Cost Effectiveness of a Control Strategy for Grid-Connected Photovoltaic Systems

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Abstract—**The electricity customers may use photovoltaic systems supported by batteries in order to fulfill a fraction of their energy requirements and to decrease the peak demand. The achievable savings primarily depend on a system control strategy. In this paper, one algorithm based on a threshold control is described and tested. The sensitivity on the most important input variables is analyzed by extensive set of numerical simulations.**

Keywords - battery energy storage system, distribution network, peak shaving, photovoltaic system

I. Introduction

In recent years, the photovoltaic (PV) systems remain the most rapidly growing energy technology worldwide. The installed PV capacity surpassed 100 GW in 2012 [1]. Nearly 38 GW was added in 2013, while new 40 GW are expected to be installed until the end of 2014 [2]. Electricity customers are encouraged to invest in such systems and to use them in a combination with grid supply in order to minimize their energy bills. The PV systems are often equipped with the battery energy storage systems (BESS) to increase the control flexibility through storing surpluses and compensating deficits of solar energy.

Different control strategies for minimization of the customer electricity bill have been proposed in the literature [3,4]. However, the studies were mainly focused on the minimization of the customer volumetric energy costs. On the other hand, the tariffs for industrial and commercial customers often include the monthly peak demand component as well. In this paper, we propose a control strategy for the PV systems that balance between the peak shaving and reducing the cost of energy.

The first steps in this study are based on simplified deterministic models. The control strategy is tested and the maximum achievable savings are calculated. As the realistic inputs such as the solar radiation and the customer load have the stochastic nature, their values may deviate from the expected values. In the latter part of the study, the inputs of importance are altered in order to quantify their influence on the final results.

II. Description and Modeling of the System

The system under consideration is depicted in Fig. 1. The customer load is supplied either by the utility grid or by the photovoltaic system. If the power available from the PV system exceeds the load requirements, the surplus may be transferred either to the grid or be stored in the battery for the later use. Possibility of charging the battery from the grid is not covered in this paper. In the reminder of the section, the individual models of the system components are described.

A. Photovoltaic System and Inverter

The photovoltaic system is one of the three sources for supplying the customer load. PV system and inverter are integrated into a joint model. Our model rely on the National Renewable Energy Laboratory modeling methodology documented in [5], which is implemented in a web calculator PVWatts. PVWatts combines a number of sub-models to predict overall system performance and includes several built-in parameters. The inputs for this model are irradiation, DC rating of the PV system, tilt, azimuth, efficiency of the modules and efficiency of the inverter. By entering data for the DC rating of the PV system and location of the system, tilt and azimuth in PVWatts calculator the generation of the PV system is computed. The results of the calculation should be interpreted as being a representative estimate for a similar actual system operating in a year with typical weather. The errors may be as high as 10 percent of annual energy for weather data representing long-time typical conditions.

B. Battery and Converter

The battery energy storage system capacity is expressed by the nominal capacity and number of autonomy hours. We use BESS for storing energy when PV system produces more energy than demanded by the load. We also use BEES for load supply when the PV system produces less energy than load demand.

