Monitoring and Analysis of 3kW Grid-Connected PV System for Performance Evaluation

Jung-Hun So†, Young-Seok Jung*, Gwon-Jong Yu*, Ju-Yeop Choi and Jae-Ho Choi*****

Abstract - Grid-connected photovoltaic (PV) systems were installed and monitored at the field demonstration test center (FDTC) in Korea in October 2002. Before long-term field testing of installed PV systems, the performances of PV components were evaluated and compared through short-term performance tests of each of the PV system components such as power conditioning system and PV module under standard test conditions. A data acquisition system has been constructed for measuring and analyzing the performance of PV systems to observe the overall effect of environmental conditions on their operation characteristics. Performances of PV systems have been evaluated and analyzed not only for component perspective (PV array, power conditioning unit) but also for global perspective (system efficiency, capacity factor, electrical power energy) by review of the field test and loss factors of the systems. These results indicate that it is highly imperative to develop an optimum design technology of grid connected PV systems. The objective of this paper is not only to evaluate and analyze the performance of domestic PV systems application through long-term field testing at FDTC but also to develop evaluation, analysis and optimum technology for long-term stability and reliability of grid-connected PV systems in Korea.

Keywords: Performance ratio, Photovoltaic system, Power conditioning system

1. Introduction

Focus on the Photovoltaic (PV) system has been increasing around the world since its reputation is becoming widespread as a clean and gentle energy source for the earth. In the future, the research and development to establish utilization technologies for the stability and reliability of PV systems will take on even more significance in this area as high-density grid-connected PV systems will be interconnected with distribution networks. To solve this matter, one of the developed countries has already been moving ahead with countermeasure research for generated problems in dispersed generations by long-term field testing. In this paper, a total of six units of a grid-connected 3kW PV system were installed at a field demonstration test center (FDTC) in Korea in Oct. 2002 [1, 2]. Before long-term field testing of each installed PV system, the performance of PV components were measured and evaluated through short-term performance testing of each of the PV system components such as the PV module under standard test conditions (STC) and the Power conditioning system (PCS) [3]. A monitoring system was constructed for measuring and analyzing the performance of the PV system to observe the overall effect of meteorological conditions on their operational characteristics by field testing. The performance of PV systems was evaluated and analyzed not only for component perspective but also for global perspective by field testing. Loss factors (faults, PCS losses, PV array losses) were also reviewed. On the basis of these investigation results, the performance of PV systems was analyzed and evaluated via simulation and compared with actual performance of PV systems. These results will indicate that it is very important to develop evaluation, analysis and optimum design technology for stability and reliability of grid connected PV systems.

2. System Description

3kW grid-connected PV systems installed in the FDTC to evaluate and analyze overall performance by long-term field testing are shown in Fig. 1. PV systems consist of a single roof mounted system and five ground mounted systems, and nominal capacity of each PV array ranges from 3 to 3.3kW. Both PV arrays are set in a fixed tilt of 18 degrees with azimuth of 0 degrees (south). Each PV array is composed of three poly-crystalline and three mono-crystalline PV modules, which are provided by different

† Corresponding Author: Korea Institute of Energy Research, Korea. (jhso@kier.re.kr)
* Korea Institute of Energy Research, Korea.
** Dept. of Electrical Engineering , Kwangwoon University, Korea. (ju yeop@daisy.gwu.ac.kr)
*** Dept. of Electrical Engineering, Chungbuk National University, Korea.(choi@power.chungbuk.ac.kr)
Received April 13, 2004 ; Accepted August 24, 2004

manufacturers. The arrangement of PV array was decided in accordance with the specification of PCS provided by different manufacturers. The parameter of PV module and PCS used at the FDTC are summarized in Tables 1 and 2.

