A STUDY ON THE PERFORMANCE OF GRID-CONNECTED PV-ECS SYSTEM CONSIDERING METEOROLOGICAL VARIATION

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Abstract – This paper describes the performance of a grid-connected PV-ECS system considering the variation of PV output due to the yearly variation of solar radiation and weather condition. A PV-ECS system has been developed and to study its performance a simulation program has been made. The validity of this simulation program has been verified by comparing the simulated results with the practical operating ones. Two modes of operation of the system – (I) optimal economic mode and (II) optimal load leveling mode have been described in this paper. To run the system in these modes, two different algorithms have also been proposed. The effectiveness of these proposed algorithms has been verified by using them to run the system in optimal economic mode and optimal load leveling mode. Again, the effect on economical benefit (mode (I)) and load leveling capacity (mode (II)) considering the change of PV output due to the yearly variation of solar radiation and meteorological condition has been studied. Finally, the economic benefits and load leveling capacities of the simulated results have been calculated and presented here.

Keywords: Photovoltaic (PV), Power Storage, Load Leveling, Energy Capacitor System (ECS), Electric Double Layer Capacitor (EDLC), and Distributed Generation

1 INTRODUCTION

Now-a-days the distributed power generator specially the one using photovoltaic (PV) is drawing the attraction of users. Although the cost of PV system is yet higher than that of conventional generating system, the use of PV-based system is gradually increasing due to the maintenance free, long lasting and environment friendly nature of PV. Regarding the PV-based power generating systems, many works are being done [1] - [7]. We have also developed a grid-connected PV-based distributed system using Electric Double Layer Capacitor (EDLC) instead of conventional battery. To get various advantages, EDLC is used in combination of electronic circuits which is called Energy Capacitor System (ECS). Modeling of EDLC is described in [8].

The proposed PV-ECS system can be run in two different modes - (I) optimal economic mode and (II) optimal load leveling mode. In the first mode of operation, emphasis is given on to get maximum economic benefit from the system and in the second mode, to level the power taken from grid line (hereafter will be referred as "buy power"). In this paper, we have proposed two different algorithms to run the system in two different modes. The algorithms will help the users to get maximum economic benefit from the system and to level the "buy power" as well.

The performance of the system depends not only on the modes of operation but also on the power generated by PV panel which varies due to the yearly variation of solar radiation and weather condition. So, the effect on the performance of the system i.e. economic benefit and load leveling capacity has been studied considering the change of PV output due to the yearly variation of solar radiation and meteorological condition. To calculate the solar radiation, modified Hottel's and Liu-Jordan's equations have been used [2]. Operations of the system, in different days of the year, have been simulated and the economic benefit and load leveling capacity have been calculated and presented in this paper.

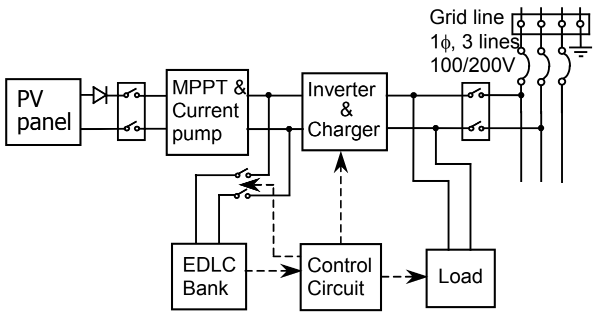


Figure 1: Block diagram of PV-ECS system.

2 BRIEF DESCRIPTION OF THE SYSTEM

A simplified block diagram of the developed system is shown in Fig. 1. The nominal maximum output of the PV panel, used in our system, is 1296W. A 1000W Maximum Power Point Tracker (MPPT) has been used to extract maximum power from the PV panel. The EDLC bank consists of four capacitor modules and each module has 252 EDLCs. To increase the storage capacity and to yield a large energy output, electronic circuits have been used with the EDLC [9]. In order to supply the DC output of MPPT and EDLC to the load and to charge the EDLC by grid power, a bi-directional ETM-PWM Power Conversion System (PCS) [10] has been used. Its maximum capacity is 1000W. The control system consists of a microcomputer, a data acquisition switch and an interfacing circuit. To simulate different load patterns, a resistive room heater of variable power has been used. The minimum value of the load is 50W and the maximum value is 1150W, but within this range the value can be set to any integer multiple of 50W. For detailed description and component sizing it is referred to [4] and [11].

3 CALCULATION OF PV OUTPUT POWER

The daily output power of PV panel has been estimated by calculating daily solar radiation. To calculate beam radiation, modified Hottel's equation [2] has been used which is given below.

$$\tau_b = a_0(1 - e^{-\xi_b \cos\theta_z}) + a_1 e^{-k/\cos\theta_z} \quad (1)$$

where, τ_b= Atmospheric transmittance for beam radiation (G_{bn}/G_{on})

G_{bn} = Beam radiation on nth day of the year

θ_Z = Zenith angle

ξ_b, a_0, a_1 and k are constants; for Kitami their values are: 6.0, 0.138344, 0.759559 and 0.381446 respectively.

