Paper

Design and Performance Evaluation of Grid Connected PV-ECS System with Load Leveling Function

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Electric double layer capacitors (EDLC) have attracted much attention as energy storage devices in recent years because of their wide variety of applications. Use of EDLC-electronics combination, called Energy Capacitor System (ECS), as an integrated supply source in place of batteries in a PV system for load leveling will play a key role in the further development of new areas of applications in PV as well as other power systems. The Electrical and Electronic Engineering department of Kitami Institute of Technology has taken up a joint collaboration research program on PV-ECS system with four research and manufacturing companies, funded by New Energy and Industrial Technology Development Organization (NEDO). In this work an effort has been taken to develop a new small distributed generation system of PV-ECS with a daily load leveling function. Another aim is to investigate the performance of ECS in respect of charge-discharge characteristics, energy efficiency and life cycle as an integrated autonomous supply source in a grid connected PV system. The overall performance of the system as a load leveling power source has been evaluated and the results are drawn graphically and discussed.

Keywords: Energy Capacitor System (ECS), Electric Double Layer Capacitor (EDLC), Photovoltaic, Load Leveling, Load Form Factor (LFF).

1. Introduction

Large capacitors of many Farads called super-capacitors or ultra-capacitors can be sources of high power having extremely long life. They can be a viable alternative to the rechargeable batteries, as the recent development demands many-fold increase of the energy density of the capacitors. Super-capacitors can now be quickly charged and discharged with high-energy efficiency and can provide high-energy output when power demand is at a peak. Moreover, the utilization of recently developed electronics circuits ensures the efficient exploitation of charging and discharging of the capacitors. A capacitor-electronics combination, called Energy Capacitor System (ECS) to utilize high energy density of the capacitors was developed so far[1]. In this system electronics circuits of parallel monitor and current pump, to assist efficient operation of charge-discharge of EDLCs providing large energy output, were used. All these development and the convenient properties of EDLC make them interesting for use as energy storage devices in systems, in which long life-time, high cycle stability and efficiency, short charging time, and maintenance-free operation are being demanded. The work of this paper is the development of a grid connected PV-ECS system as a small distributed generator with a view to determine and analyze the specific characteristics of the ECS for possible operational areas and comparable ratings with respect to system integration.

2. Brief outline of the developed experimental system

As shown later in Fig.4, the PV-ECS experimental system consists of PV array, ECS, Inverter, Charger and Load, etc.

2.1 Load demand

Fig.1 indicates a designed specific pattern of a load for peak value and daily power demand profile for a resistor room heater. In the figure we can see that, from 23 to 07 hours the load requires only 50W of power. The load demand is symmetric from 07 hours to 09 hours and from 14 hours to 17 hours requiring 700W power. The peak demand of power by the load is 1000W, which starts from 09 hours and continues up to 14 hours. From 17 hours to 23 hours the load is operated with 600W of power and after that the power demand falls to 50W again. The average energy consumed by the load per day is 12.5kWh.

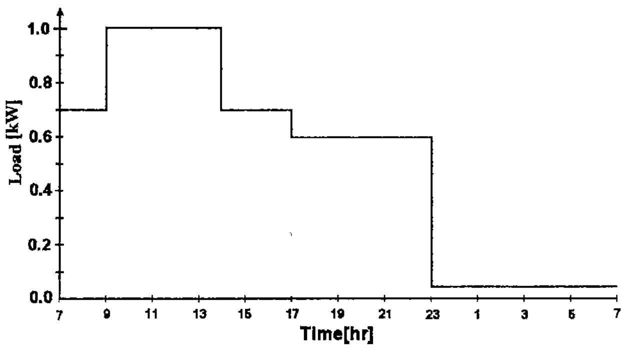


Fig.1 Daily load profile

2.2 System sizing

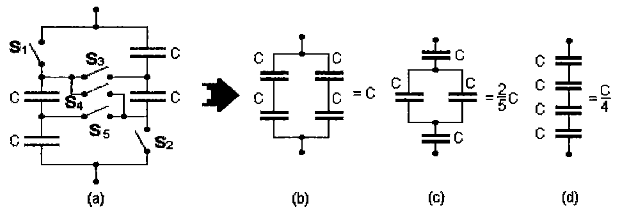
Photovoltaic system sizing consists of determining the number of solar array size, storage capacity for a certain period of autonomy and the kVA rating of the inverter that will satisfy the load requirement with an acceptable level of range. In the sizing of the PV-ECS system, the daily load, the mean daily irradiation on the plane of inclination of the array at the site, the DC and AC circuit voltage, maximum depth of discharge, losses in the storage system, losses in the power conditioning and control system, etc., have been taken into account.

