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A Study on the Performance of Grid-Connected PV-ECS System Considering Meteorological Variation of Bangladesh

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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 of Bangladesh. A PV-ECS system has been considered and to study its performance a simulation program has been developed. The validity of this simulation program has been verified by comparing the simulated results with the practically obtained results. Two modes of operation of the PV-ECS system – (I) optimal economic mode and (II) optimal load leveling mode have been proposed in this paper. To run the system in these modes, two different algorithms have also been developed. To study their performance, the algorithms have been used to run the system in optimal economic mode and optimal load leveling mode. Again, the variations of economical benefit (in mode (I)) and load leveling capacity (in mode (II)) for the change of PV output because of the yearly variation of solar radiation and meteorological condition have been studied. Finally the economic benefits and load leveling capacity 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

I. Introduction

Now-a-days distributed power generating systems specially those using photovoltaic (PV) is drawing attractions all over the world. Although the initial cost of PV system is yet higher than that of conventional power system, the use of the first is gradually increasing due to the low maintenance, long lasting and environment friendly advantages. Regarding the PV-based power generating system many researches are being done [1-8]. In this paper, a grid-connected PV-based distributed system using Energy Capacitor System (ECS) instead of conventional battery has been considered as ECS has many advantages over lead-acid batteries. ECS is a very long lasting energy storage system which consists of Electric Double Layer Capacitor (EDLC) and some electronics circuits.

The performance of PV-ECS system depends on the power produced by the PV panel, which varies due to the meteorological change. So in this work the performance of a grid-connected PV-ECS system, in the context of the variation of PV output due to the yearly variation of solar radiation and the variation of weather conditions, has been studied. To study the performance of the system, a simulation program has been developed and its performance has been verified by comparing the simulated results with the practically obtained results [2]. 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, emphasis is given on to level the power taken from grid line (hereafter power taken from grid line will be referred as "buy power").

In this paper, two different algorithms to run the system in two different modes have been developed. The algorithms will help 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. The output of the PV panel varies due to the yearly variation of solar radiation and weather condition. So the effect of the change of PV output on the performance of the system i.e. economic benefit and load leveling capacity has been addressed in this paper.

To calculate the solar radiation modified Hottel's and Liu-Jordan's equations have been used [8]. 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.

II. Brief Description of the System

A simplified block diagram of the proposed system is shown in Fig. 1 [6]. The nominal maximum output of the PV panel, used in the 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 [10]. 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 grid-tied inverter [11] 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[4].

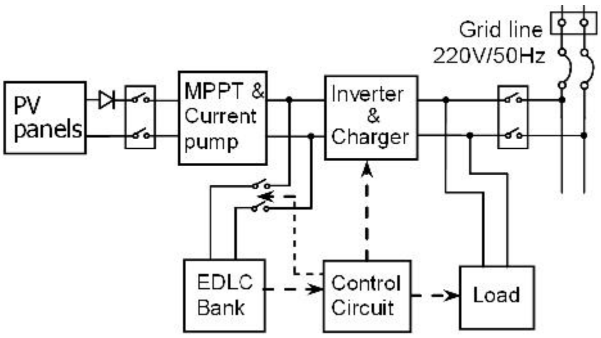


Fig. 1. Block diagram of PV-ECS system.

III. 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 Dhaka City their values are: 6.0, 0.122013711, 0.741522392 and 0.394685396 respectively.

Extraterrestrial radiation G_{on} on n^{th} day of the year can be calculated by the following equation [3].

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

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, ξd = a constant = 6.

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

$$\Re = (\tau_b + \tau_d)\, G_{on} \;\ldots\ldots\ldots(5)$$

To justify the validity of Eq. (5) total solar radiation on 25 October 2009 in Dhaka has been calculated and practically measured. These are shown in Fig. 2. Although, the practically measured radiation has some fluctuations, but the average of data is almost same as the calculated data.