Extraterrestrial radiation, G_{on}, on nth day of the year can be calculated by the following equation [12].

$$G_{on} = G_{sc}\,(1 + 0.033\cos\frac{360n}{365}) \quad (2)$$

where, G_{sc} = Solar constant = 1353 W/m^2

n = day of the year

Again, to calculate the diffuse radiation modified Liu and Jordan's equation [2] has been used which is

$$\tau_d = 0.2710\,(1 - e^{-\xi_d \cos\theta_z}) - 0.2939\tau_b \quad (3)$$

where, ξ_d = a constant = 8

Using Eqs. (1), (2) and (3) total solar radiation, $\Re$, can be calculated as

$$\Re = (\tau_b + \tau_d)\, G_{on} \quad (4)$$

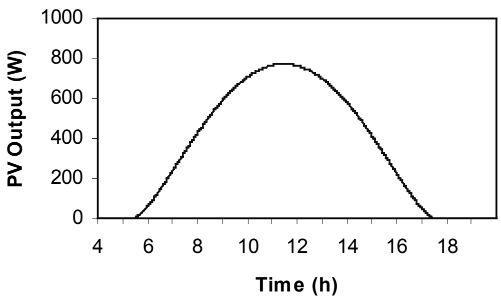


Figure 2: Calculated PV output on 11th April 2003.

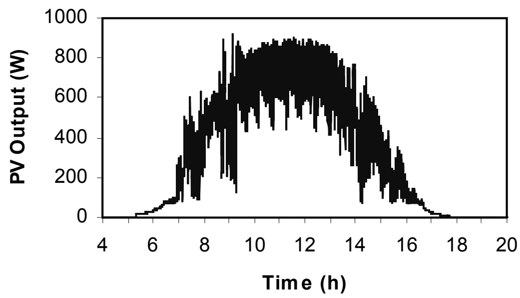


Figure 3: Practically obtained PV output on 11th April 2003.

Finally the PV output (P_{pv}) can be estimated by the following equation.

$$P_{pv} = \Re \times \cos\theta \times \eta_m \times A_p \times \eta_p \quad (5)$$

where, $\Re$ = Solar radiation (W/m^2)

θ = angle of incidence

η_m = efficiency of MPPT = 90%

A_p = area of PV panel = 8.505m^2

η_p = efficiency of PV panel = 11% (at 25°C with a rate of change of -0.052%/°C)

Considering the above values, the PV output for a typical sunny day has been estimated and the practical output for the same day has been measured for comparison. These are shown in Figs. 2 and 3 respectively. The integrated energy of the estimated PV output is 5.41kWh and that of the practically obtained output is 4.95kWh i.e. the error in the estimation is 10%. The estimated daily total PV output for different months of the year is shown in Fig. 4.

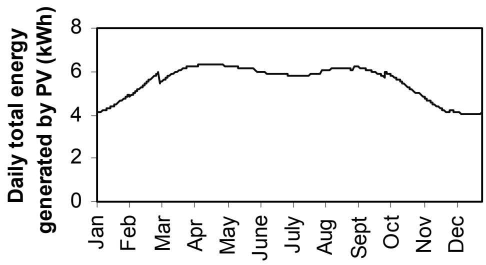


Figure 4: Estimated daily total PV output for different months of the year.

4 SIMULATION OF THE SYSTEM

A program has been developed to simulate the operation of the entire system. The flowchart of the program is given in Fig. 5. To verify the validity of the simulation program, simulated results have been compared with the practically obtained ones. In Fig. 6 the simulated and practically obtained power flow patterns for a typical sunny day are shown. Here, the load power (P_{load}), "buy power" (P_{buy}) and PV power (P_{pv}) are shown. The integrated energy of the simulated P_{load}, P_{buy} and P_{pv} are 12.23kWh, 8.58kWh and 4.91kWh respectively and that of the practically obtained P_{load}, P_{buy} and P_{pv} are 11.96kWh, 8.75kWh and 4.44kWh respectively. So the errors in simulated results are 2% for load power, 2% for "buy power" and 10% for PV power.

5 MODES OF OPERATION OF THE SYSTEM

The optimal economic mode and optimal load leveling mode of operation of the PV-ECS system are described in the following subheadings.

5.1 Optimal economic mode of operation

As mentioned earlier, the aim of this mode of operation is to get maximum economic benefit from the system. To run the system in this mode, the following tasks are to be done on priority basis (first priority is given to the first task and so on).

