JPE 8-4-10

# Utility Interactive PV Systems with Power Shaping Function for Increasing Peak Power Cut Effect

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**ABSTRACT**

This paper describes the Utility Interactive PV (UIPV) system which can improve the peak-cut effect by adding an energy storage device of batteries to the power converter. The proposed system has three possible operation modes depending on relative condition of PV output, which can have the power shaping function covering the peak power for 3 hours. A new power circuit and an application algorithm have been applied to the UIPV system which is based on working PV system during a 3-hour peak time. The energy relationship by the proposed system is analyzed theoretically and experimentally. The proposed system is evaluated at the viewpoint of cost and total spacing, which enables the proposed UIPV system to have the reduction of the peak power demand and hence to improve the power capacity of peak cut.

**Keywords**: Peak power cut effect, Energy storage device, UIPV system, Operation Modes, Peak cut power capacity

## 1. Introduction

Power electronics, the studies related to renewable energy systems with grid-connection, have been mainly focused on technical development related to power generation, maximum power and anti-islanding protection [1-3]. In particular the Utility-Interactive Photovoltaic (UIPV) system has an annual utilization rate of 12.5%[4], which means the power rating with continuous power output for one year, considering all environmental conditions.

In practical terms, a certain peak point of power consumption exists in large-scale loads such as in office buildings and factories for a fixed period, i.e., one day. If this peak power would be greater than the power level contracted, so the consumers should pay much more in electricity charges. The more cooling systems are used such as air conditioners, the higher the exceeding possibility of the predetermined level, and hence the more the electrical charges. So reducing power consumption by load control, i.e., peak-cutting is intensively required to save the electric charges at each load unit, which can improve the efficient utilization at the power utilities [5].

Manuscript received June. 25, 2008; revised Sept. 1, 2008
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During the summer season on the Korean Peninsula the daily peak of power consumption occurs during 3 hours between noon and 3 o'clock in the afternoon as in Fig.2[4,6]. The generating characteristics of the PV system are suitable to reduce the peak power demand in summer, because it has the highest power output for roughly 3 hours. The PV system has nearly the same time interval as the daily peak time [7], but there is a time delay between peak power demand and peak power generation of the PV system around noon. This delay time would make the effect of peak-cut effect, and the case study[8] was reported by the reduction of 16~33[%].

The use of energy storage devices such as batteries could be considered in order to compensate for this delay and also to improve peak-cut effect. The time gap could be covered by shifting the output energy of the UIPV system using the stored energy of a battery, which is called power-shaping function. To accomplish the proposed idea, the control sequence related to three operation modes of power balance, shortage and surplus are suggested for various operating conditions of PV systems. A battery charger is added to the PV system and also a new power topology with a continuous current is proposed to overcome the defect of the conventional boost converters with the discontinuous current.[9,10]

To show the validity of the suggested system, 1[kW] UIPV system with new boost converter and battery is studied in this paper. As a result the proposed system could require smaller spacing and lower cost, which is reduced to one half of the conventional systems. Also it can be revealed that the proposed system with a battery has the possibility of reducing the peak power demand through the field test results.

## 2. The Proposed UIPV System

The proposed UIPV system of Fig.1(a) has 1 kWp PV-array, new DC boost converter with three-winding transformer, battery, inverter.

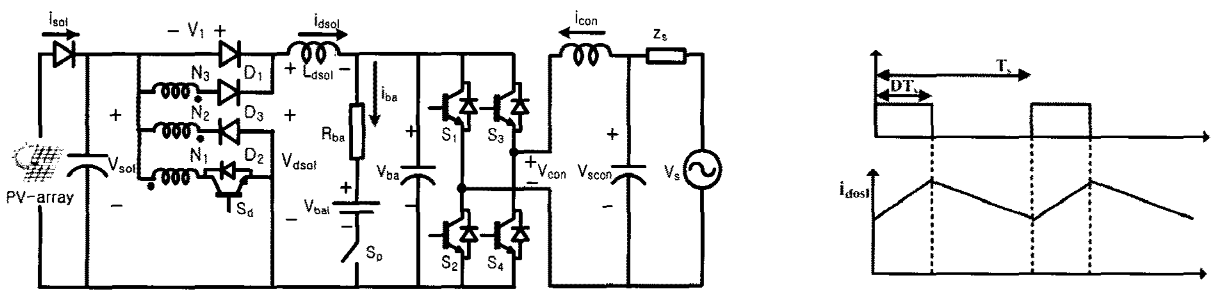
### 2.1 New Boost DC-DC Converter

In the conventional boost converters the current has the discontinuity, and so it deteriorates the performance of the battery. To improve this defect, a boost DC-DC converter with the continuous current is suggested as in Fig.1(a).