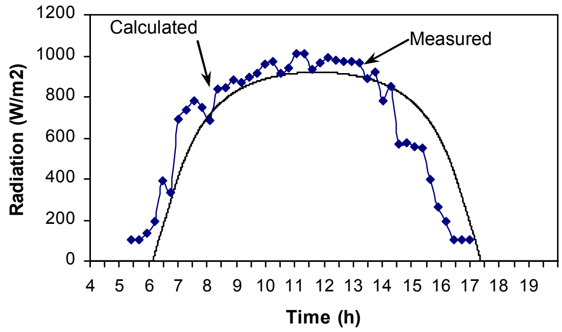


Fig. 2. Calculated and practically measured solar radiation in Dhaka.

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

$$P_{pv} = \Re \times \cos\theta \times \eta_m \times A_p \times \eta_p \quad (6)$$

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).

In this simulation an average temperature of 30°C has been considered.

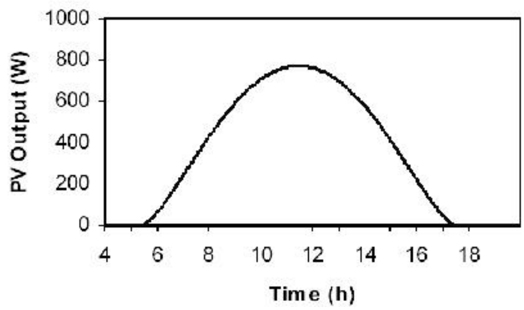


Fig. 3. Estimated PV output on 11th April 2004.

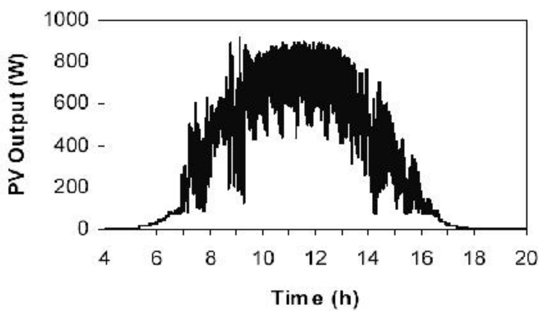


Fig. 4. Practically measured PV output on 11th April 2003.

Considering the above values, the PV output for a typical sunny day was estimated and the practical output for the same day was measured for comparison in Kitami, Japan. These are shown in fig. 3 and fig. 4 respectively. Fig. 3 and Fig. 4 show that the graphs of the estimated and practically measured PV outputs have almost the same shape. 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 about 10%. These data prove the validity of the estimation process. Using this process, the daily total PV outputs for different months of the year for Dhaka City have been estimated and are shown in Fig. 5.

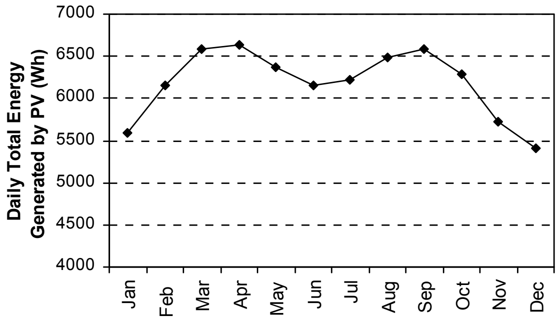
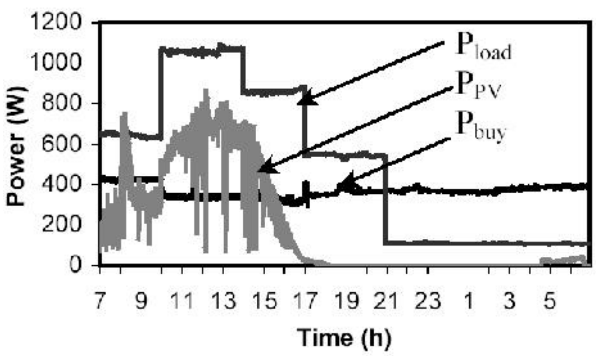