2.2.1 Array sizing

The number of PV modules needed in series is obtained by dividing the system voltage by the voltage of one module. Based on this calculation, one string of 9 series connected PV modules will provide 180 V, 7.2 A and power of 1289.52 Wp which is close to the peak load. The expected mean daily energy output of the PV array has been calculated using the assumed PV's utilization factor of 10% and 90% of inverter efficiency and this figure is 2.8kWh. Basic characteristics of PV module are shown in Appendix 3.

2.2.2 Sizing of storage device

Sizing of storage device is the determination of the storage capacity of the ECS so that the load leveling function is realized. As all the storage capacity is allowed to discharge for the day's autonomy, the actual capacity to be installed is determined by dividing this total capacity by the maximum percentage usable. The number of EDLC banks necessary in series is calculated by dividing the load nominal voltage by the operating voltage of one EDLC bank. Four banks of capacitors are used in the system. One bank consisting of 7 parallel strings of 36 series connected EDLCs requires 252 capacitors. In four banks, there are 1008 total capacitors having energy storage capability of 2276Wh (as for basic characteristics of EDLC cell and bank, see Appendix 1 and 2). In order to exploit the storage capability efficiently and to generate stabilized power output through inverter, ECS is charged and discharged in three different combinations using switches S_1, S_2, S_3, S_4, and S_5, as shown in Fig.2. During discharge mode when switches S_1 and S_2 are closed and all other switches are opened the combination-I (Fig.2-b) results. When the switches S_3 and S_5 are closed and all other switches are opened the combination-II (Fig.2-c) is obtained decreasing the value of equivalent capacitance. For combination-III (Fig.2-d) switch S_4 is closed and the other switches are opened. Through this switching operation the terminal voltage of ECS varies from 180V to 120V. During the charging mode, the capacitor bank is switched using the above switching conditions in such away that the equivalent combinations start from reverse direction i.e. from combination-III to combination-I with gradual increment of the equivalent capacitance values. Using this switching operation, we can utilize about 88.6% of total energy storage capacity of 2276Wh.



(a) Arrangement of ECS; (b) Combination-I;
(c) Combination-II; (d) Combination-III
Fig.2 Switching operation of ECS

2.2.3 Charger

The charger is an ac to dc switching mode rectifier power supply with the output of 250W. It has negligible ripple factor. The input is AC 100V, 50Hz and the output is DC 180V. The charger has an efficiency of more than 80% and it is used only for ECS charging operation.

2.2.4 Inverter sizing

A single-phase three-line inverter of high efficient, low harmonic distortion and moderate size has been selected for the system. It has 4.4kW, 3-line AC 202/101V and power efficiency of 95% for a maximum dc input of 350V. It has the capability to switch-off if the input voltage is too high or low and it can restart when the dc input voltage reaches a set minimum. It has also a constant power output function. The built in maximum power point tracker (MPPT) in the inverter continuously matches the dynamic impedance of the PV-array to the fixed impedance of the load for all insolation levels and extracts maximum amount of energy from the PV-array for the input of the inverter.

2.2.5 Parallel monitors

Parallel monitors are electronic circuits used to monitor and control the uniform level of charge voltage of each capacitor for efficient exploitation of the operation of capacitors. The primary purpose of the circuit is to keep the operating voltage at a uniform level. As all the capacitors in series are not identical, the applied voltage across serially connected capacitors for charging will not be equally distributed. Thus for safety reasons minimum operating voltage among the capacitors is used as an applied voltage for all capacitors. This leads to an ineffective use of capacity in terms of energy utilization. The parallel monitor circuit has also the capability to stabilized voltage to each terminal capacitor and fluctuation free output voltage by utilizing 100% of the capability of the capacitors. If the voltage across the capacitor rises above 2.5V, then the electrolyte of the EDLC will be damaged, and the load could fail. Fig.3 represents a parallel monitor circuit with the equivalent circuit of the capacitor cell. In this circuit, a diode is reversing biased with a reference voltage of 2.5V and is connected at the input of the parallel monitor. This ensures all the capacitors attached with parallel monitor to be charged 100% of their ratings.

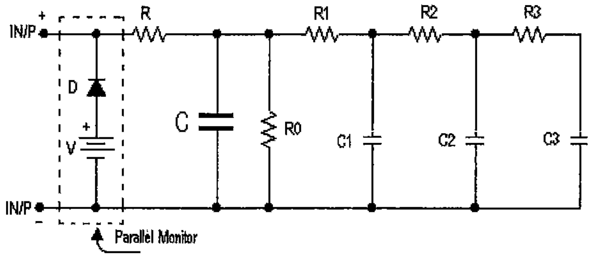


Fig.3 Equivalent circuit of EDLC with parallel monitor

2.3 PV-ECS system configurations

Fig.4 represents the simplified block diagram of the PV-ECS system and Fig.5 shows the developed control and data monitoring system and ECS. The PV array is connected to the input of the inverter through a switch K_1 (K_1 is "ON" during daily operation) and to the ECS by another switch K_2. The output of the inverter is connected in parallel to the load and to the grid line.