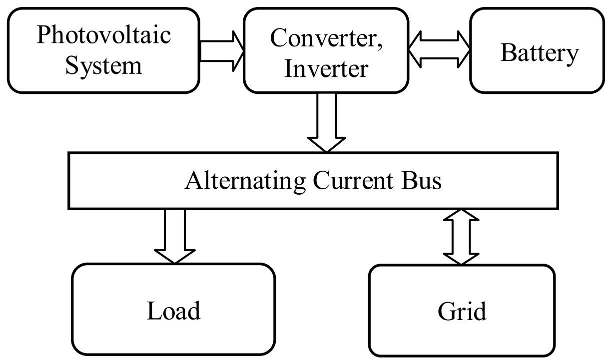

Figure 1. The grid-connected PV system

Nomenclature			
Abbreviations		C_{off}	Electricity prices (Off-peak) [BAM/kWh]
BESS	Battery energy storage system	C_{on}	Electricity prices (On-peak) [BAM/kWh]
PV	Photovoltaic	C_f	Feed-in tariff [BAM/kWh]
Indices		C_{pd}	Peak demand price [BAM/kW]
h	Hour	T_{on}	Time of occurrence of the on-peak daily tariff [h]
Parameters		T_{off}	Time of the end of the on-peak daily tariff [h]
η_{ch}	BESS charging efficiency (%)	*Variables*	
η_{dch}	BESS discharging efficiency (%)	P_{Gmax}	The monthly grid peak demand [kW]
η_{inv}	DC/AC electric conversion efficiency (%)	P_B	Charge/discharge rate of the BESS [kW]
δ	BESS hourly self-discharge rate (%)	E_B	Stored energy in the BESS [kWh]
Δt	Sampling interval [h]	P_L	The electrical load of the customer [kW]
W_{ref}	The nominal capacity of BESS [kWh]	P_{pv}	The electricity generated by the PV system (AC) [kW]
W_{Bmin}	Minimum stored energy in the BESS [kWh]	P_G	Power supplied by the grid [kW]
W_{Bmax}	Maximum stored energy in the BESS [kWh]	P_N	Net power of the grid [kW]
P_{Bmax}	Maximum charge/discharge rate of the BESS [kW]	W_{Goff}	Energy delivered in the grid (Off-peak) [kWh]
P_{Gthr}	Threshold for the power supplied by the grid [kW]	W_{Gon}	Energy delivered in the grid (On-peak) [kWh]
P_{pvdc}	DC rated power [kW]	W_G	Total energy delivered in the grid (W_{Gon}+W_{Goff}) [kWh]
		W_{Loff}	Energy supplied by the grid (Off-peak) [kWh]
		W_{Lon}	Energy supplied by the grid (On-peak) [kWh]

BEES is modeled by two equations for three working states. If the power of the battery P_B is less than zero, the battery is in charge process. This process we can describe with (1):

$$W_B(h) = W_B(h-1)\left(1-\frac{\delta\Delta t}{24}\right)+\eta_{ch}\cdot P_B(h)\cdot\Delta t. \qquad (1)$$

In (1) the first summand models the self-discharge while the second describes the battery charging from the PV system. The charging process ends when the BESS reaches the maximum capacity. In the second case when the power of the battery is higher than zero, the battery is in discharging process. The discharging process ends when the BESS is on minimum stored energy. This state we can also describe with (1). Finally, the second equation models the battery at no operation. Equation (2) takes into account only self-discharge process in the battery:

$$W_B(h) = W_B(h-1)\left(1-\frac{\delta\Delta t}{24}\right). \qquad (2)$$

C. Load

The load is considered known for the month under consideration. It is modeled by an array of the hourly values P_L. An example of the monthly load profile of an industrial customer from Banja Luka is shown in Fig. 2.

D. Grid

In this paper, we consider the grid as uninterrupted source of infinite power. The grid is used for supplying the base load. The grid is also used when the battery is empty and the PV system is not capable of producing enough energy. Electricity tariffs for industrial and commercial customers in many utilities worldwide include both the volumetric and peak demand component. Therefore, one of our primary targets is to reduce the grid peak demand and to decrease its negative effect on the customer energy bill. Tariff information used in this study corresponds to actual situation in the Republic of Srpska [7,8].

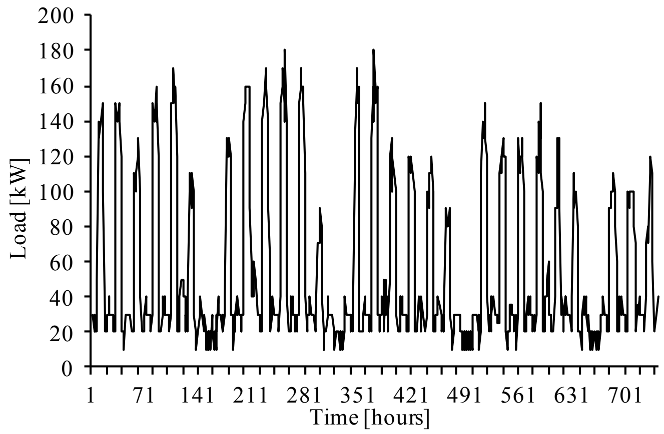

Figure 2. The monthly load profile

E. Control Strategy

We use an automatic controller to adjust the load flow in the customer AC bus for the minimization of the overall energy cost. If the net metering is used for calculating energy exchange between the customer and distribution network, the following cost function is employed:

$$C=(W_{Lon}-W_{Gon})\cdot C_{on}+(W_{Loff}-W_{Goff})\cdot C_{off}+P_{Gmax}\cdot C_{pd}. \qquad (3)$$

The photovoltaic sources, as the source of renewable energy, may be incentivized by a feed-in tariff for the energy supplied to a distribution network. In such a case, the customer cost function is written in the following manner:

$$C(P_{Gthr})=W_{Lon}\cdot C_{on}+W_{Loff}\cdot C_{off}+P_{Gmax}\cdot C_{pd}-W_G\cdot C_f. \qquad (4)$$

Both for cases (3) and (4) the goal for controller is to minimize the cost function C. The input data for the controller are the production of PV system, load, stored energy in BESS and threshold power. The output data are charge or discharge rate of the BESS and power supplied by the grid. The proposed control algorithm is shown in Fig. 3. The controller first com-