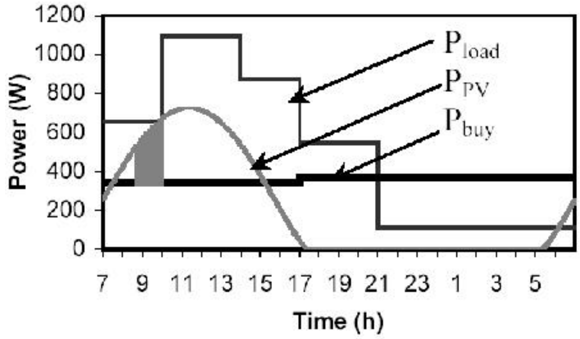
Fig. 5. Estimated daily total PV output for different months of the year.

IV. Simulation of the System

A program was developed to simulate the operation of the system. The details of the simulation program have been published in [2]. To verify the validity of the simulation program, simulated results have been compared with the practically measured results. The practical data was taken in Kitami, Japan. In Fig. 6 the simulated and practically obtained power flow patterns for a typical sunny day are shown. The integrated energy of the simulated load (P_{load}), PV output (P_{pv}) and "buy power" (P_{buy}) are 12. 23kWh, 8.58kWh and 4.91kWh respectively and that of the practically obtained P_{load}, P_{pv} and P_{buy} 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.



(a) Practically obtained



(b) Simulated

Fig. 6. Daily power flow patterns on 1st June 2004.

V. 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.

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 have to be done on priority basis (first priority is given on 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 discharges it fully during peak hours (when the price of electricity is high). If the sum of ECS energy and 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.

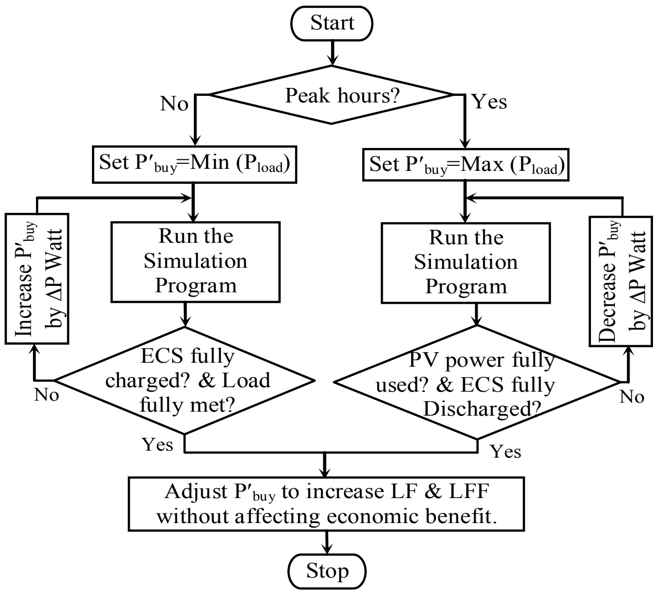


Fig. 7. Algorithm for optimal economic operation.

To run the system in this optimal economic mode, the "buy power" has to be set to an optimum level so that the above conditions are satisfied. This optimum value of "buy power" can be set by using the algorithm of 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 in run mode. If the PV power is not fully used and ECS is not fully discharged, P'_{buy} will be decreased by ΔP. In this way P'_{buy} will be decreased until the ECS is fully discharged and PV power is fully used.

If the total energy of ECS and PV output is greater than that of 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.

For off-peak hours, P'_{buy} will be set to the minimum value of the load pattern. Then the simulation program will be run. If the load demand is not fully satisfied and ECS 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 ECS is fully charged and 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.