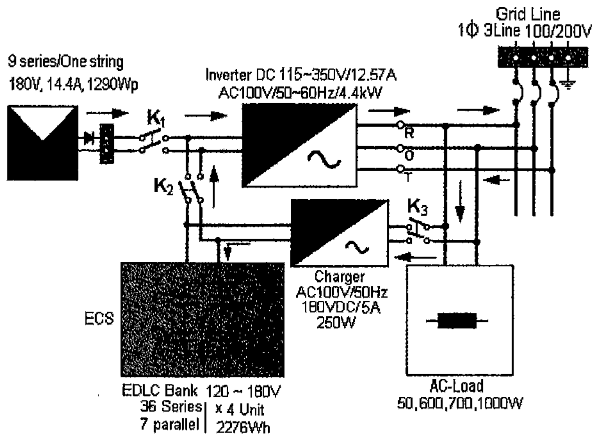


Fig.4 Block diagram of grid connected PV-ECS system

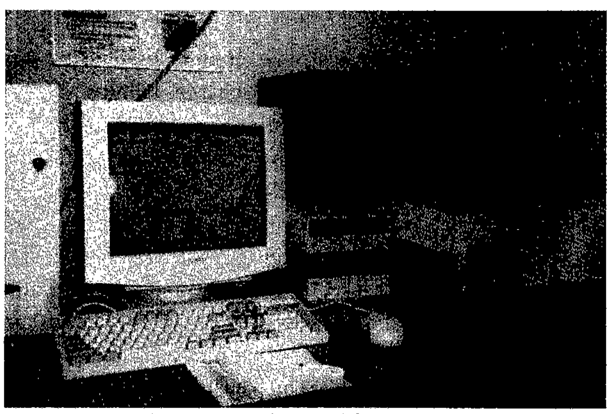


Fig.5 Grid connected PV-ECS system equipment

The input of the charger is connected to the grid line through the switch K_3 and its output is directly connected to the EDLC bank to charge the bank during nighttime. Operation and control of the plant and its data monitoring and acquisition were accomplished by microcomputer-based system.

3. Daily operation of PV-ECS system

As indicated in the previous chapter, for the peak load of one-kilo-watt, the PV's rated maximum output is 1289.52 watts and they are fairly matched.

But, since PV's operating output depends on a solar energy available, it may not be enough for the peak load power with high reliability, especially for cloudy weather. To supply this deficient power, we assume that at least αW is derived from a grid line for the time period of 9:00~14:00 and if PV output is more than the peak load minus α, that is (1000 - α)W, then the excess PV power is used to charge the ECS bank or sold to the grid line. We also assumed that if PV output is less than a specific value, for example 300W, then the inverter is in a Constant Power (CP) operation mode (in Fig.4, K_1, K_2 on, K_3 off), otherwise in MPPT mode (K_1, K_3 on, K_2 off). To clarify the relationship between switching condition and inverter and ECS operation modes, switche's ON, OFF states are shown in Table 1.

Table 1. Switching condition for inverter and ECS operation modes

Switches	Inverter		ECS	
	MPPT mode	CP mode	Charging (Inverter MPPT mode)	Discharging (Inverter CP mode)
K1	ON	ON	ON	ON
K2	OFF	ON	OFF	ON
K3	ON	OFF	ON	OFF

Flowchart of the daily operation of the grid connected PV-ECS system is shown in the following Fig.6. That is,

(1) From 07:00 to 09:00: The requirement of the load is 700W. During this time, when the PV power is less than 300W, the inverter is set for CP operation mode and PV, ECS bank and grid supply the load demand. When the PV power exceeds 300W, the MPPT operation mode of the inverter is activated and PV or/and grid supplies this load 700W and the excess PV power is used to sell to the grid line or to charge the ECS. This operation mode of inverter is the same for the following time period of 14:00~17:00.

(2) From 09:00 to 14:00: The load pattern shows that the peak power demand of 1000W starts from 09:00 ends at 14:00. If the PV array generates more power than 300W, the inverter works in MPPT mode and supplies 1000W to the load. The rest of power produced by the PV array is delivered to the grid line or to charge the ECS. As mentioned earlier, to maintain the reliable power supply, α is set at 300W in this experiment.

(3) From 14:00 to 17:00: The load demand of 700W is supplied from the PV as long as PV output is higher than load demand and the excess power is delivered to the grid line or

to charge the ECS if possible. When PV output becomes less than the load demand, the deficit power is supplied from the grid line and ECS. When the PV output is expected to be zero, the whole demand of 700W is supplied from the grid line and the ECS.