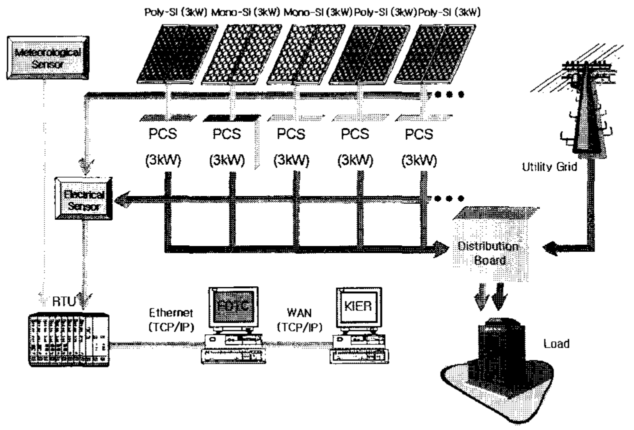


Fig. 1 System overview

Table 1 Specifications of PV module at STC

Module	Rated [W]	V_{MPP} [V]	I_{MPP} [A]	V_{OC} [V]	I_{SC} [A]
A	78	17.2	4.46	21.5	4.88
B	50	17.1	2.92	21.0	3.17
C	53	17.4	3.05	21.7	3.35
D	68	16.2	4.2	21.2	4.7
E	75	17.3	4.35	21.8	4.75
F	75	17.3	4.35	21.8	4.75

Table 2 Specifications of PCS (under rated conditions)

PCS	Rated [W]	DC input [V]	Efficiency [%]	THD [%]
A	4kW	200	95% or more	5% or less
B	3kW	255	90% or more	5% or less
C	3kW	340	90% or more	5% or less

The PV systems are fully monitored and supervised not only to evaluate and analyze the performance of PV systems on environmental conditions but also to develop PV system application technology with meteorological sensors and electrical sensors. The measured data of the PV systems are collected in a one second sampling period so that operational characteristics can be evaluated and analyzed. PV systems have been monitored from Mid-October 2002 to present. Measurement data are recorded averaged every six minutes and hourly and stored on a computer disk. The installed monitoring system can be remotely supervised through a wide area network. In this monitoring system, the following items are measured to evaluate and analyze the performances of PV systems.

Electrical measurement items
- DC and AC voltages
- DC and AC currents
- AC power
- Load Power
- Power to/from Utility grid
- Utility grid and PCS frequency

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

3. System Performance

3.1 Array performance

PV systems installed at the FDTC are becoming widespread domestically and the performance of PV systems is compared and analyzed from October 2002 to March 2003 to develop the optimum design of PV system components (PCS, PV module and array) and installation method of PV systems. The monthly output energy of PV array and its efficiency in PV systems for the monitoring period are shown in Figs. 2 and 3. The total DC output power energy generated by PV array is respectively 1.71MWh (system 1), 1.05MWh (system 2), 1.43 MWh (system 3), 1.67MWh (system 4), 1.51MWh (system 5), and 0.76MWh (system 6). In the case of PV systems (systems 2 and 6), DC output energy of the PV array is decreased in comparison with other PV systems. The reason why performance of the PV array is decreased is not due to PV array troubles but rather PCS troubles. DC output power generated by the PV array is linearly dependent on irradiance except for lower irradiance due to the nonlinear characteristics. With the exception of PV arrays of PV systems (systems 2 and 6), the monthly conversion efficiency of PV arrays varies from 7.2% to 10.9%. In January 2003, PV array conversion efficiency drops dramatically, which can be caused by environmental conditions such as snow and external temperatures below zero. That means that the conversion efficiency of the PV array does not strongly depend on irradiance but rather on module surface temperature from analysis results of PV system performance [3]. Therefore, there is a necessity for carrying out a detailed temperature correction of the PV module efficiency. This dependence has been investigated on DC output versus meteorological characteristics such as irradiance and PV array surface temperature.