Suppose the switch $S_d$ of Fig.1(a) of the boost converter is turned on. The voltage of winding $N_1$ becomes positive at the dotted side, and the voltages of winding $N_2$ and $N_3$ become positive at the dotted ones. As the diode $D_3$ is turned on, so the boosted voltage $V_{dsol}$ added by the voltage $V_1$ appears at the DC output side.

The power of boost converter $V_1 I_{dsol}$ is transferred from the primary winding $N_1$ with the switch $S_d$ to the DC link side. So the inductor current $i_{dsol}$ begins to rise during ON-time $DT_S$ of Fig.1(b). Also if $S_d$ is turned off during the OFF-time $(1\text{-}D)T_S$, then both diodes $D_1$ and $D_2$ are turned on, and so the energy stored at $N_2$ is discharged through $D_2$ to the capacitor paralleled with the PV array. The output voltage $V_{dsol}$ is equal to the PV output voltage $V_{sol}$ through turned-on $D_1$. Then the current becomes decreased and so continuous current $i_{dsol}$, which has lower ripples, is observed. As seen in Fig.1(b), even if $S_d$ is turned off for OFF-time $(1\text{-}D)T_S$, then the current $i_{dsol}$ keeps flowing continuously. This is a merit of the proposed topology of boost converter.

The average output of boost converter controlled by $S_d$, is derived as




(a) Power circuit with proposed boost converter (b) Continuous output current of boost converter

Fig. 1 The proposed UIPV system

$$V_1 = \frac{N_3}{N_1} \cdot D \cdot V_{sol} \quad (1)$$

where D means the duty ratio of switch $S_d$. The DC link voltage $V_{dsol}$ becomes the sum of PV array output voltage $V_{sol}$ and the boosted voltage $V_1$. Under steady state the power relationship of Fig.1 is obtained as

$$P_{sol} = V_{sol} I_{sol} = V_{dsol} I_{dsol} = V_{sol} I_{dsol} + V_1 I_{dsol}. \quad (2)$$

### 2.2 Basic Operation

In the utility interactive PV systems, the factors such as voltage and frequency, power factor, THD should be met as the requirements of the Power Company, which are 220[V]±13[V], 60[Hz]±0.3[Hz], PF=90%, THD= 5[%] respectively. The PV array is set to 1[kWp] and the nominal voltage is 340[V]. The boosted converter has the switching frequency of 20[kHz] and duty cycle is set to the value less than 50%, and the actual boosted ratio is 114.7%. Total battery bank has nominal voltage of 396[V] and 30[Ah] rating, and the switching frequency of the inverter is set to 10[kHz].

Fig.1(a) has three power parts of boosted DC-DC converter, battery with switch $S_P$ and the power converter composed of four switches. The switch $S_P$ is used to charge the battery and also for peak power cut action, and if $S_P$ is open, then the UIPV system cannot perform the peak cut function.

When the power converter continues to work as a DC-AC inverter, it sends the PV power to the Grids for 3-hour peak-cut action, and the battery may be under the discharge state according to the operation condition. And the power converter could be an AC-DC rectifier in a case where the power is supplied from the Grids to charge the battery. Also the battery could be charged by PV array through the boost converter except for the peak-cut time interval. In this case the operation of the inverter stops, and the generated PV power $P_{sol}$ is delivered to the battery.

## 3. The Proposed Control Sequence

Fig.2 shows the daily load curves of power consumption[4] for various loads, and most loads begin to increase at 7:00 AM and have each peak between 12:00 PM ~ 3:00 PM except for residential loads.

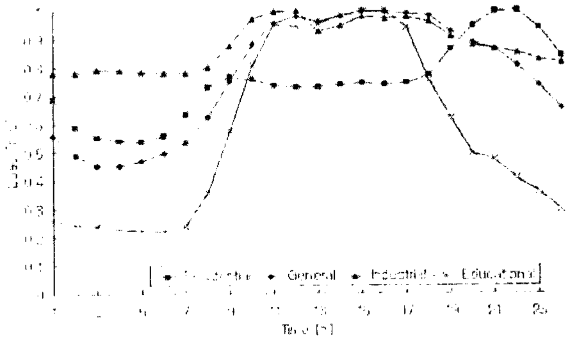
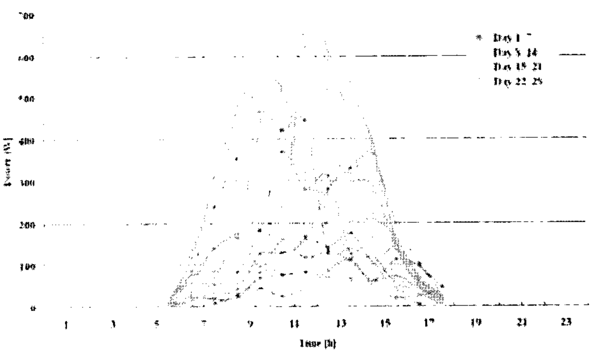
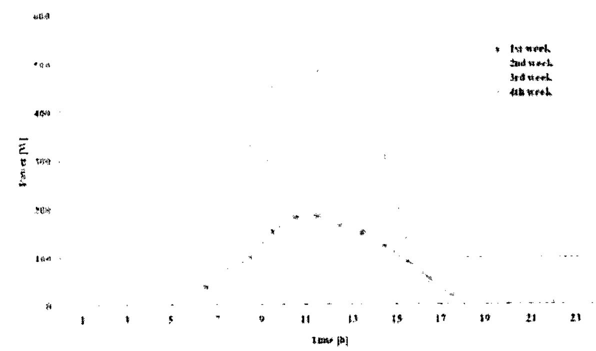