(4) From 17:00 to 23:00: The operating power of the load is 600W. This power is supplied simultaneously from the ECS and the grid line.

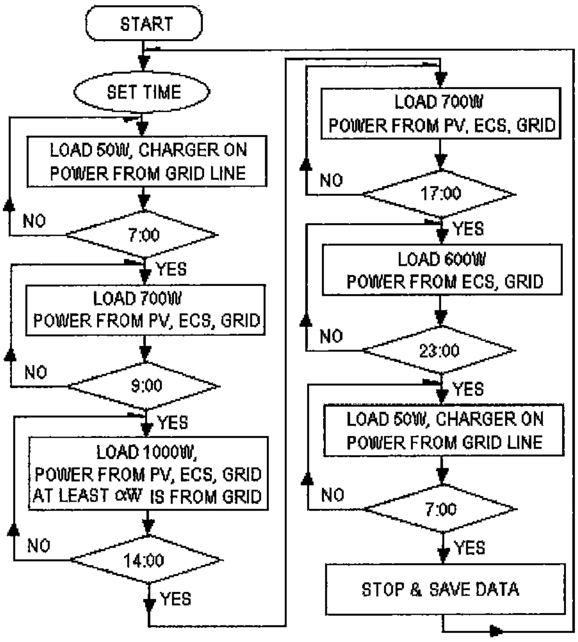


Fig.6 Flow diagram of grid connected PV-ECS system operation

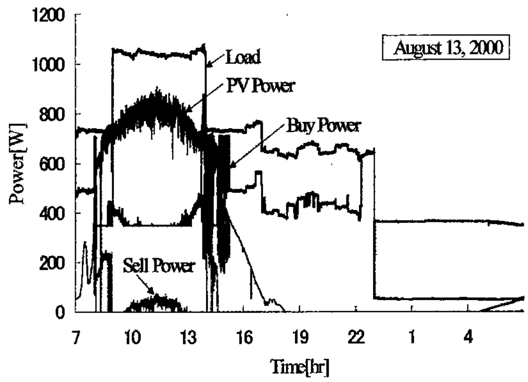


Fig.7 Daily power flow performance on sunny day

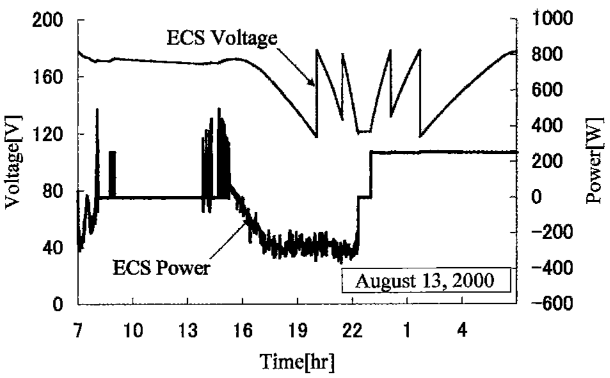


Fig.8 Charge and discharge of ECS on sunny day

If ECS is fully discharged, the grid line alone operates the load supplying 600W of power.

(5) From 23:00 to 07:00: From Fig.1, it is observed that the load requires 50W of power from 23:00 to 7:00. As during this time the PV array output is expected to be zero, the grid line delivers this power to the load and recharges the ECS.

4. Results and discussion

4.1 Performance of the PV-ECS system

Figs.7 and 9 represent the performance of the power flow of the system of two representative days, on a bright sunny day and a cloudy day respectively. It is observed from these figures that according to load pattern the performance of power flow of the system can be elaborated for those days.

In Fig.7, due to the inverter's relatively slow operation mode change (MPPT ⇔ CP), we see some spikes in the buy power curve, for example around 15 hours. Power is supplied from the grid line during these operation mode changes. This phenomenon is expected be overcome by using an improved inverter with faster mode change function.

The performance is more or less similar to the results as observed in Fig.9 for the cloudy day except that during daytime when the PV output is small due to cloudy weather, the grid line shares in supplying power to operate the load.

Figs.8, 10 indicate the discharging and charging operation of the ECS for the above sunny and cloudy days respectively.