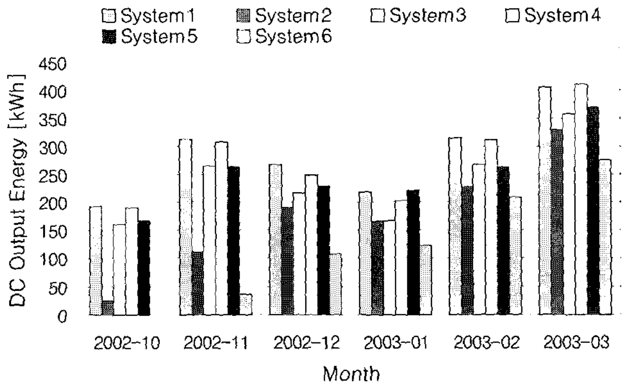


Fig. 2 Monthly DC output energy

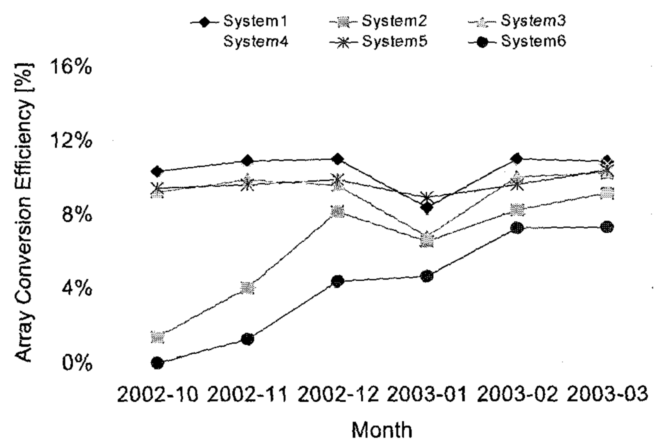


Fig. 3 Monthly DC output energy

3.2 PCS performance

The monthly averaged efficiency of PCS and its operation performance for the monitoring period are shown in Figs. 4 and 5. Both PCSs are equipped with a MPP tracking system. The inverter starts supplying energy to the grid when irradiance is about 100 W/m^2 and stops supplying energy when irradiance goes down to about 80 W/m^2. Before the inverter begins supplying energy to the grid, it has to carry out the auto test procedures. The efficiency of the PCS for irradiance values higher than about 200 W/m^2 is approximately constant but for the lower irradiance, the efficiency is strongly dependent on irradiation. The total averaged efficiency of the PCS is individually 88.7% (system 1), 75.3% (system 2), 82.4% (system 3), 78.5% (system 4), 87% (system 5), 86.3% (system 6) and total averaged availability of the PCS ranges from 40.4 to 30.2%. Through performance results of PCS availability, in the case of PV systems (systems 2 and 6), it is known that performance of the PV system is declined because the PCS ceases operation for a lengthy time due to faults or troubles caused by the field testing. When irradiance changes suddenly, the PCS installed in the PV systems (systems 2 and 6) are halted and are also lower in efficiency than other systems. The cause of lower efficiency is faults or troubles of the PCS since actual performance of the PCS according to field testing is less efficient than performance provided by manufacturers as described in Table 2.