Fig. 2 The daily load curves

Also the output power generated by 1kWp PV system is represented as in Fig.3, and these data are measured during August 2007. Fig.3(a) shows daily power, and (b) average power for each week from the curves of Fig.3(a). It can be seen the power generated by PV system changes largely for every week, and the power becomes so much lower than the nominal value of 1 kW PV power because August comes during the rainy season in Korea.



(a) daily power output



(b) daily average power for each week.

Fig. 3 The AC power generated by 1 kWp PV system measured for 4 weeks

Here, we define the daily generating energy of PV-array, $E_{PV}$, as

$$E_{PV} = \int_0^{generation\ time} v_{sol} i_{sol} dt \ [kWh] \quad (3)$$

if all factors such as utilization factor, rating of PV and generation time are predetermined statistically. By comparing $E_{PV}$ to the annual average generation energy $E_{AAG}$ obtained as the daily average of total generation energy summation for 1 year,(in this paper $E_{AAG}$ is set to 3kWh because 1 kW PV system woks for 3 hours only), three possible operation modes can be considered as follows:

① Mode I : $E_{PV} = E_{AAG}$
② Mode II : $E_{PV} > E_{AAG}$
③ Mode III : $E_{PV} < E_{AAG}$.

The conceptual diagram of these Modes is described in Fig. 4. In Mode I (solid line in Fig. 4), two energies, $E_{PV}$ and $E_{AAG}$ have the same amount. This means the daily generating energy (area ScdT) is equal to the annual average value (area abfe = $1/3 E_{AAG}$). Hence the inverter continues to send both PV generated energy (area abdc) and battery discharged energy (area cdfe) to the Grids during the pre-determined 3 hours. In Mode I, the preset generation power is 1[kW], and hence the UIPV system operates under peak cutting action of 1[kW] for 3 hours. The battery keeps discharging during the 3 hours, and the discharged energy is equal to the energy summation of area A and A'. The area A' means the battery energy which was charged actually during the previous day from the after-cutting action of PV array. If the charging state of the battery becomes insufficient, then the shortage power for charging should be supplied from the Grids.

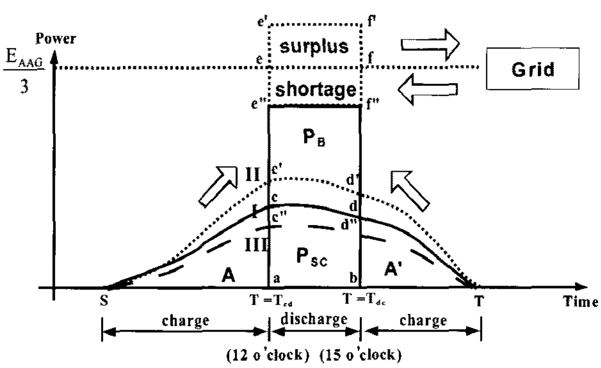



Fig. 4 The related control sequence of the proposed UIPV system

In Mode III (broken line in Fig. 4) the daily generating energy (area Sc"d"T) becomes less than the annual average value $E_{AAG}$. As the PV system has lower output and it is hard to charge the battery sufficiently, the Grids would supply the shortage energy (e"f"fe) by the amount required to charge the battery. For shortage power the cheapest energy would be chosen such as midnight electricity (normally midnight energy from 11 o'clock at night to 9 o'clock the next morning), which is a half of the regular price according to the policy of KEPCO (Korea Electric Power Company). In Mode II (dotted line in Fig. 4), the daily generating energy (area Sc'd'T) exceeds the annual average value, and so the surplus energy (eff'e') more than the preset 1[kW] value is sent to the Grids for off-peak power time as in Mode II of Fig. 9.