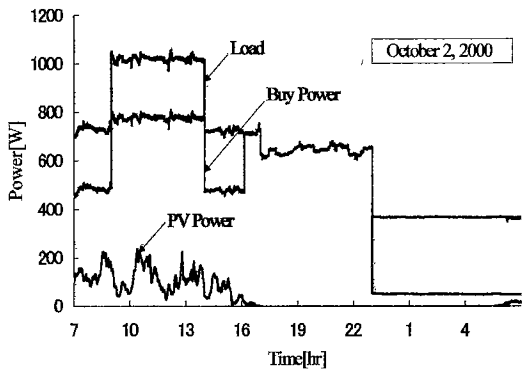


Fig.9 Daily power flow performance on cloudy day

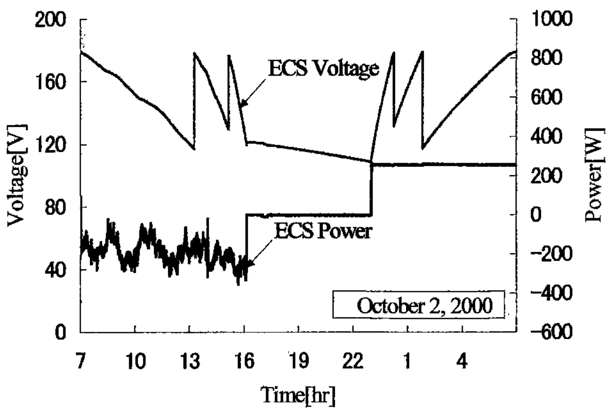


Fig.10 Charge and discharge of ECS on cloudy day

In the duration of discharge mode the bank starts discharging linearly from 180V to 120V supplying power to the load. When the switches S_3 and S_5 are closed and all other switches are opened, the combination-II (Fig.2-c) results and the bank also start discharging linearly from 180V to 130V supplying power to the load. For combination–III (Fig.2-d), switch S_4 is closed and the rests are opened. This results in a sharp rise of voltage to 180V from 130V and then discharges to approximately 120V.

During charging mode of operation of the ECS, it is observed from the figures that the capacitor bank is switched using the same switching conditions as explained in the above discharge mode operation. The only difference is that the equivalent combinations start from reverse direction i.e. from combination-III to combination-I with gradual increment of the equivalent capacitance values.

4. 2 Analysis of system operation

The daily load form factors of buy power (ratio of total energy of above the average power to the daily total energy), the peak cutting rates and the efficiencies of the system components are determined for the above two representatives days. For sunny day, the load form factor (LFF) is 7.0% when PV-ECS power exists and when PV-ECS power does not exist the LFF is 30.2%. For the cloudy day, the corresponding values are 13.4% and 30.2% respectively. The peak cutting rates for these days are found to be 18.5% and 23.1% respectively. The efficiencies of inverter, EDLC bank, and charger are 85.1%, 80.0%, and 86.4% respectively in the sunny day. The corresponding values of efficiencies in the cloudy day are 80.2%, 84.7%, and 80.8% respectively.

For the sake of detailed study of the operation of the system as a load leveler, daily average power supply, daily maximum supply of power by the grid and the load form factors of the power supplied from grid line when PV-ECS power exists and does not exist over 160 days are investigated. The average peak cutting rates of the system over these days are also calculated. The results are shown in Figs. 11, 12, 13 and 14 respectively.

Fig.11 represents the average daily load power delivered by the grid line for a number of days. The figure shows that without power from PV-ECS the grid line supplies an average daily load power of 543.27W for the load and ECS (including the losses of power in the charger and in the ECS). But when the PV-ECS power exists, the average daily load power supply from the grid line is decreased to 488.06W.

The sharp variations of load power of the system are due to variations of solar irradiation for various duration of the sunny and sunless hours of the days.

The averages of the maximum daily load power purchased by the load from the grid line are shown in the Fig.12.

The grid supplies 1060.80W of average daily maximum power to the load when the PV-ECS power doesn't exist. When the PV-ECS output exists, the grid supplies an average daily maximum power of 904.10W to the load. The abrupt variation of the maximum load power over the days as seen in the Fig.12 is due to the changes in solar insolation.

The variations of the load form factor (LFF) of the power supplied from grid line are indicated in Fig.13. It is observed in the figure that during the absence of PV-ECS power, the average of load form factor has a constant value of 30.20%. But when PV-ECS power exists, the average value of LFF becomes 11.40% and the load leveling function of PV-ECS system is realized.

Fig.14 shows the variations of the peak cutting rates. It is evident from the figure that the average value of the peak cutting rate is 14.90%. Sharp variations of the values of the peak cutting rates depend on the weather condition.

It is evident from the figures (Figs.7-10) that during discharge time, the ECS is capable of providing power to the load efficiently at the time of no sunshine hours. It is also clear that the charge-discharge operations of the capacitors are satisfactory. Excellent changeover performances of the switching circuits are also noticed in selecting various power operations of grid line, PV array, and ECS.