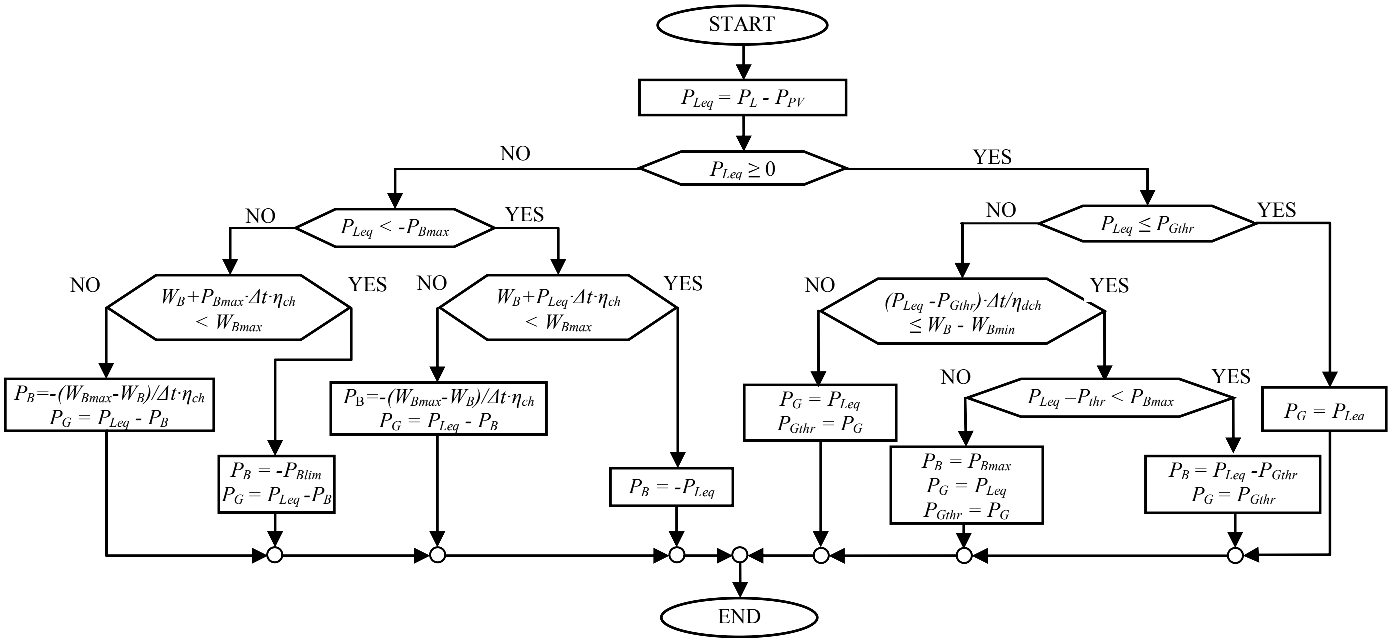

Figure 3. The control algorithm flow chart

pares the load and generation of the PV system. If the difference is negative and less than negative value of the maximum charge rate of BESS and there is enough empty capacity in BESS, the BEES is charged. In the second case, if there is not enough capacity in BEES, the BESS is charged up to its maximum capacity and the rest is delivered to the distribution network. In the third case, if the difference is negative and higher than negative value of the maximum charge rate of the BESS, the BESS is charged and distribution network is supplied. The rate of charging of the BESS and grid supply depend on the state of the BESS charge. If the difference between the load and generated energy in the PV system is positive and less than the user defined power threshold P_{Gthr}, the load is supplied from the grid. However, if difference is positive and higher than the limit of power supplied by the grid and there is enough energy in the BESS, the load is supplied by distribution network with power limit and the BESS is discharged. But if there isn't enough energy inside BESS, the load is supplied from the distribution network and additionally the power threshold must be appropriately increased.

Obviously, very important issue in this control strategy is to choose the appropriate threshold for the power drawn from the grid. In a deterministic case with all the inputs being certainly known, the optimal threshold may be found by a simulation based search process. The customer cost would then be minimized. On the other hand, if the inputs deviate from their expected values the cost effectiveness of the algorithm will be more or less reduced below the theoretical maximum.

III. Sensitivity Analysis

In this section we examine how some important input variables influence the overall cost effectiveness of the control algorithm. We analyze the selection of the grid power threshold, the sequence of the sunny and overcast days as well as the changes in the customer load.

A. Test Case Description

Test customer is a medium industrial customer from Banja Luka. As an example, we observe the month of July. The load profile is given in Fig. 2. The production of the PV system, as calculated in PVWatts, is shown in Fig. 4. The other system parameters used in all the simulations are listed in Table I.