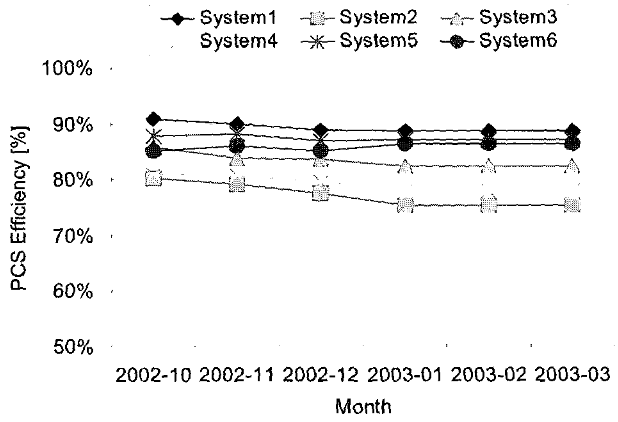


Fig. 4 Monthly averaged PCS efficiency

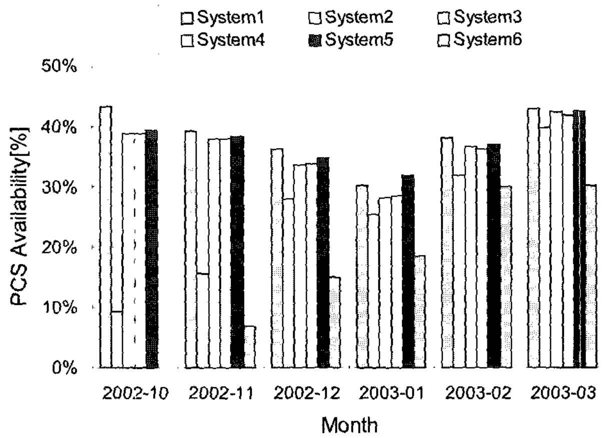


Fig. 5 Monthly averaged PCS availability

3.3 Whole System Performance

Figs. 6, 7 and 8 show the monthly output energy and monthly averaged capacity factor and system efficiency of the PV system. On an absolute basis, the total output energy of each PV system during an operation period is all energy generated between 0.64 and 1.54MWh respectively. The efficiency and capacity factor of each PV system ranges from 3.8 to 9.4% and from 5.2 to 11.8%. As demonstrated in the figures, in the case of the PV array (system 3), when irradiance goes down to about 300W/m^2, conversion efficiency of the PV array is varied suddenly from 3 to 10% due to nonlinear characteristics of PV array I-V performance for meteorological conditions. That means that it is difficult to accurately track MPP control because performance of the PV system is varied dramatically due to PV module performance degradation and series-parallel unbalance of the PV array. Therefore, performance of the PV system is lowered since PV array (system 3) losses are increased more than those of the PV systems. Conversion efficiency of the PV array (system 4) is also varied suddenly from 4 to 10% due to nonlinear characteristics of PV array I-V performance for meteorological conditions when irradiance falls below 300W/m^2. In the case of the PV array (systems 1 and 5) conversion efficiency is comparatively constant in the range of 8 to 11% for a wide range of irradiance. But since the PV array (system 5) is installed as a roof mounted type, PV array losses by temperature rise compared to other PV systems are increased and generation performance is more or less declined. The performance of the PCS (system 4) is decreased due to PCS losses for lower PCS efficiency. When irradiance is under 300W/m^2, the variation of PCS performance is generated largely due to nonlinear characteristics of PV array I-V performance for meteorological conditions. Therefore, it is known that PCS performance is diminished because PCS losses are increased largely by MPPT failure according to the effects of stability and quick response.

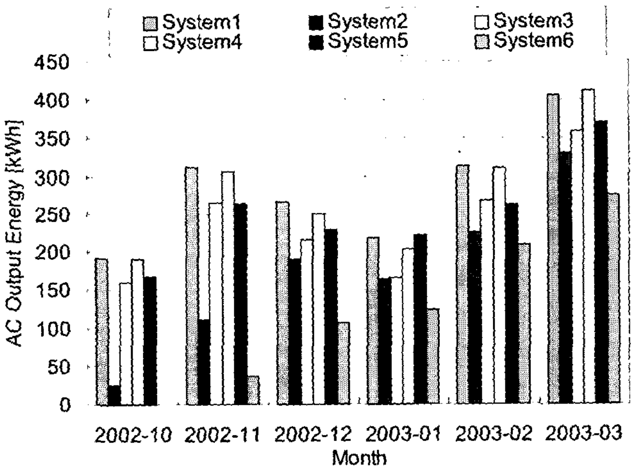


Fig. 6 Monthly PV system energy output

Since performance of the PV system is strongly dependant on loss factors such as shading, PCS losses, MPPT mismatch, etc., these loss factors must be evaluated and analyzed accurately. Therefore, performance characteristics of the PV system were analyzed during the monitoring period using performance ratio (PR) evaluated loss factors of the PV system. PR is one of the most important factors to evaluate and analyze characteristics indices of PV systems [3,4]. The main aspects causing PR decrease refer to shading, array temperature rise, MPPT mismatch, and PCS losses etc.