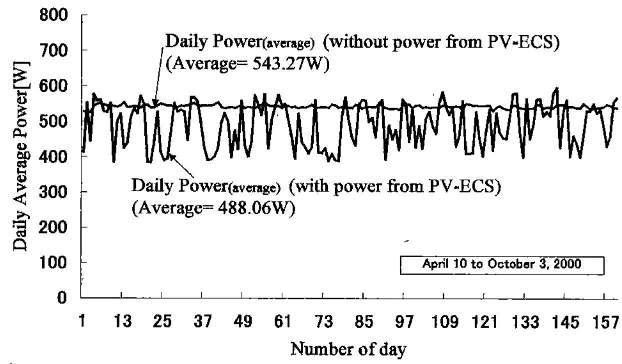


Fig.11 Daily average of load power supplied by the grid

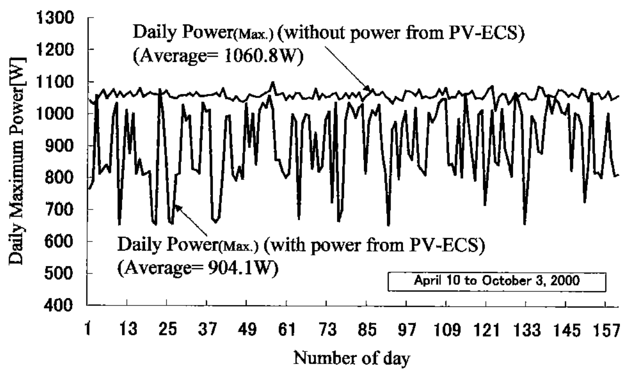


Fig.12 Daily maximum of load power supplied by the grid

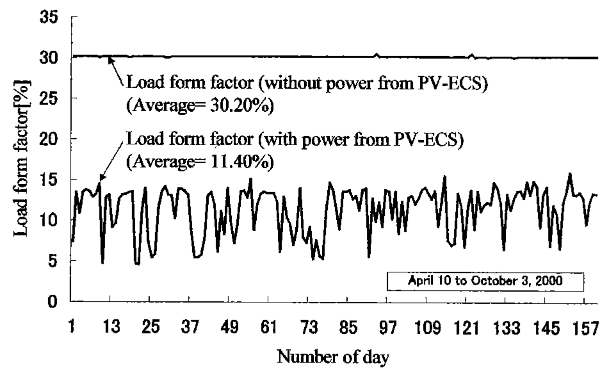


Fig.13 Load form factors of the power supplied by the grid

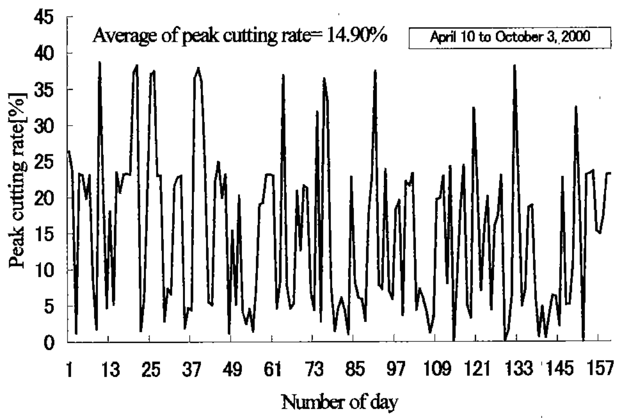


Fig.14 Peak cutting rates during 160 days

Total amount of daily energy consumed by the load and the energy supplied by different sources are shown in Table 2. In the Figs.15, 16 are also indicated the amount of daily PV power output, the daily ECS power in/output, the daily utilization of load power, etc. Otherwise, the ECS efficiency, the inverter efficiency and the charger efficiency indicated by % are obtained from the daily system evaluation.

Table 2. The amount of daily energy consumed by the load and the daily energy supplied by different sources

Item	Sunny day	Cloudy day
PV energy sold to the grid line [Wh]	299.3	0.0
Energy supplied to the load/charger by inverter output after sold to the grid [Wh]	5911.2	2219.8
Total energy flow from PV or ECS and grid provide to the load and charger [Wh]	15758.4	15538.6
Energy supplied by the charger taking from the grid and PV-ECS bank[Wh]	2567.9	2551.6
Energy flow from the grid and PV-ECS to the load [Wh]	13190.6	12987.0
Energy supplied by the ECS to the gird line and load [Wh]	1767.7	1745.4

The efficiencies of system are corresponding to the variation of PV power output of different weather days. As seen in Figs.15, 16, it can be observed that the individual operations of the inverter, charger and ECS are within the range of acceptance.