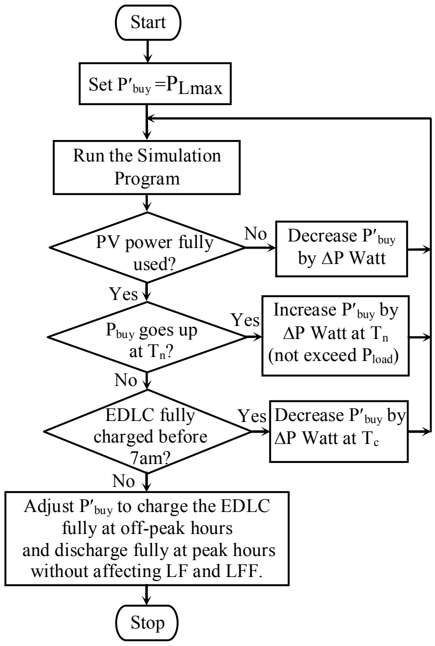
Optimal load leveling mode of operation

The aim of this mode of operation is to level the "buy power" and thus to improve its LF and LFF. The following things have 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 the optimum value of "buy power" has to be set to meet the above conditions. The algorithm to set this optimum value is shown in Fig. 8.

At first, the algorithm will set P'_{buy} to the maximum power of the load profile and run the simulation program. If 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 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 beginning 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 become 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.



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. 10pm~19pm of Fig. 16(a)).
T_c = Time period when the EDLC is charged (e.g. 23pm~7am of Fig.16(a))

Fig. 8. Algorithm for optical load leveling.

VI. Simulation Results

To simulate the operation of the system, a typical commercial load pattern (Fig. 9) has been considered. The average value, LF and LFF of this load pattern are 492W, 49.2% and 29.7% respectively. Operation of the system has been simulated for this load pattern using the simulation program with the help of the algorithm of described in section 5.

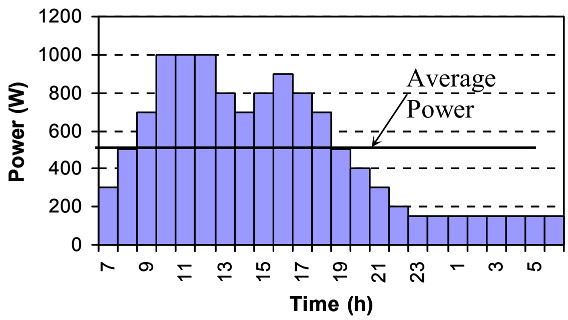
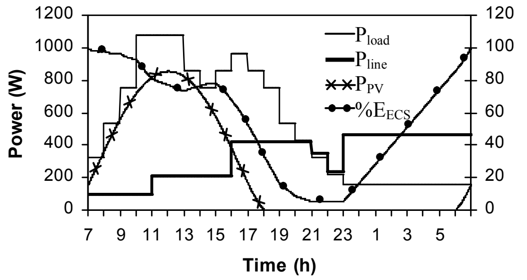


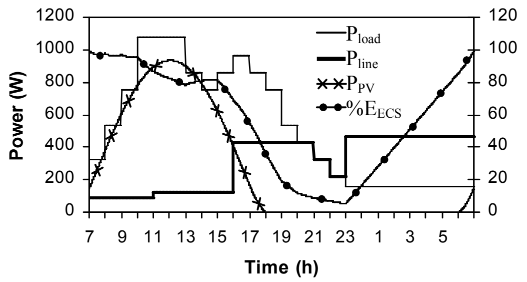
Fig. 9. Load pattern used for simulation.

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, with and without using the PV-ECS system, has been calculated. In this calculation it is considered that the price of electricity from 7am to 23pm (R_p) is higher than that of from 23pm to 7am (R_o) i.e. $R_p = \alpha R_o$. Here, $\alpha = 1.6$ has been assumed,



a) on 15th January



b) on 15th April

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

which is a threshold value to overcome the loss of the system. The yearly variation of the economic benefit is shown in Fig. 11 and the data are given 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% at 10% interval for an arbitrary day 15th July. Fig. 12 shows some simulation results. The variation of the economic benefit with the decrease of PV output are shown in Table 2 and Fig. 13.