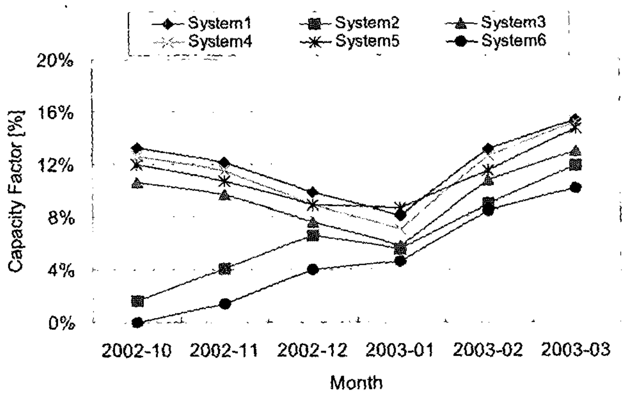


Fig. 7 Monthly averaged PV system capacity factors

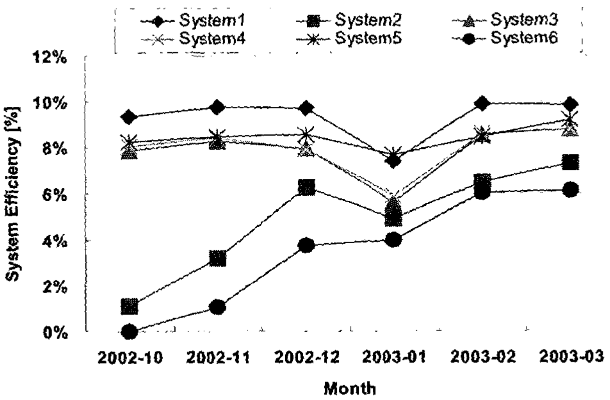


Fig. 8 Monthly averaged PV system efficiency

PR is defined as ratio of the actual performance of a photovoltaic system to the theoretically possible performance and can be calculated using Equation (1)

$$PR = (E_{PV} \times G_{STC})/(P_{PV,nom} \times G_A) \qquad (1)$$

Where ***PR*** is performance ratio, $\boldsymbol{E_{PV}}$ is system output energy, $\boldsymbol{P_{PV,nom}}$ is nominal output power at STC, and $\boldsymbol{G_A}$ is total irradiation respectively [4].

With the definition in Equation (1), the monthly averaged performance ratio (PR) of PV systems is shown in Fig. 9. The total averaged PR of PV systems ranges from 40.8 to 78.9%. In general, if PR is under 70%, various troubles will most likely occur causing system performance obstruction such as inverter faults, PV module depreciation, meteorological conditions (shading, dirt, snow), MPPT mismatch, etc. Fig. 10 presents the analysis results of PR, capture losses (Lc) and system losses (Ls) of PV systems for 1 year of the monitoring period. Ls are due to losses in DC to AC energy conversion. Lc are due to PV array losses. Using design parameters provided by specification of PV components such as PCS and PV modules, performance of the PV system is simulated by the PVSYST analysis tool for PV. As a result, the PR ranges of 74.8 to 78.9% and both of the PV systems are operated comparatively well without occurrence of difficulty. However, on the basis of actual measured results, PR ranges from 40.8 to 78.1%, and the Lc and Ls of each PV system individually range from 13.3 to 51.3% and from 7.8 to 15.7%. It is known that PV systems (systems 2, 3, 4 and 6) have some troubles on system performance obstruction. From performance results of PV systems by field testing, in the case of PV systems 2 and 6, the PR of the PV system is lower than that of other PV systems. The cause of lowered PR is a PV system that has halted operation for a long period of time due to PCS troubles and delayed installation. When irradiance goes down to about 300W/m^2, in the case of PV system 3, the PCS has more difficulty in tracking MPP because conversion efficiency of the PV array is varied suddenly from 3 to 10% due to the nonlinear characteristics of PV array I-V performance for meteorological conditions. Decrease of the PR can be caused by Lc such as PV module degradation and series-parallel unbalance of PV array. In the case of PV system 4, when irradiance is fallen below 300W/m^2, conversion efficiency of the PV array is also varied suddenly from 4 to 10% due to nonlinear characteristics of PV array I-V performance for meteorological conditions and the PCS is less efficient than performance provided by the manufacturer. Actual efficiency of the PCS is less than 7% in comparison with the specifications described in Table 2. The cause of lower efficiency is generated by the incorrect optimum selection and design of the PCS component devices. Therefore, it is known that the performance of PV system 4 is declined due to Ls increase for lower PCS efficiency. Supposing that the performance of PCS system 4 provides almost the same performance output as the specification provided by the manufacturer, approximated regression models of the PV component devices are applied and performance of the PV systems can be estimated using a simulation tool. As a result, the PR is 0.73 and the PV system is expected to operate comparatively well.