According to the Fig.3, the energy loss in the ECS is caused from the loss of energy in the internal resistance of the capacitors and in the leakage resistance. The loss of power in the leakage resistance can be calculated by: $P_{loss}(R_0)= V_C^2/R_0$, where R_0 is the leakage resistance and V_C is the voltage across the EDLC. The comparatively low efficiency of the ECS in a sunny day is considered to be a result of leakage loss of the daily operation of ECS. From Fig.8 and 10 it is observed that the ECS voltage in the sunny day remains higher than that in the cloudy day, and it can be expected that the loss of energy by leakage current in the sunny day is higher than the loss of energy in the cloudy day.

The unbalance of energy at the meeting point of ECS, inverter and PV array in Figs.15, 16 is considered to be caused by the measurement error arises from the sampling time gap between PV output and inverter input.

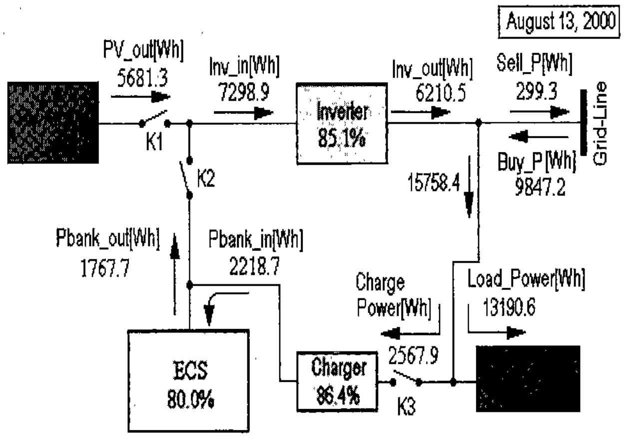


Fig.15 Daily energy flow diagram (sunny day)

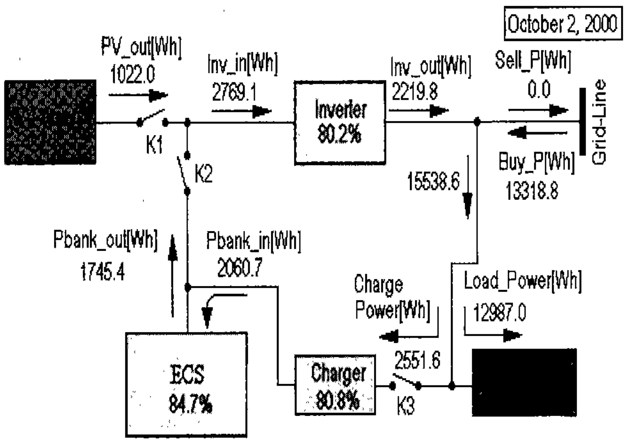


Fig.16 Daily energy flow diagram (cloudy day)

5. Conclusions

The integration of EDLCs as storage devices in grid connected PV-ECS system for load leveling needs detailed study and analysis of electrical and energetic features of EDLCs as an integrated part of the system. Design of compact size, lightweight, high energy density, long life and low cost EDLCs will make their application more economic to various power supply systems. Although grid connected PV-ECS system used in load leveling is still at the stage of infancy but extensive researches on EDLCs are going on in various laboratories[4-6] and it can be anticipated that more and more such systems will be installed in different fields. The grid connected PV-ECS system will also have an increasing role to play in the coming years to have the opportunity to supply power as distributed systems. For future market penetration, overall grid connected PV-ECS system optimization in terms of load leveling function will be very important.

Not only ECS storage devices but also PV modules must be cheaper, more efficient and reliable. It is also important that the rest of the system especially power conditioning and ECS storage, must be optimized such that consumer application is particularly energy efficient.

Energy efficiency improvements of systems with EDLC, prototype development and field experiences will take more times to verify long-term field reliability. Study of the analysis of real time performance of the system, development of reliable low cost monitoring system, and cost reduction of the system and components as a whole are extremely important for reliability and acceptance to the general people.

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Appendix

Appendix 1: Specifications of EDLC and the EDLC charge-discharge characteristic are shown in Table A1 and Fig. A1 respectively.

Table A1 EDLC specifications

Voltage	Capacitance	Energy density
2.5 V	2600 F	6.5 Wh/kg

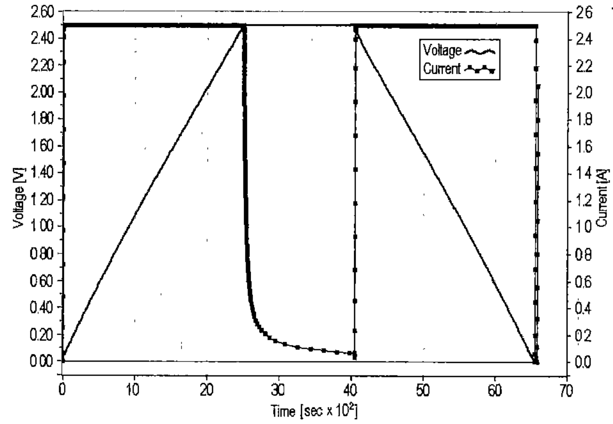

Fig.A1 EDLC charge-discharge characteristic

Appendix 2: Specifications of EDLC bank is shown in Table A2.