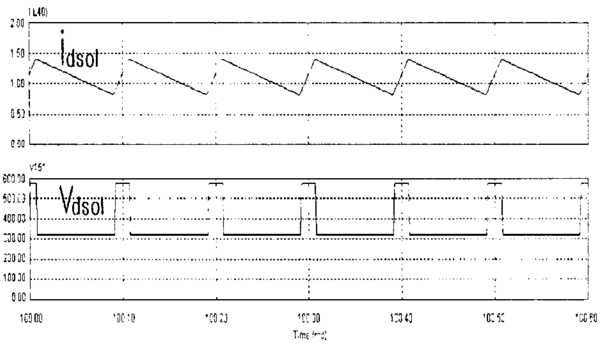
Actually the surplus energy cannot exceed the rated power rating of 1[kW], and hence the surplus power would be sent to the Grids during that time except for peak power time as shown in Fig.9(b). These explanations are basic control sequence ideally, and so various operation Modes can be expected.

## 4. The Results Studied

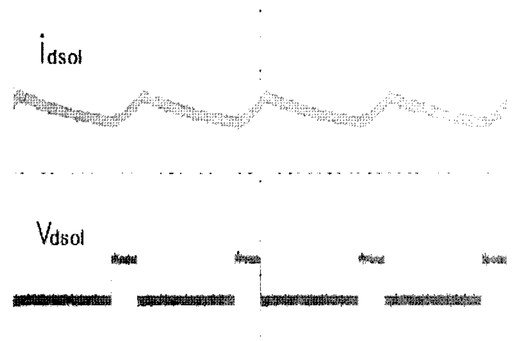
The operation characteristics of the proposed UIPV system are analyzed through digital simulation to verify the validity. In simulation we assumed the operation conditions that the rated PV-array voltage is 340[V], and Grid voltage 220[V] low voltage AC line. And total power sent to the Grids is set to 1[kW] for 3 hours, and hence the generated PV-array output levels are set to 0.2, 0.4 and 0.6[kW] for every Mode.

### 4.1 Output waveforms

Fig.5 shows the waveforms of output current $i_{dsol}$ and DC link voltage $v_{dsol}$. As the output voltage $v_{dsol}$ is a summation of voltage $v_l$ of winding $N_3$ and the PV voltage $V_{sol}$, and then the waveform $v_{dsol}$ has the pulsed output on the constant PV voltage $V_{sol}$. As expected, the output current flows continuously for a whole period, which means lower level DC current and much reduced crest factor. Therefore the battery charging current has an average value with low peak amplitude, which could reduce the ripple factor.

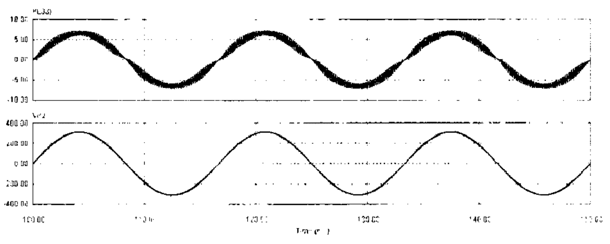



(a) simulated waveforms

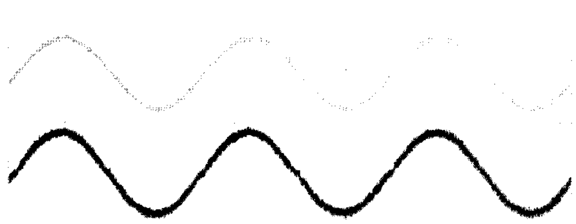



(b) experimental waveforms

Fig. 5 Waveforms of output current $i_{dsol}$ and DC link voltage $v_{dsol}$



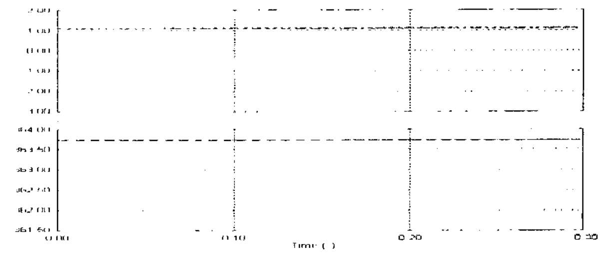
(a) simulated waveforms



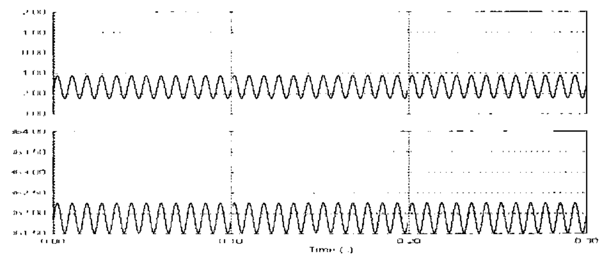
(b) experimental waveforms

Fig. 6 Filtered waveforms of inverter current ($-i_{con}$) and voltage $v_{scon}$

The L-C filtered waveforms of inverter voltage and current can be seen in Fig.6. The current waveform has little ripples but become nearly sinusoidal, and hence the current has unity power factor and very low harmonics. The same can be seen at the experimental results.