4. Conclusion

Monitoring systems and 3kW grid-connected PV systems, which are becoming prevalent in Korea, are installed at the FDTC. Performance characteristics of PV systems and loss factors are reviewed by long-term field testing. As a result, in the case of PV system 2 and 6, PV array losses are dropped dramatically but the cause of PV system performance decrease is generated by stopping the PV system operation for a great length of time due to PCS troubles and delayed installation. Therefore, decrease of the PR is not the result of capture losses (Lc) but system losses (Ls). In the case of PV system 3, performance of the PV system is declined since PV array losses are increased by about 14% or more due to PV module degradation and series-parallel unbalance of the PV array. In the case of PV system 4, efficiency of the PCS is dropped to the range of 3 to 9% compared with the specification for a wide range of operations due to PCS losses according to incorrect optimum selection and design of PCS components such as the reactor, transformer and generation performance.

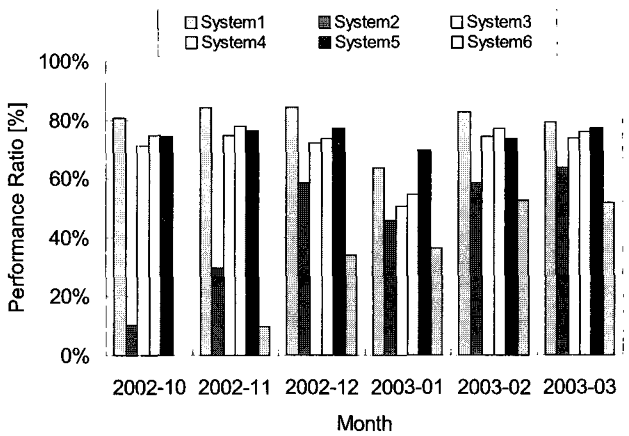


Fig. 9 Monthly averaged PV system performance ratio

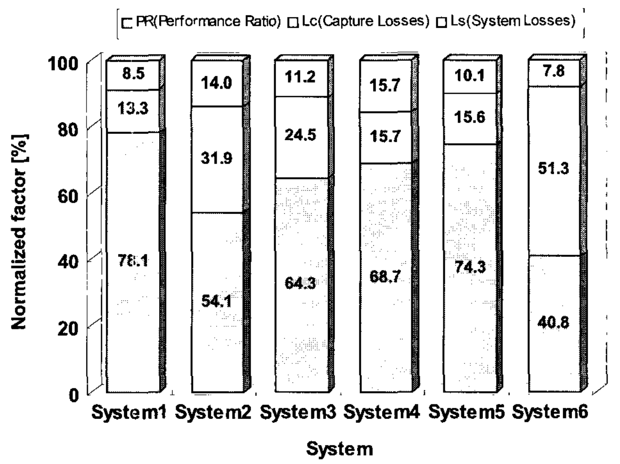


Fig. 10 Analysis results of PV systems

Supposing that the performance of PV systems (systems 2, 3, 4, and 6) components have the same performance as the specifications described in the Table. The performance of the PV systems will be able to improve by about 15% or more in comparison with actual performance by field testing. On the basis of analysis results, to establish utilization technology such as performance improvement, reliability and stability of PV systems and generating problems due to the grid-connected PV systems, evaluation, analysis and optimum technologies for PV systems will be planned in order to develop and confirm their validity.