1. Use all of the power generated by PV panel.
2. Charge the EDLC fully during off-peak hours (time duration of the day when the price of electricity is low) and discharge it fully during peak hours (when the price of electricity is high). If the sum of the EDLC energy and the PV energy is greater than that required by the load during peak hours, sell the extra energy of PV to grid line.
3. Try to level the “buy power” for all day long.

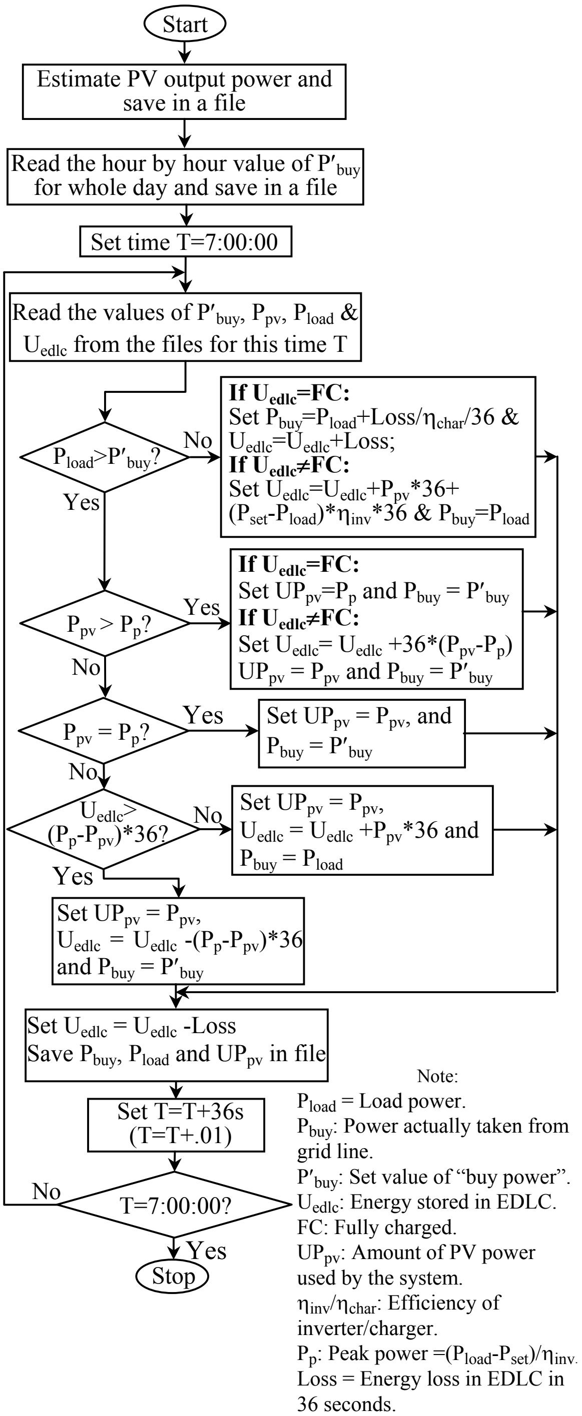


Figure 5: Flowchart of the simulation program.

To run the system in this optimal economic mode, everyday we have to set the “buy power” to an optimum level so that the above conditions are satisfied. This optimum value of “buy power” can be set by using the algorithm shown in Fig. 7.

The algorithm will set the “buy power” (P'_{buy}) for the load pattern in two time slots i.e. peak hours and off-peak hours. For peak hours, P'_{buy} will be set to the maximum value of the load pattern during this time. Then the simulation program will be run. If the PV power is not fully used and the EDLC is not fully discharged, P'_{buy} will be decreased by ΔP. In this way, P'_{buy} will be lowered until the EDLC is fully discharged and PV power is fully used.

If the total energy of the EDLC and PV output is greater than that required for the load during peak hours, P'_{buy} will be negative which means that extra energy of PV will be sold to grid line.

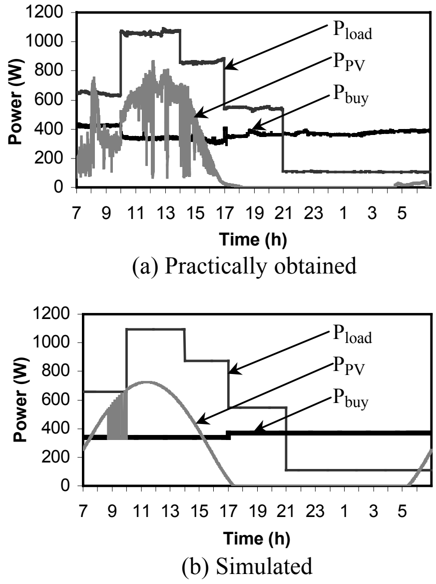


Figure 6: Daily power flow patterns on 1st June 2004.

