})}{\eta_{\text{PCU,Meas}}}, \tag{4}$$

where $R_{\eta,\text{PCU}}$ is the residual between measured and estimated efficiency of PCU and $\eta_{\text{PCU,Meas}}$, $\eta_{\text{PCU,Esti}}$ are the measured and estimated efficiencies of PCU, respectively.

With the definition in Eqs. (3) and (4), the performance results of regression coefficient and residual efficiency of each PCU for irradiance on plane of PV array are summarized in Table 5.

As described in Table 5, from the PCU (systems 1 and 4) performance it can be estimated that the residual of the PCU is under 1.6% for a full range of irradiance. When irradiance is 200 W/m² or less, the residual between measured and estimated efficiency of the PCUs (system 2 and 3) are more or less big. This means that PCU cannot be accurately performed to track MPP because conversion efficiency of PV array is varied suddenly due

Table 5
Residual comparisons of PCU efficiency

PCU		System 1	System 2	System 3	System 4
Regression coefficient	Yo	12.61	19.03	6.75	0
	A	81.67	59.36	37.84	86.61
	B	0.003	0.004	0.0025	0.0036
	C	–	13.85	38.96	23.15
	D	–	0.0007	0.01	0.0002
Efficiency Irradiance (W/m^2)		Residual (%)	Residual (%)	Residual (%)	Residual (%)
	200	0.2	14.3	12.6	0.6
	400	1.6	1.1	4.3	1.2
	600	0.4	0.4	0.7	1.2
	800	1.3	0.8	0.4	1.0

to nonlinear I–V characteristics of PV array on meteorological conditions for lower irradiance. When irradiance is higher than 200 W/m^2, the residual of the PCU (systems 2 and 3) has some difference in the range of 0.4–4.3%. From these analysis results by field test, if generation performance of the PV systems and components can be approximated by modeling equation using regression analysis, the performance of PV systems can be estimated and analyzed accurately for meteorological conditions and also, diagnosed losses factors and problems generated by operation. And also, the measured and specified output power of PV array and PCU provided by manufacturers are compared and shown in Figs. 7–10.

The residual between measured and specified performance of each PV array can be calculated as follows:

$$R_{PV} = \frac{(P_{PV,Meas} - P_{PV,Spec})}{P_{PV,Spec}},$$ (5)

where R_{PV} is the residual between measured and specified output power of PV array, $P_{PV,Meas}$ the averaged output power of PV array at 25 °C of PV surface temperature based on measured results (kW) and $P_{PV,Spec}$ the specified output of PV array provided with manufacturers at STC (kW).

The residual between measured and specified performance of each PCU is described as follows:

$$R_{\eta,PCU} = \frac{(\eta_{PCU,Meas} - \eta_{PCU,Spec})}{\eta_{PCU,Spec}}$$ (6)

where $R_{\eta,PCU}$ is the residual between the measured and specified efficiency of PCU and $\eta_{PCU,Meas}$, $\eta_{PCU,Specs}$ are the averaged efficiencies of PCU based on measured results and the specified efficiency of PCU provided with specification, respectively. The residual comparisons between measured and specified performance of PV array and PCU to irradiance on plane of PV array are summarized in Table 6.

The residual of PV array and PCU ranged from 4.5% to 38.5% and from 0.4% to 7.9%, respectively, for irradiance on plane of PV array. The big residual of PV array compared with PCU was generated due to several loss factors such as the error of measurement

Table 6
Residual comparisons of PV system output power

PV system		System 1	System 2	System 3	System 4
Surface temp. 25 °C	Irradiance (W/m^2)	Residual (%)	Residual (%)	Residual (%)	Residual (%)
PV array	200	19.9	38.5	29.9	19.0
	400	14.4	24.8	21.8	16.5
	600	11.1	19.0	9.4	12.5
	800	4.5	11.9	5.1	7.7
PCU	200	6.2	6.4	1.0	7.4
	400	2.9	6.2	5.6	1.4
	600	0.4	4.1	8.0	0.8
	800	1.5	2.4	8.6	2.2

accuracy, variation of meteorological conditions, PV module deterioration and so on. The residual of PV array (system 2) was high compared with the rest of the PV arrays. The big residual of PV array (system 2) was caused by increased PV array losses. In the PV array (system 3), when irradiance was under 400 W/m^2, the cause of big residual was the increased PV array losses due to surface temperature rise and mismatch. In general, the performance of PCU decreases residual in proportion to higher irradiance. However, on the contrary, the residual of the PCU (system 3) increased because the PCU contained various troubles due to design faults of PCU components such as a MPPT control, reactor, and transformer. Therefore, the efficiency of PCU diminished from 3% to 9% for a wide range of PCU operation compared with specification as described in Table 2.

4.3. Analysis results of the whole-system performance

Since the performance of PV system is strongly dependent on loss factors such as shading, PCS losses, mismatch, PV array temperature rise, etc. There is a necessity for reviewing these loss factors to evaluate and analyze accurately the performance of PV system. Therefore, the performance characteristics of PV systems are compared and analyzed using performance ratio (PR). PR is one of the most important performance indices to evaluate and analyze the characteristics of PV systems [7,8]. PR defined as the ratio of the actual performance to the theoretically possible performance of PV system can be calculated as follows:

$$PR = (E_{PV} G_{STC})/(P_{PV,nom} G_A), \tag{7}$$

where PR is the performance ratio, E_{PV} the system output energy to grid (kWh), G_A the irradiation on plane of PV array (kWh/m^2), $P_{PV,nom}$ the nominal power of PV array at STC (kW) and G_{STC} is 1 kW/m^2.