Acknowledgements

This work was supported by the Energy Technology R&D project from the Republic of Korea's Ministry of Commerce, Industry and Energy.

References

[1] Didier Thevenard, "Performance monitoring of a northern 3.2kWp grid-connected photovoltaic system", pp.1711 – 1715, *IEEE*, 2000.

[2] E. E. Van Dyk, E. L. Meyer, F. J. Vorster, and A. W. R. Leitch, "Long-term monitoring of photovoltaic devices", *Renewable Energy*, vol. 25, Issue 2, pp. 183-197, Feb. 2002.

[3] T. Sugiura, T. Yamada, H. Nakamura, M. Umeya, K. Sakura, and K. Kurokawa, "Measurements, analyses and evaluation of residential PV systems by Japanese monitoring program", *Solar Energy Materials & Solar Cells*, vol. 75, Issues3-4, pp. 767-779, Feb. 2003.

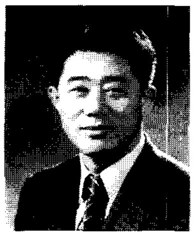
[4] M. Sidrach-de-Cardona, and Ll. Mora Lopez, " Performance analysis of a grid-connected photovoltaic system", *Energy*, vol. 24, Issue 2, pp. 93-102, Feb. 2003.

Jung-Hung So

He received his B.S. and M.S. degrees in Electrical Engineering at Yeungnam University, Korea in 1994 and 1996, respectively. Since 1996, he has been a Researcher at the Photovoltaic System Research Center of the Korea Institute of Energy Research. His primary research interests are photovoltaic systems and virtual instruments. He is a member of KIEE, KIPE, and KSES.

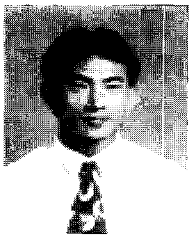
Young-Seok Jung

He received his B.S. and M.S. degrees in Electrical Engineering at Chungbuk National University, Korea in 1994 and 1996, respectively. Since 1996, he has been a Researcher at the Photovoltaic System Research Center of the Korea Institute of Energy Research. His primary research interest is grid connected PCS (Photovoltaic Conditioning System). He is a member of KIEE, KIPE, KSES, and IEEE.



Gwon-Jong Yu

He received his B.S. degree in Electrical Engineering at Chosun University, Korea in 1982, and his M.S. and Ph.D. degrees from Kobe University, Japan, in 1985 and 1989, respectively. Since 1996, he has been a Center Manager at the Photovoltaic System Research Center of the Korea Institute of Energy Research. His primary research interests are photovoltaic systems and dispersed generation. He is a member of KIEE, KIPE, KSES, and IEEE.



Ju-Yeop Choi

He received his B.S. degree in Electrical Engineering from Seoul National University, Korea in 1983, his M.S. in Electrical Engineering from the University of Texas, Arlington, USA in 1990, and his Ph.D. in Electrical Engineering form Virginia Tech., USA in 1994. He was with the Intelligent System Control Research Center, Korea Institute of Science and Technology from 1995 to 2000. Since 2000, he has been an Assistant Professor of Electrical Engineering at Kwangwoon University. His primary research interests are switching converters, soft switching and power conditioning systems for photovoltaic systems. He is a member of KIEE, KIPE, and KSES.

Jae-Ho Choi

He received his B.S., M.S., and Ph.D. degrees in Electrical Engineering at Seoul National University, Korea in 1979, 1981, and 1989, respectively. From 1981 to 1983, he worked as a Full-time Lecturer in the Dep. of Electronic Engineering at Jungkyoung Technical College. Since 1983, he has been a Professor of Electrical and Electronics Engineering at Chungbuk National University. His primary research interests are the DSP based UPS system, active power filter development power quality issues, and dynamic UPS, etc. He is a member of KIEE, KIPE, IEEE, IEEJ, and EPE.