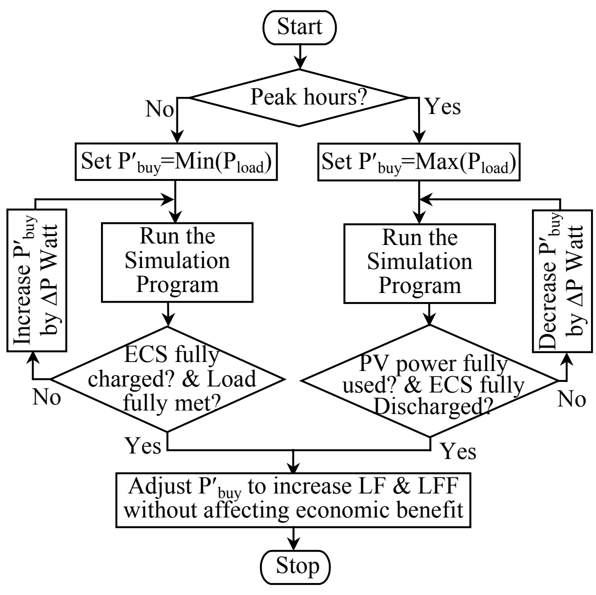


Figure 7: Algorithm for optimal economic operation.

For off-peak hours, P'_{buy} will be set to the minimum value of the load pattern in this time. Then the simulation program will be run. If the load demand is not fully satisfied and the EDLC is not fully charged, P'_{buy} will be increased by ΔP. In this way, P'_{buy} will be increased until the optimum level is reached for which the EDLC is fully charged and the load demand is fully met. Finally, the "buy power" will be adjusted to improve Load Factor (LF) and Load Form Factor (LFF: ratio of the total energy above the average power to the daily total energy) without decreasing economic benefit.

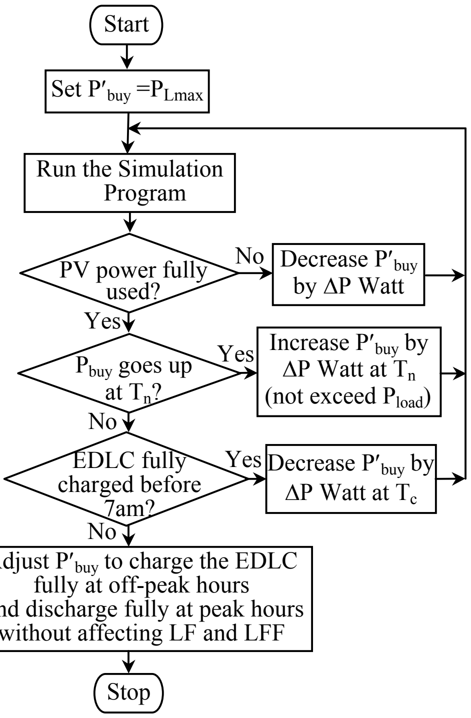
5.2 Optimal load leveling mode of operation

The aim of this mode of operation is to level the "buy power" and thus to improve its LF and LFF. The following things are to be done on priority basis to run the system in this mode.

1. Use all of the power generated by PV panel.
2. Try to level the "buy power" for all day long.
3. Charge the EDLC fully during off-peak hours and discharge it fully during peak hours.

Here, also we have to set the optimum value of "buy power" to meet the above conditions. The algorithm to set this optimum value is shown in Fig. 8.

As a start, the algorithm will set P'_{buy} to the maximum power of the load profile and run the simulation program. If the PV output power is not used fully, P'_{buy} will be decreased by ΔP and run the simulation program again. This loop will be iterated until the PV power is fully used. In the simulation result, if P_{buy} (power actually taken from gird line) goes up during T_n i.e. if energy of EDLC exhausts before the begining of charging time, P'_{buy} will be increased by ΔP during T_n and will run the simulation program again. In this way the optimum value of "buy power" will be set during T_n. At the last branch of the loop, if EDLC is fully charged before 7am, P'_{buy} will be decreased by ΔP during T_c and run the simulation program again. In this way, P'_{buy} will be lowered until the power taken from grid line becomes smooth enough. Finally, the value of P'_{buy} for all day long will be adjusted to increase economic benefit i.e. to charge the EDLC fully during off-peak hours and discharge fully during peak hours, without decreasing the LF.



Note:
P_{Lmax}= Maximum power of load profile.
T_n = Time period before the charging time of EDLC when PV output is zero or very low (e.g. 15pm~23pm of Fig. 14(a)).
T_c = Time period when the EDLC is charged (e.g. 23pm~7am of Fig. 14(a)).

Figure 8: Algorithm for optimal load leveling.

6 SIMULATION RESULTS

To simulate the operation of the system, we have considered a typical commercial load pattern as shown in Fig. 9. The average value, LF and LFF of this load pattern are 550W, 55% and 27.27% respectively. Operations of the system have been simulated for this load pattern using the simulation program of Fig. 5 together with the algorithms described in section 5.