The main aspects causing PR decrease refer to shading, efficiency decrease by PV array temperature rise, mismatch, PCU losses, etc. With the definition in Eq. (7), Fig. 11 shows the comparison between measured and specified performance analysis of PV systems during one year of monitoring period.
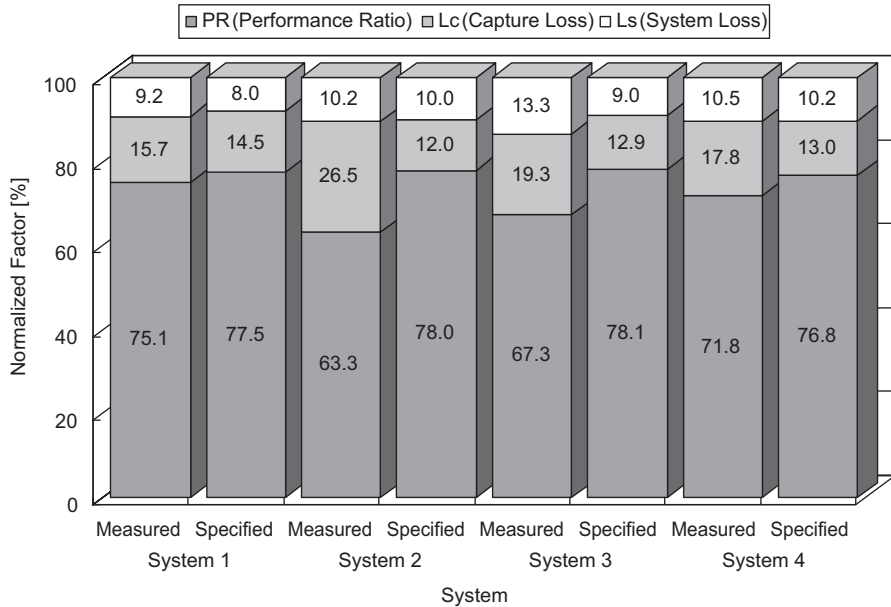
Fig. 11. Performance analysis of PV system.

The annual averaged PR ranged from 63.3% to 75.1% and capture losses Lc and system losses Ls were individually from 15.7% to 26.5% and from 9.2% to 13.3%. In general, if PR is under 70% in small scale PV system, various troubles will most likely occur causing system performance obstruction such as PCU faults, PV module depreciation, meteorological conditions (shading, dirt, snow), mismatch, etc. [8]. From those performance analysis results, the performance of PV systems was simulated using PVSYST program with specified parameters provided by specifications of PV components and compared with measured performance results of PV systems. As a result, the PR ranged of 76.8% to 78.1% and both PV systems operated comparatively well without troubles as shown in Fig. 11. The residual of capture losses (Lc) and system losses (Ls) between measured and specified performance of PV systems were individually from 1.2% to 14.5% and from 0.2% to 4.3%. That means that PV systems (systems 2 and 3) have various troubles of system performance obstruction. In the PV system (system 2), when irradiance went down to 300 W/m^2, the conversion efficiency of PV array varied suddenly from 3% to 10% due to PV module performance deterioration on meteorological conditions and mismatch of PV sub-arrays. Therefore, the decrease of PR was caused by increased Lc. In the PV system (system 3), when irradiance fell below 300 W/m^2, the conversion efficiency of PV array also varied suddenly from 4% to 10% due to performance deterioration of PV array for meteorological conditions. And also, the estimated efficiency of PCU was less than 7% in comparison with specification as described in Table 6. The cause of lower efficiency was design faults of PCU components. Therefore, it was known that the performance of PV system (system 3) comparatively declined due to increased Lc for lower PCU efficiency.

Supposing the performance of PCU (system 3) has almost the same performances as specification provided by manufacturer, approximated regression models of PV

components were applied to estimate the performance of PV systems with PVSYST program. As a result, the PR was 72% and PV system was expected to operate comparatively well without faults.

5. Conclusions

Monitoring system and four 3 kW grid-connected PV systems were installed at FDTC to investigate the overall effect of operational characteristics. The performance of 3 kW grid-connected PV systems were compared and analyzed during one year of monitoring period and loss factors were also reviewed. As a result, the performance of PV system (system 2) declined since PV array losses increased about 14% or more due to PV module deterioration and mismatch of PV sub-arrays. In the PV system (system 3), the PCU efficiency dropped in the range of 3–9% for a wide range of operation. The performance of PCU declined with increased 5% or more PCU losses due to design faults of PCU components such as reactor and transformer, etc.

Supposing the performance of PV system (system 2 and 3) has the same performance as specification described in Table 2, the performance of PV systems has a capability to improve 13% or more in comparison with actually measured performance identified by field test. On the basis of monitoring results, an evaluation and analysis approach for PV system will be planned to develop and confirm their validity to establish practical technologies of PV systems.

Acknowledgments

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