(a) Battery current and voltage when charging



(b) Battery current and voltage when discharging

Fig. 7 Waveforms of battery current and voltage when charging and discharging

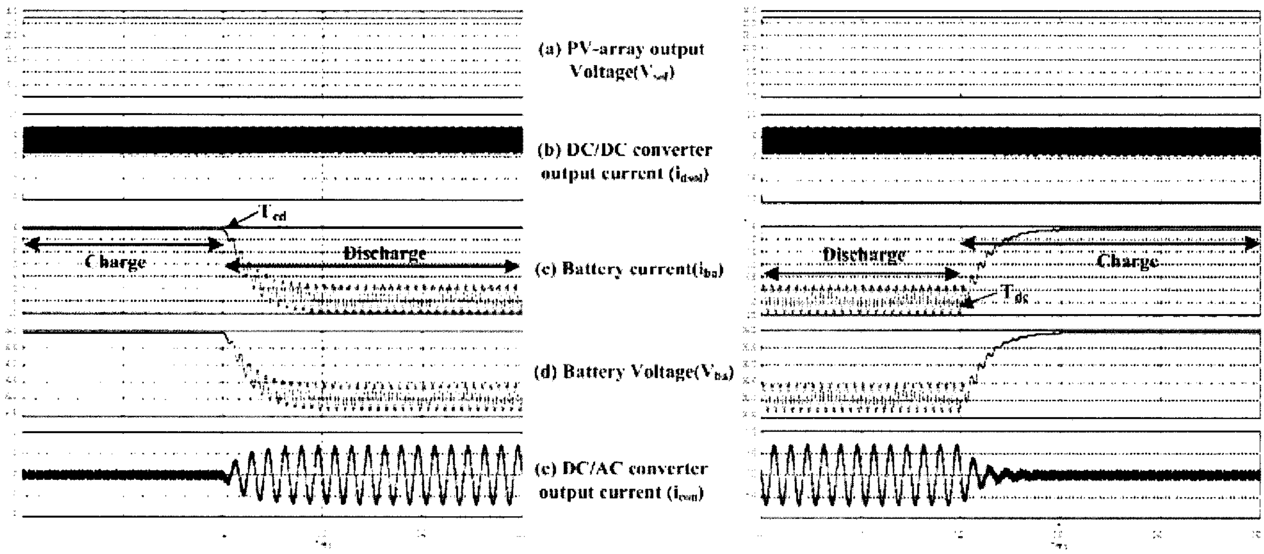
Fig.7 represents the waveforms of battery current and voltage when charging and discharging. It is very hard to find the ripples of battery current and voltage when it is charged, but the 120Hz ripples can be seen in the waveforms of battery current and voltage because the battery is connected directly to the 220[V] AC line.

### 4.2 Dynamic characteristics

Fig.8 shows the dynamic characteristics of the battery when the proposed UIPV system is operated. Fig.8(b) shows that the battery current with lower ripple flows continuously to show the merit of the proposed boost converter. In the proposed system, the battery is very important to perform the Modal operation for peak-cut action, and then to maintain the output capacity 1[kW] for 3 hours. To check the dynamics of the batteries, both charging and discharging states are investigated as shown in Fig.8(c) and (d). The left-hand side ( I ) of Fig.8(c) shows the transient operation of the UIPV system when Mode is changed from charging to discharging at $T_{cd}$ of Fig.4. Also the right-hand side ( II ) of Fig.8(c) shows the transients when Mode is changed from discharging to charging at $T_{dc}$ of Fig.4. In Fig.8(d) it can be observed that battery voltage reaches into steady state within a few cycles, very quickly, which can be interpreted as the fast response enough to catch up with peak-cut action.

The simulated results of all Modal operations are given at Fig.9. (a) is the variations of solar insolation level for one day, (b) inverter current (- $i_{con}$), (c) battery charging current $i_{ba}$, (d) battery energy level, (e) inverter instantaneous output power $p_{con} = v_{scon}\ i_{con}$ (f) battery instantaneous output power $p_{ba} = v_{ba}\ i_{ba}$, respectively. In Mode Ⅰ, the UIPV system reaches at the energy balancing state, i.e., the energy charged into the battery by A and A' is equal to the energy discharged from the battery as shown in Fig.4. The average powers with solid lines are given at Fig.9(e) and (f). In Mode Ⅱ, the PV system generates more energy because of higher insolation level, and hence the surplus energy is sent to the Grids during a certain time interval $\Delta_{II}$ after 3 hours.

Therefore externally sent is the extra power by the inverter and battery more than 3[kWh] of Mode Ⅰ. In Mode Ⅲ, the PV system has the generation power less than Mode Ⅰ, and so the shortage power should be supplied externally to maintain the rated 1 kW power capacity. During $\Delta_{III}$ the shortage amount is supplied from the 220[V] AC line as shown in Fig.9(b).