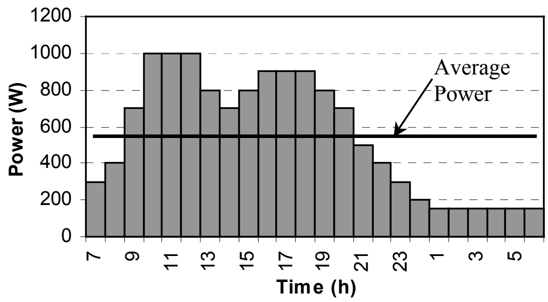


Figure 9: Load pattern used for simulation.

6.1 Optimal economic mode

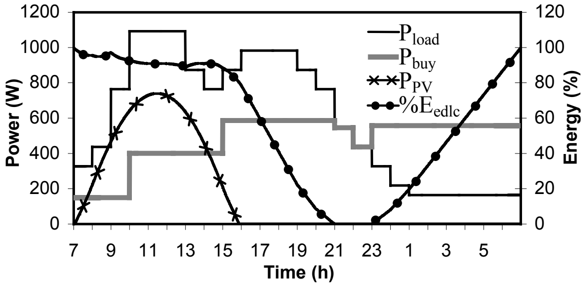
The effect of yearly variation of PV output on economic mode of operation has been studied using the algorithm shown in Fig. 7. Operations of the system on the 1st and 15th instant of different months of the year have been simulated by calculating the PV output power using the method of section 3. Some simulated power flow patterns are shown in Fig. 10. The cost of electricity to run the load (i.e. operational cost), with and without using the PV-ECS system, has been calculated. In this calculation we have considered that the price of electricity from 7am to 23pm (R_p) is higher than that from 23pm to 7am (R_o) i.e. $R_p = \alpha R_o$. We have assumed $\alpha = 1.6$ which is a threshold value to overcome the loss of the system. Total cost is calculated as $E_p \times 1.6R_o + E_{op} \times R_o$ (where, E_p = energy consumed by the load in peak hours, and E_{op} = that consumed in off-peak hours). Savings are calculated as $100*(C_{wo}-C_w)/C_{wo}$ (where, C_{wo} = cost of electricity without using PV-ECS and C_w = that using PV-ECS). The yearly variation of the economic savings is shown in Fig. 11 and the data are presented in Table 1.

To study the effect of weather condition on economic mode of operation, simulations have also been done by changing the PV output from 100% to 10% in 10% interval for an arbitrary day (20th April). Fig. 12 shows some simulation results. The variations of the economic benefit with the decrease of PV output are shown in Table 2 and Fig. 13.

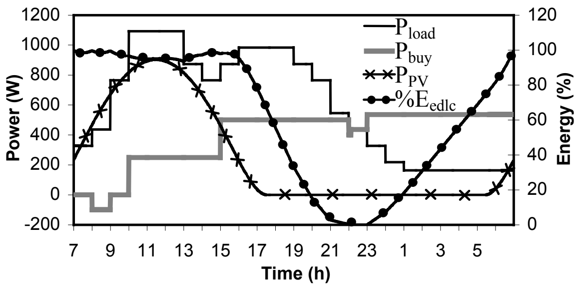
6.2 *Optimal load leveling mode*

To run the system in optimal load leveling mode, we have used the algorithm of Fig. 8 and simulated the operation for the 1st and 15th instant of different months of the year. Simulated power flow patterns for 1st January and 1st May are shown in Fig. 14. The yearly variations of LF and LFF are shown in Fig. 15 and the data are provided in Table 1.

Again, to study the effect of weather condition on load leveling capacity, operations of the system on 20th April have also been simulated by changing the PV output from 100% to 10% in 10% interval. The simulated power flow patterns for 100% and 50% PV output are shown in Fig. 16. The variations of LF and LFF due to the decrease of PV output are shown in Fig. 17 and the data are given in Table 2.



(a) for 1st January



(b) for 1st May

Figure 10: Power flow patterns in optimal economic mode, considering yearly variation of PV output.

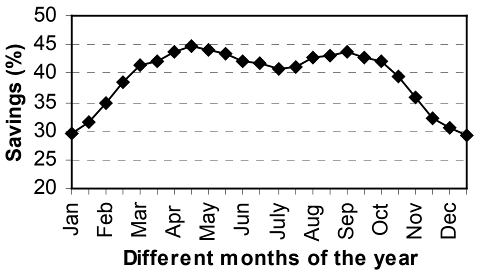
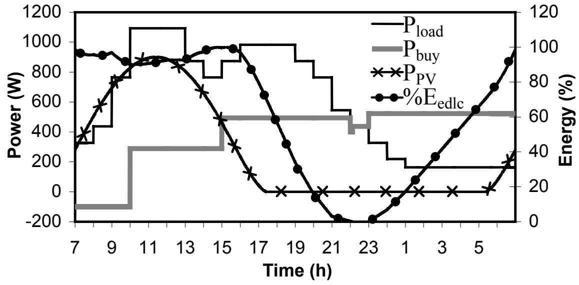
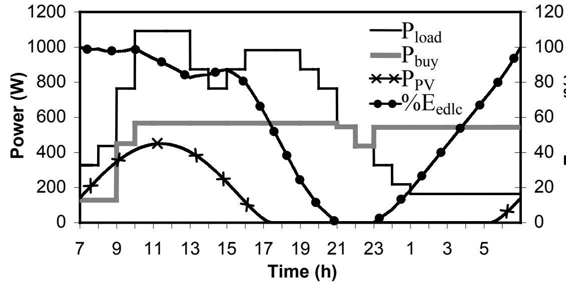