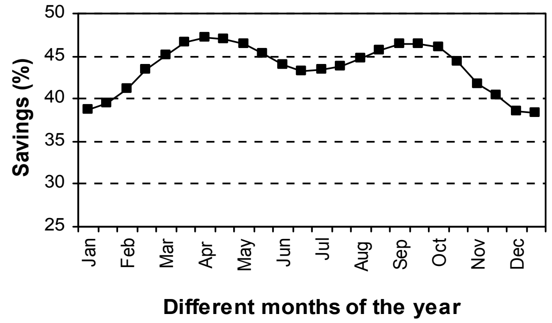
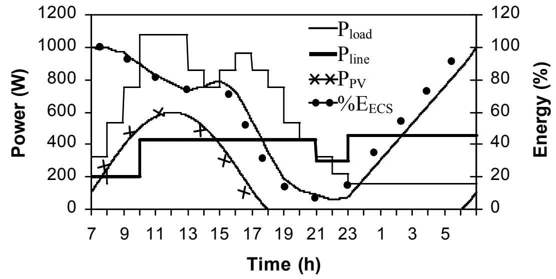
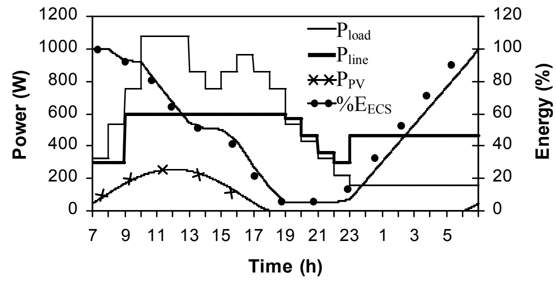


Fig. 11. Yearly variation of economic benefit.



a) for 70% PV output



a) for 70% PV output

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

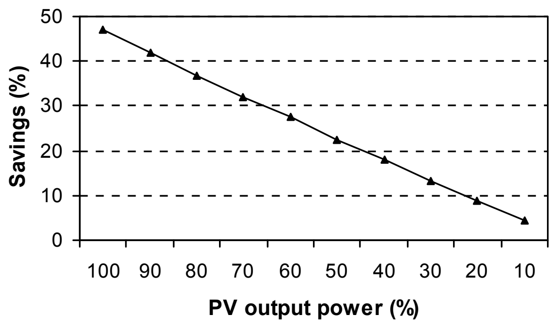


Fig. 13. Variation of economic benefit considering PV output change due to weather condition.

Simulation in optimal load leveling mode

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

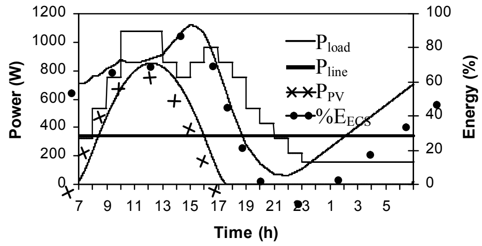
Again, to study the effect of weather condition on load leveling capacity, operations of the system on 15th July have also been simulated by changing the PV output from 100% to 10% at 10% interval. The simulated power flow patterns for 70% and 30% PV output are shown in Fig. 16. The variations of LF and LFF due to the decrease of PV output are shown in Fig. 17 and the data are given in Table 2.