Table A2 EDLC bank specifications

Number of EDLC cell	252 pieces
Operating voltage	25, 35 ~ 90 V
Capacitance	506 F
Stored energy	569 Wh

Appendix 3: PV modules were provided by the Kyocera Corporation. It's specifications are shown in Table A3.

Table A3 Specifications of PV module

Nominal maximum output	145.00 W
Open circuit voltage (Voc)	24.896 V
Short circuit current (Isc)	7.442 A
Maximum output voltage (Vmp)	19.77 V
Maximum output current (Imp)	6.92 A

The I-V characteristic curve of PV module is shown in Fig. A2

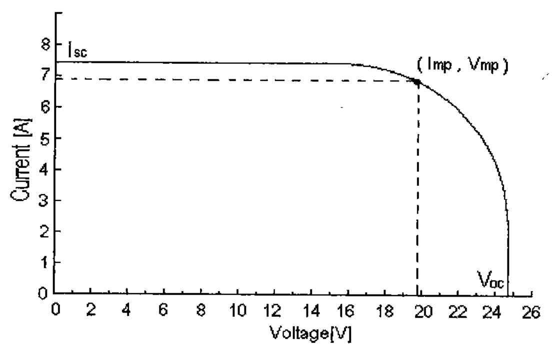

Fig.A2 I-V characteristic curve

Romny Om (Student Member) received his Bachelor Degree in Electrical Engineering (B.E.) from Cambodia Institute of Technology in 1988 and his Master Degree in Electrical Engineering (M.E.) from Kitami Institute of Technology in 1996 where he is currently enrolling in a Ph. D. program. His research is mainly focusing on power system engineering, and on a development of Energy Capacitor System for electrical actuator applications.

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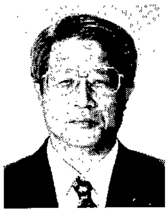
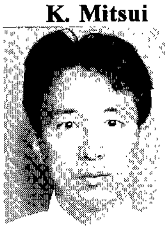


R. K. Mazumder (Member) received his B.S., M.Sc. and Ph.D. degree from Dhaka University in 1967, 1976, and 1990 respectively. He is a professor of Department of Applied Physics and Electronics, Dhaka University, Bangladesh. He was a visiting professor at Kitami Institute of Technology invited by JSPS from October 1999 to March 2000, where he engaged in research on the PV-ECS system Operation.

K. Nakamura (Member) received his Bachelor Degree in Electrical Engineering (B.E.) from Kitami Institute of Technology in 1980. At the same year, he joined the Kitami Institute of Technology as a technical associate and then become assistance professor in 1994. His research mainly concerns on an evaluation of a power system planning, the development of new type of energy storage devices and the evaluation of the photovoltaic system for residences. He is a member of Japan Solar Energy Society.

K. Mitsui (Member) received his Bachelor Degree in Electronics Engineering (B.E.) from Yamanashi University in 1986. At the same year, he joined Kikusui Electronics Company. In 1993, he was sent on loan agreement by his firm to KIC Company, U.S.A, and then in 1995, he joined Power Systems Company. His research mainly deals with a development of electronic circuits, a measurement systems and electric double layer capacitors. He is a member of the Institute of Electronics, Information and Communication Engineers.



M. Yamagishi (Member) received his Bachelor Degree in Electrical Engineering (B.E.) from Aoyama Gakuin University, Department of Science and Electrical and Electronic Engineering in 1971. At the same year, he joined Kikusui Electronics Company. He is engaged in development of a regulated dc power supply and electronic load equipments. In 1990, he was a chief of department of power-supply engineering. Then in 1993, he has established the Power Systems Company. He concentrates on research and development of an Energy Capacitor Systems. Currently he is a company representative director. He is a member of the Institute of Electronics, Information and Communication Engineers of Japan, the Electrochemical Society of Japan.

M. Okamura (Member) received his Bachelor Degree in Electrical Engineering (B.E.) from Waseda University in 1959 and at the same year, he joined the Japan nuclear power company. In 1964, he was a visiting associate in the field of atomic energy at Argon, U.S.A. In 1987, he has established the Okamura Laboratory Inc., and engaged research development on radiation measurement, electronic circuit, computer application and software. Currently, he is a lead of the Okamura Laboratory. He is a member of Atomic Energy Society of Japan, the Institute of Electrical Engineers of Japan, and the Electrochemical Society of Japan.