Figure 11: Yearly variation of economic benefit.



(a) for 100% PV output



(b) for 50% PV output

Figure 12: Power flow patterns in optimal economic mode, considering PV output change due to weather condition.

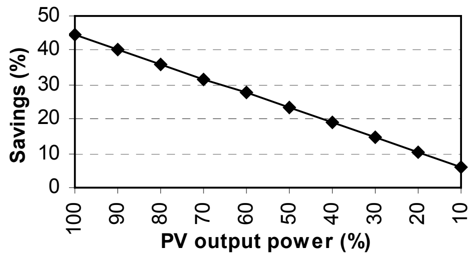


Figure 13: Variation of economic benefit considering PV output change due to weather condition.

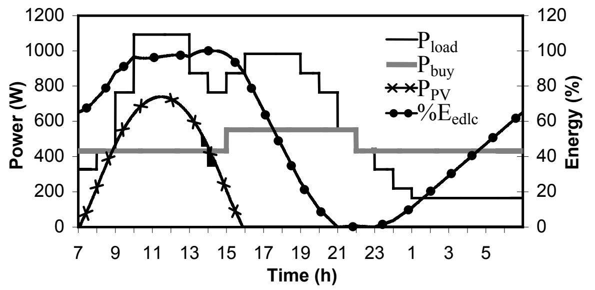
7 DISCUSSION

As shown in the graphs of Fig. 10, when the system is run in optimal economic operation mode, PV output (P_{PV}) is used fully and the EDLC is fully charged during off-peak hours (23pm~7am) and fully discharged during peak hours (7am~23pm) which is represented by $\%E_{edlc}$ i.e. % of energy of EDLC. To do this, we have to sell some power to grid line at 8am, as the PV output is greater than the load demand at this time, for 1st May (Fig. 10(b)). As depicted in Fig. 11, the yearly variation of economic benefit i.e. financial savings is as same as the yearly variation of daily total output of PV panel (Fig. 4). It is quite natural that the higher the output of PV panel the greater the economic benefit can be achieved from the system.

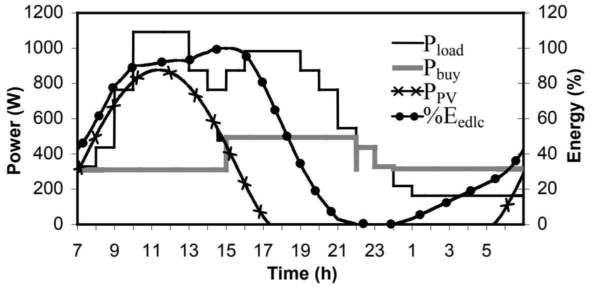
In Fig. 12, the EDLC is fully charged in off-peak hours and fully discharged in peak hours to get maximum economic benefit from the system. Here also we have to sell some energy to grid line from 7am to 10am to use the PV output fully (Fig. 12 (a)). Again, as shown in Fig. 13 economic benefit decreases with the decrease of PV output due to the cloudiness of weather.

Date	Economic mode of operation			Load leveling mode of operation	
	Cost without PV-ECS	Cost with PV-ECS	Savings (%)	LF (%)	LFF (%)
1 Jan	22.15R_o	15.60 R_o	29.56	84.60	5.31
15 Jan	”	15.15 R_o	31.57	83.26	5.53
1 Feb	”	14.45 R_o	34.75	81.73	6.56
15 Feb	”	13.59 R_o	38.61	79.00	8.04
1 Mar	”	12.99 R_o	41.34	77.46	8.95
15 Mar	”	12.85 R_o	41.99	76.81	9.38
1 Apr	”	12.43 R_o	43.87	75.36	10.24
15 Apr	”	12.25 R_o	44.68	74.22	10.9
1 May	”	12.39 R_o	44.03	75.11	10.39
15 May	”	12.51 R_o	43.51	75.68	10.05
1 June	”	12.84 R_o	42.02	77.68	8.96
15 June	”	12.92 R_o	41.68	78.67	8.44
1 July	”	13.12 R_o	40.76	80.26	7.64
15 July	”	13.05 R_o	41.05	80.20	7.69
1 Aug	”	12.67 R_o	42.78	78.26	8.72
15 Aug	”	12.60 R_o	43.11	77.31	9.21
1 Sept	”	12.44 R_o	43.85	75.20	10.3
15 Sept	”	12.67 R_o	42.79	74.63	10.52
1 Oct	”	12.80 R_o	42.19	73.48	11.11
15 Oct	”	13.45 R_o	39.29	73.31	10.2
1 Nov	”	14.23 R_o	35.76	77.07	8.79
15 Nov	”	12.85 R_o	32.35	79.33	7.43
1 Dec	”	15.39 R_o	30.52	81.26	6.54
15 Dec	”	15.69 R_o	29.14	83.42	5.65