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

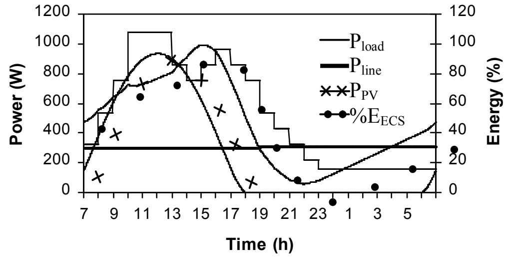
Date	Economic mode of operation			Load leveling of operation	
	Cost without PV-ECS	Cost with PV-ECS	Savings (%)	LF (%)	LFF (%)
1 Jan	19.53R_0	11.97R_0	38.72	100	00
15 Jan	”	11.83 R_0	39.40	100	00
1 Feb	”	11.48 R_0	41.22	100	00
15 Feb	”	11.04 R_0	43.49	99.97	0.06
1 Mar	”	10.72 R_0	45.11	99.29	0.18
15 Mar	”	10.42 R_0	46.65	98.52	0.81
1 Apr	”	10.32 R_0	47.13	97.69	1.21
15 Apr	”	10.36 R_0	46.95	97.74	1.16
1 May	”	10.48 R_0	46.35	99	0.28
15 May	”	10.68 R_0	45.34	99.59	0.11
1 Jun	”	10.93 R_0	44.01	99.78	0.06
15 Jun	”	11.08 R_0	43.26	100	00
1 Jul	”	11.07 R_0	43.34	100	00
15 Jul	”	10.98 R_0	43.79	99.78	0.06
1 Aug	”	10.79 R_0	44.77	99.59	0.11
15 Aug	”	10.60 R_0	45.71	99.2	0.25
1 Sept	”	10.46 R_0	46.46	97.74	1.17
15 Sept	”	10.46 R_0	46.46	97.49	1.22
1 Oct	”	10.55 R_0	45.97	98.22	0.8
15 Oct	”	10.88 R_0	44.28	99.28	0.19
1 Nov	”	11.36 R_0	41.81	99.67	0.06
15 Nov	”	11.62 R_0	40.51	100	00
1 Dec	”	12.00 R_0	38.56	100	00
15 Dec	”	12.03 R_0	38.39	100	00

VII. 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 ECS is fully charged during off-peak hours (23pm~7am) and fully discharged during peak hours (7am~23pm) i.e. 100% of energy of ECS has been used by the system. 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. 5). 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, it can be seen that the ECS is fully charged in off-peak hours and fully discharged in peak hours to get maximum economic benefit from the system. Again, as shown in Fig. 13 economic benefit decreases with the decrease of PV output due to the cloudiness of weather.



(a) for 15 January



(b) for 15 April

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

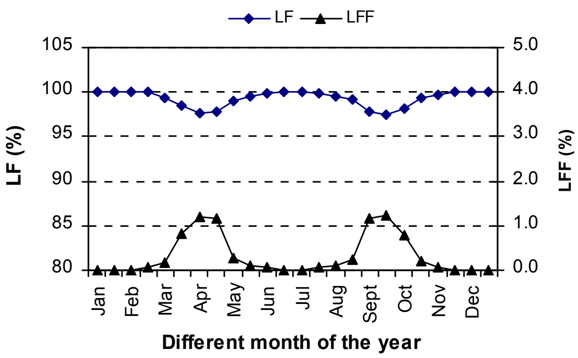
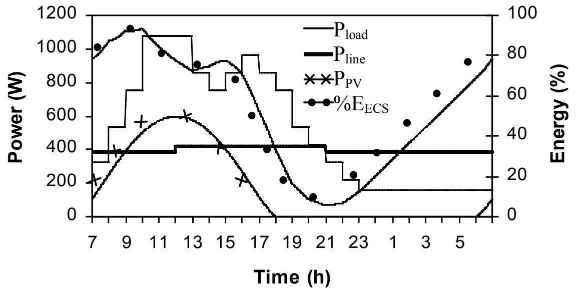
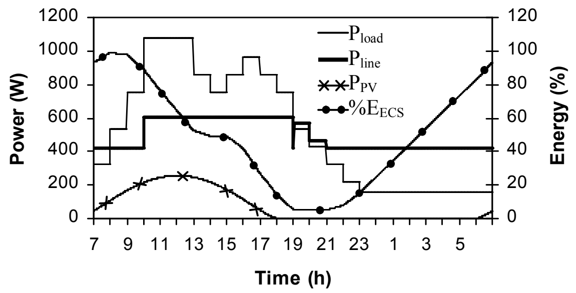


Fig. 15. Yearly variations of LF and LFF.