( Ⅰ ) charging to discharging transient ( Ⅱ ) discharging to charging transient

Fig. 8 The dynamics of UIPV system when the conditions of battery changes

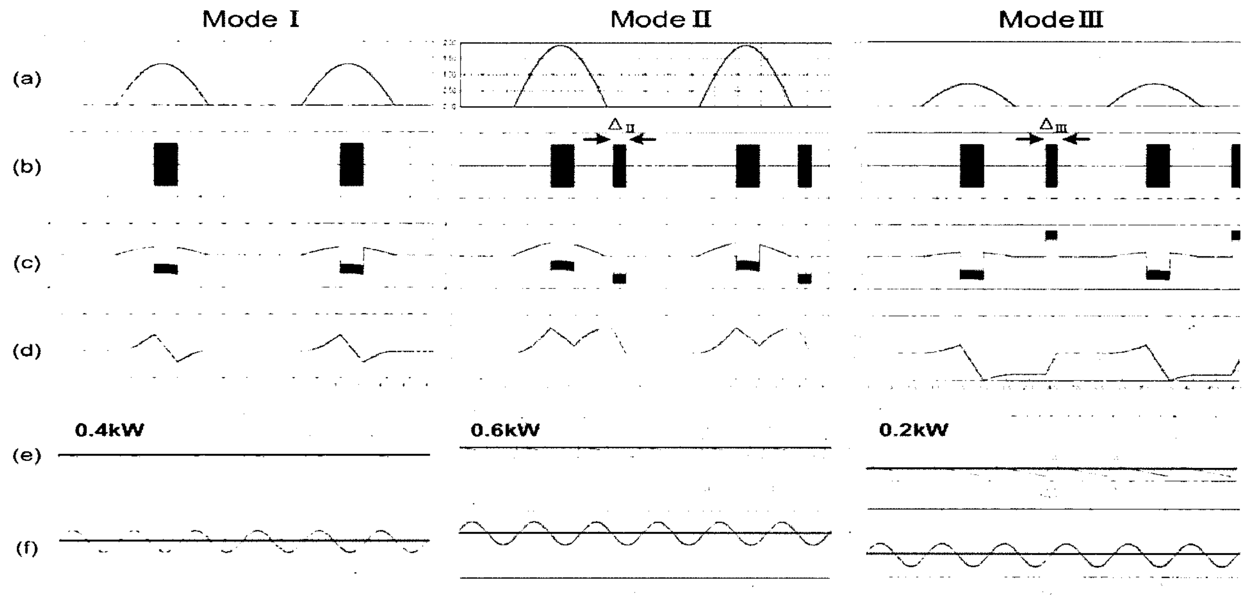
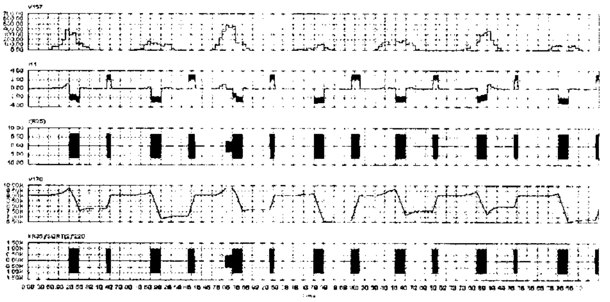
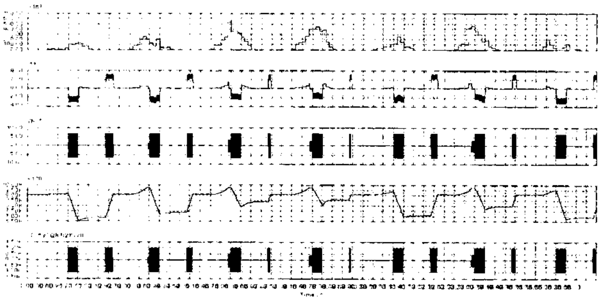



Fig. 9 Comparison of simulated results at each Modal operation

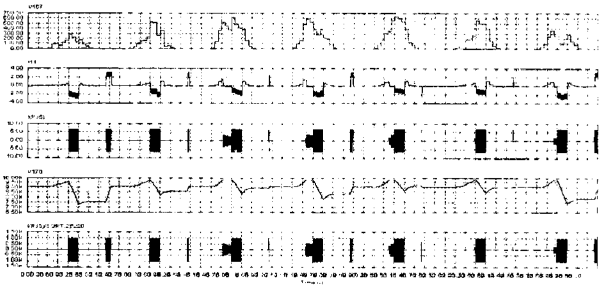
Fig.10 shows the operation results of the week-based average AC power generated by 1 kWp PV system as in Fig.4. For 4 weeks AC output power is not the same as the others and these belong to Mode Ⅲ because PV system has worked during the rainy season. In ModeⅢ, as PV system has lower power generation, so the shortage power should be supplied externally to charge the battery for many days of Fig.10. Short positive pulses in the second row of Fig.10 mean battery charging current, as in Mode Ⅲ (c) of Fig. 9. If these short pulses become negative, then PV system works at Mode Ⅱ, and the surplus power is sent to the Grids. The ModeⅡ can be seen at the fifth day of Fig.10(c) and the first and second day of Fig.10(d). Also the solar power is increasing day by day in the 2nd week