Table 1: Data obtained for optimal economic mode and optimal load leveling mode.



(a) for 1st January



(b) for 1st May

Figure 14: Power flow patterns in optimal load leveling mode, considering yearly variation of PV output.

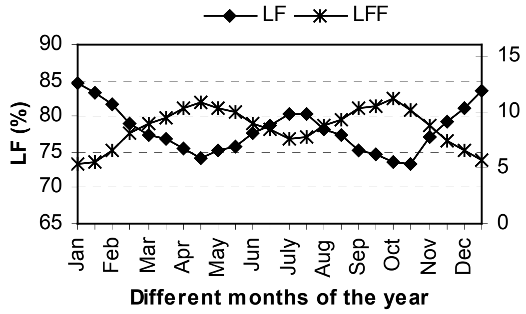
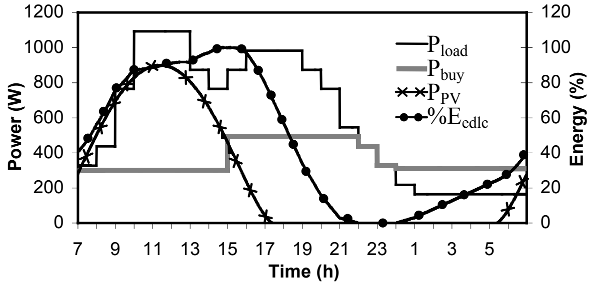
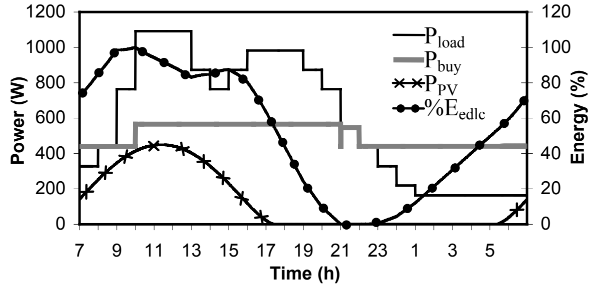


Figure 15: Yearly variations of LF and LFF.



(a) for 100% PV output



(b) for 50% PV output

Figure 16: Power flow patterns in optimal load leveling mode, considering PV output change due to weather condition.

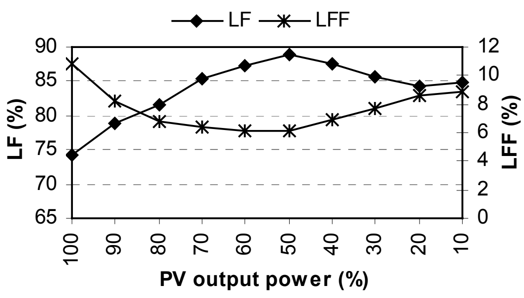


Figure 17: Variations of LF and LFF considering PV output change due to weather condition.

As shown in Figs. 14 and 16, when the system is run in optimal load leveling mode, flatter “buy powers” are obtained compared to those of Figs. 10 and 12 although the weather conditions were same. In this operation better LF and LFF have been achieved at the cost of economic benefit i.e. the EDLC is not fully charged during off-peak hours. Regarding the yearly variation of load leveling capacity (Fig. 15), LF and LFF worsen as the PV output increases (decrease of LF & increase of

PV output (%)	Economic mode of operation			Load levelign mode of operation	
	Cost without PV-ECS	Cost with PV-ECS	Savings (%)	LF (%)	LFF (%)
100	22.15R_o	12.24 R_o	44.73	74.32	10.88
90	”	13.20 R_o	40.41	78.84	8.26
80	”	14.16 R_o	36.07	81.55	6.73
70	”	15.12 R_o	31.71	85.33	6.45
60	”	16.07 R_o	27.45	87.27	6.14
50	”	17.03 R_o	23.11	88.84	6.11
40	”	17.99 R_o	18.76	87.48	6.88
30	”	18.95 R_o	14.41	85.68	7.66
20	”	19.92 R_o	10.06	84.23	8.58
10	”	20.88 R_o	5.72	84.78	8.91

Table 2: Simulated data for optimal economic mode and optimal load leveling mode considering PV output change due to weather condition.