As shown in Fig. 14 and 16, when the system is run in optimal load leveling mode, more uniform "buy power" is obtained compared to that of Fig. 10 and Fig. 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 ECS is not fully charged during off-peak hours and fully discharged during peak hours. Regarding the yearly variation of



a) for 70% PV output



b) for 30% PV output

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

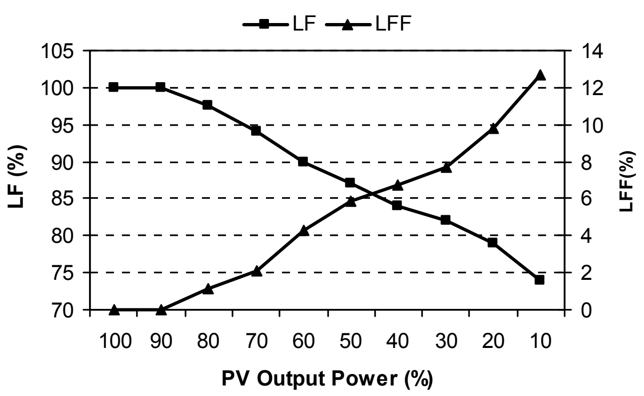


Fig. 17. Variations of LF and LFF considering PV output change due to weather condition.

load leveling capacity (Fig. 15), LF and LFF deteriorates as the PV output increases. The reason behind this would be clear from 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 deteriorate gradually.

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

PV output (%)	Economic mode of operation			Load leveling mode of operation	
	Cost without PV-ECS	Cost with PV-ECS	Savings (%)	LF (%)	LFF (%)
100	$19.53R_o$	$10.36R_o$	46.93	100	0
90	$19.53R_o$	$11.36R_o$	41.82	100	0
80	$19.53R_o$	$12.32R_o$	36.9	97.5	1.1
70	$19.53R_o$	$13.28R_o$	32	94	2.06
60	$19.53R_o$	$14.16R_o$	27.5	90	4.3
50	$19.53R_o$	$15.14R_o$	22.5	87	5.87
40	$19.53R_o$	$16.01R_o$	18	84	6.7
30	$19.53R_o$	$16.92R_o$	13.36	82	7.7
20	$19.53R_o$	$17.81R_o$	8.8	79	9.8
10	$19.53R_o$	$18.67R_o$	4.4	74	12.71

As shown in Fig. 15, yearly variation of the load leveling capability also follows the yearly variation of PV output power (Fig. 5) 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 deteriorate gradually. Explanation of this variation is - as the PV output decreases, the "buy power" level during 10am~19pm has to be increased to meet the load demand. Hence the LF and LFF worsen gradually.

VIII. Conclusions

In this work the performance of PV-ECS system has been investigated considering meteorological variation. 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 and using the algorithms. The yearly variation 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 also show the variation of the system's performance for the year round in the context of meteorological change.

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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, 121-B(9), 1112-1119, 2001.
2. Rahman M. H., J. Nakayama, K. Nakamura, and S. Yamashiro, "Development of an Advanced Grid-Connected PV-ECS System Considering Solar Energy Estimation, Transactions of IEE Japan, 125-B(4), 399-407, 2005.
3. Rahman S. and B. H. Chowdhury, "Simulation of Photovoltaic Power Systems and Their Performance Prediction" IEEE Trans. on Energy Conversion, 3 (3), 440-446, Sep. 1988.
4. Rahman M. H., 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), Hong Kong, July 2003.
5. Nayar C. V., 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, 15 (3), pp 348-353, Sep. 2000.
6. Rahman M. H., 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, 75-80, Spain, September 2003.
7. Rahman M. H., 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, 115-120, Japan, July, 2004.
8. Toyama M., S. Yamashiro, M. Sasaki and S. Araki, "A study on electric parameters of EDLC power storage device", The International Conference on Electrical Engineering Proceedings, 520-524, Japan, July, 2004.
9. Okamura M., "A new capacitor-electronics power storage",13th EVS proceedings, 6H-01, 1996.
10. Oshima M., E. Masada, "A single-phase PCS with a novel constantly sampled current-regulated PWM scheme" IEEE Transaction on Power Electronics, 14(5), 823-830, Sep. 1999.
11. Rahman M. H., 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, 103-104, Japan, October, 2004.
12. Duffie J. A. and W. A. Beckman, Solar Engineering of Thermal Processes, New York: John Willey and Sons, 1980, 6-65.