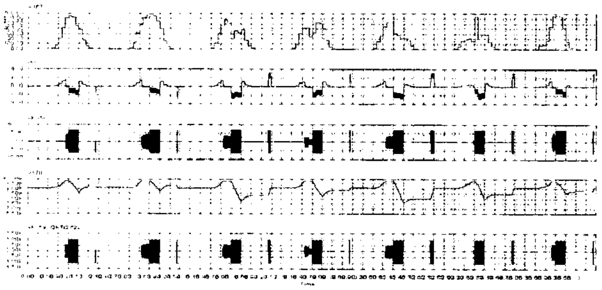
(a) 1st week



(b) 2nd week



(c) 3rd week



(d) 4th week

Fig. 10 Operation results of the week-based average AC power generated by 1 kWp PV system

Table 1 Daily energy flow of UIPV system for 4 weeks

| Day | | 1st | 2nd | 3rd | 4th | 5th | 6th | 7th | 1st | 2nd | 3rd | 4th | 5th | 6th | 7th |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $V_{ba}$[V] | | 361.9 | 361.9 | 361.9 | 361.9 | 361.9 | 361.9 | 361.9 | 361.9 | 361.9 | 361.9 | 361.9 | 361.9 | 361.9 | 361.9 |
| Energy | | 1st week | | | | | | | 2nd week | | | | | | |
| $E_S$ | I[A] | 2 | 2.5 | 2.3 | 2.5 | 2.5 | 2 | 2.5 | 2.5 | 2.5 | 2 | 1.5 | 2.3 | 2 | 2.5 |
| | $\Delta_I$[h] | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| | [Wh] | 2171.4 | 2714.3 | 2497.1 | 2714.3 | 2714.3 | 2171.4 | 2714.3 | 2714.3 | 2714.3 | 2171.4 | 1628.6 | 2497.1 | 2171.4 | 2714.3 |
| $E_R$ | I[A] | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 |
| | $\Delta_{III}$[h] | 0.6 | 1.8 | 1.2 | 2.4 | 1.2 | 0.9 | 0.9 | 2.1 | 1.5 | 0.6 | 0.6 | 1.8 | 0.9 | 0.9 |
| | [Wh] | 542.9 | 1628.6 | 1085.7 | 2171.4 | 1085.7 | 814.3 | 814.3 | 1900.0 | 1357.1 | 542.9 | 542.9 | 1628.6 | 814.3 | 814.3 |
| $E_T$ | [Wh] | 1628.6 | 1085.7 | 1411.4 | 542.9 | 1628.6 | 1357.1 | 1900.0 | 814.3 | 1357.1 | 1628.6 | 1085.7 | 868.6 | 1357.1 | 1900.0 |
| Energy | | 3rd week | | | | | | | 4th week | | | | | | |
| $E_S$ | I[A] | 2.3 | 1.6 | 1.4 | 1.8 | 1.3 | 1.5 | 2.3 | 1.4 | 1.3 | 2 | 1.7 | 2 | 1.7 | 1.2 |
| | $\Delta_I$[h] | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| | [Wh] | 2497.1 | 1737.1 | 1520.0 | 1954.3 | 1411.4 | 1628.6 | 2497.1 | 1520.0 | 1411.4 | 2171.4 | 1845.7 | 2171.4 | 1845.7 | 1302.8 |
| $E_R$ | I[A] | 2.5 | 2.5 | 2 | 2.5 | -1 | 1 | 2.5 | -1 | -2 | 2.5 | 2 | 2.5 | 2.5 | 2.5 |
| | $\Delta_{III}$[h] | 1.2 | 0.6 | 0.3 | 0.9 | $\Delta_{II}$=0.2 | 0.2 | 0.9 | $\Delta_{II}$=0.2 | $\Delta_{II}$=0.2 | 0.6 | 0.3 | 1.2 | 0.6 | 0.3 |
| | [Wh] | 1085.7 | 542.9 | 217.1 | 814.3 | -72.4 | 72.4 | 814.3 | -72.4 | -144.8 | 542.9 | 217.1 | 1085.7 | 542.9 | 271.4 |
| $E_T$ | [Wh] | 1411.4 | 1194.3 | 1302.8 | 1140.0 | 1483.8 | 1556.2 | 1682.8 | 1592.4 | 1556.2 | 1628.6 | 1628.6 | 1085.7 | 1302.8 | 1031.4 |

of Fig.10(b). which can be seen at Table 1 listed as $\Delta_{II}$ within the row $\Delta_{III}$. Also the solar power is increasing day by day in 3rd week of Fig.10(c) Then the remaining energy in the battery becomes larger, and hence so the battery charging current at night time becomes shorter and shorter.