LFF means their deterioration). The reason behind this would be clear if we look at the graphs of Fig. 14. As the output of PV panel increases, to use it fully, we have to lower the “buy power” from 7am to 15pm. Hence, the LF and LFF worsen gradually. As shown in Fig. 15, yearly variation of the load leveling capability also follows the yearly variation of PV output power (Fig. 4) inversely, i.e. poor load leveling is achieved for higher PV output for the specified load pattern of Fig. 9.

In Fig. 17, as the output power of PV panel decreases gradually due to the cloudy weather, LF and LFF improve up to a certain level and then worsen again. Explanation of this variation is – as the PV output decreases, the “buy power” level during 7am~15pm and 23pm~7am (Fig. 16(a)) can be increased and hence LF and LFF improve. After a certain level, we have to increase the “buy power” level during 15pm~22pm to meet the load demand, in addition to that of 7am~15pm and 23am~7am (Fig. 16(a)). Hence, the LF and LFF worsen again.

8 CONCLUSIONS

In this work, an advanced grid-connected PV-ECS system has been developed and its performance has been studied. To increase the durability of the system, a new storage device ECS is used. To get the maximum economic benefit and maximum load leveling facility from the system, two different algorithms have been proposed. The effectiveness of the algorithms has been studied by running the system in various weather conditions using the algorithms. The yearly variations of economic benefit and load leveling capacity of the system have been studied and presented here. The effect of the variation of PV output power due to the weather condition has also been described. The results prove the feasibility of the system as a distributed power generator using renewable energy, validity of the algorithms and also show the variation of the system’s performance for all the year round in the context of meteorological change. In this work, although we have used smooth estimated PV power, the system can work properly with the intermittent practical PV output power. In that case, EDLC works as a smoothing device as well as a storage device.

REFERENCES

[1] R. Om, S. Yamashiro, R. K. Mazumder, K. Nakamura, K. Mitsui, M. Yamagishi, M. Okamura, “Design and Performance Evaluation of Grid Connected PV-ECS System With Load Leveling Function,” Trans. of IEE Japan, vol. 121-B, no. 9, pp 1112-1119, 2001.

[2] M. H. Rahman, J. Nakayama, K. Nakamura, and S. Yamashiro, “Development of an Advanced Grid-Connected PV-ECS System Considering Solar Energy Estimation”, Transactions of IEE Japan, vol. 125-B, no. 4, pp 399-407, 2005.

[3] S. Rahman and B. H. Chowdhury, “Simulation of Photovoltaic Power Systems and Their Performance Prediction”, IEEE Trans. on Energy Conversion, vol. 3, no. 3, pp 440-446, Sep. 1988.

[4] M. H. Rahman, J. Nakayama, K. Nakamura, and S. Yamashiro, “An Intelligent Grid-Connected PV-ECS System With Load Leveling Function”, The International Conference on Electrical Engineering Proceedings, ICEE-066 (Pro. CD), July 2003.

[5] C. V. Nayar, M. Ashari and W. W. L. Keerthipala, “A Grid-Interactive Photovoltaic Uninterruptible Power Supply System Using Battery Storage and a Back Up Diesel Generator”, IEEE Trans. on Energy Conversion, vol. 15, no. 3, pp 348-353, Sep. 2000.

[6] M. H. Rahman, J. Nakayama, K. Nakamura, and S. Yamashiro, “An Intelligent Grid-connected PV-ECS System With Load Leveling Function”, 3rd IASTED International Conference on Power and Energy Systems Proceedings, pp 75-80, September 2003,.

[7] M. H. Rahman, J. Nakayama, K. Nakamura, and S. Yamashiro, “Development of a Distributed Power Generator of PV-ECS Using a Day-ahead Weather Forecast”, The International Conference on Electrical Engineering Proceedings, pp 115-120, July, 2004.

[8] M. Toyama, S. Yamashiro, M. Sasaki and S. Araki, “A Study on Electric Parameters of EDLC Power Storage Device”, The International Conference on Electrical Engineering Proceedings, pp 520-524, July, 2004.

[9] M. Okamura, “A New Capacitor-Electronics Power Storage”, 13th EVS proceedings, 6H-01, 1996.

[10] M. Oshima, E. Masada, “A Single-Phase PCS With a Novel Constantly Sampled Current-Regulated PWM Scheme”, IEEE Transaction on Power Electronics, Vol. 14, no. 5, pp 823-830, Sep. 1999.

[11] M. H. Rahman, K. Nakayama, S. Yamashiro, “Optimal Economic Operation of Grid-Connected PV-ECS System”, Joint Convention Record, the Hokkaido Chapters of the Institute of Electrical and Information Engineers, pp 103-104, October, 2004.

[12] J. A. Duffie and W. A. Beckman, Solar Engineering of Thermal Processes, New York: John Willey and Sons, 1980, pp 6-65.