Table 1 describes daily energy flow of the UIPV system for 4 weeks, which has three important energy levels $E_S$, $E_R$ and $E_T$. $E_S$ means the energy generated by the UIPV system, and $E_R$ the energy for battery charging supplied from the Grids and $E_T$ the energy sent to the Grids. Depending on the solar insolation level for each day, the relationship between $E_S$, $E_R$ and $E_T$ is quite different as in Table 1. The working time $\Delta_I$ is set to 3 hours as mentioned before but discharging time $\Delta_{II}$ and charging time $\Delta_{III}$ are varying unpredictably because of different operating and loading conditions.

Because of the rainy weather, ModeⅢ of three operation modes appears mostly. However for a few days ModeⅡ can be seen at Table 1 listed as $\Delta_{II}$ within the row $\Delta_{III}$. At these Modes the surplus energy is sent back to the Grids by the UIPV system.

### 4.3 Evaluation

To evaluate the proposed system and its control sequence, consider the comparison to the conventional PV system. First, the installation space becomes much reduced to one third. When the unit area of 50W PV module is considered as roughly 0.425 m² (=1.291 X 0.331), total space required is 25.5 m² in the 3kW PV system and also the proposed 1kW system has 8.5 m². However a little more space would be required for the battery bank, but if it is placed under the solar array, more actual space is not necessary. Also total cost is reduced to about 44.8%. It can be estimated as $15,878.40 for the conventional 3kW system and as $7,113.60 for the proposed 1kW one (including battery cost as $2133) when the price of one PV module is $267.64. Finally at the viewpoint of the contribution for peak-cut, the conventional system may have higher power and hence a little larger contribution could be made, but it would be varied randomly and so the contribution could not always be guaranteed for working time. Statistically it has the peak cut power by 0.51[kW]~1.05[kW]. However, the proposed system has constantly contributed to the Grids at least by the 1kW preset power.

It would vary randomly from the operation conditions such as loading and solar insolation, but statistically it has been reported that the peak cut power by the conventional system is roughly 0.51[kW]~1.05[kW], where the contribution could not always be guaranteed for working time of the UIPV system. As in Table 2 the proposed system has constantly contributed to the Grids at least by the 1kW preset power. Define the capacity of peak cut as a ratio of peak cut power per kW. Then the ratio of the proposed system is set to 1, and also that of the conventional system is 0.17~0.35. Therefore the proposed system has larger capacity of peak cut by 2.86 up to 5.88 than that of the conventional system.

Table 2 The comparison between the conventional 3-kWp system and the proposed 1-kWp system

| | | Conventional 3kWp System | Proposed 1kWp System |
|---|---|---|---|
| Installation space of PV array | | 25.5 m² | 8.5 m² |
| System cost | System | $15,878.4 | $4,980.6 |
| | Battery | 0 | $2,133.0 |
| | Total cost | $15,878.4 | $7,113.6 |
| Peak power cut | | 0.51~1.05[kW] | 1[kW] |

## 5. Conclusions

To improve the peak-cut effect, the UIPV system with energy storage device such as battery and its operation sequence are proposed in this paper. The peak-cut action is possible by adding an energy storage device of a battery during the predetermined time interval. Therefore differently from the conventional PV system as an energy source, the proposed system with battery basically cuts the peak electrical power demand at the Utilities network for the preset 3 hours. Also for better battery life the newly designed boost converter is suggested, which can make the crest factor lower and the current continuous.

In this paper the proposed PV system holding 1[kW] power output is to work for peak-cutting function, and also by three operation modes defined, and the proposed operation sequence suggested. The comparison between the conventional 3kW system and the proposed system is made through both the simulated results and the actual data for 4 weeks of August 2007. As a result the proposed PV system can be verified as a peak cutter. Also the proposed UIPV system can be expected to have good peak-cut characteristics such as reduced total cost, reduced installation spacing and improved peak cut capacity.

For further study longer operational experience and data would be needed to make the UIPV system apply to the actual utility as a peak cutter.

## Acknowledgment

This work has been supported by KESRI(R-2005-B-114), which is funded by MKE(Ministry of Knowledge Economy).

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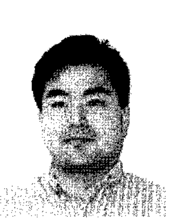

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