TABLE I. System Information

Parameters	Value	Unit	Reference
P_{pv}	200	kW	
P_{Bmax}	100	kW	
$W_{ref,}\ W_{Bmax}$	*750*	kWh	
W_{Bmin}	*75*	kWh	
δ	0.140	% per day	[3]
η_{ch}	89	%	[6]
η_{dch}	89	%	[6]
η_{inv}	96	%	[6]
C_{off}	0.054	BAM/kWh	[7] (tariff group I)
C_{on}	0.108	BAM/kWh	[7] (tariff group I)
C_{pd}	15.867	BAM/kWh	[7] (tariff group I)
C_f	0.3178	BAM/kWh	[8]
T_{on}	7	h	[7] (tariff group I)
T_{off}	23	h	[7] (tariff group I)

B. Selection of the Grid Power Threshold

By changing the grid power threshold P_{Gthr}, the customer electricity bill is affected to a certain extent. Simulation results are shown in Fig. 5. The cost of energy are calculated by using expression (4). It can be noticed that the optimal threshold is 82 kW and the minimal energy bill for July is 2338 BAM. If the threshold is larger than 82 kW, the cost of energy increases, as we allow a greater peak demand drawn from the grid. For $P_{Gthr} > \max(P_{Leq})$ the energy costs don't any further depend on the chosen threshold. In the second case, if the threshold is less than 82 kW, the cost of energy changes in dependent when the threshold is exceeded.

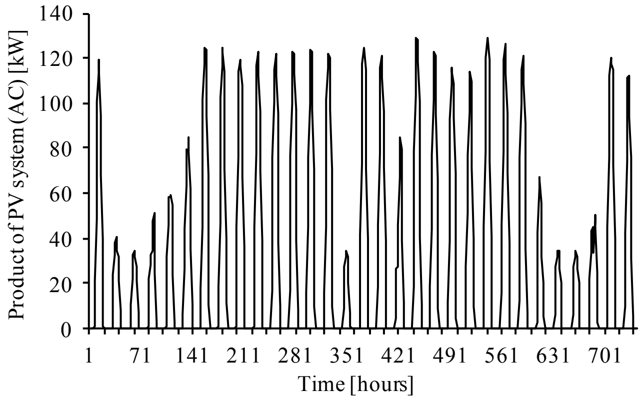

Figure 4. Production of the PV system

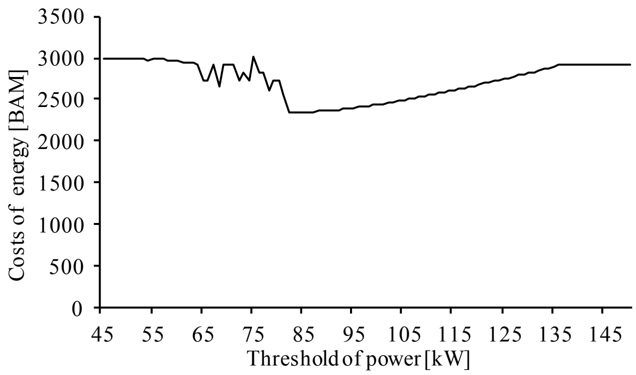

Figure 5. Cost of energy in function of power threshold

C. Sequence of Sunny and Overcast Days

The next experiment is a change of the sequence of sunny and overcast days, while the total energy produced by the PV system is kept constant. The impact on the grid power threshold and the cost of energy is analyzed in several cases. In the first case, the sunny and overcast days are uniformly distributed. In other cases we have several overcast days in a block. Table II presents a number of overcast days in each case, the optimal threshold power and the cost for this power. Fig. 6 presents the energy cost as the function of the chosen threshold for different cases. Fig. 7 presents threshold deviation from the one we have for the reference case.

TABLE II. NUMBER OF OVERCAST DAYS

Event	Number of overcast days in block	Optimal threshold [kW]	Cost for optimal threshold [BAM]
Case A1	1	71	2497
Case B1	3	77	2450
Case C1	4	80	2393
Reference case (R)	5	82	2338
Case D1	6	89	2447
Case E1	8	95	2519
Case F1	9	99	2539

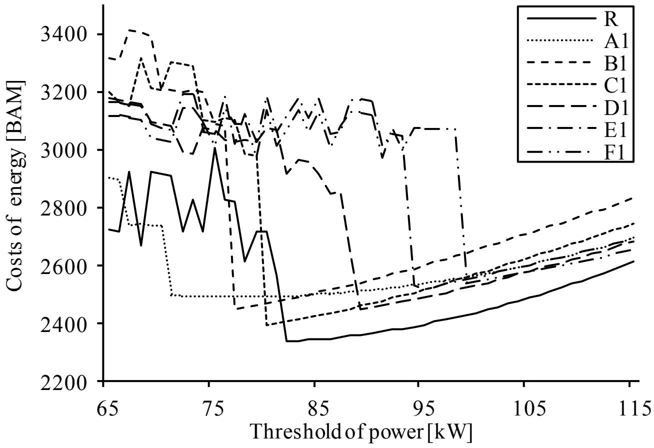

Figure 6. Cost of energy as a function of power threshold for several cases

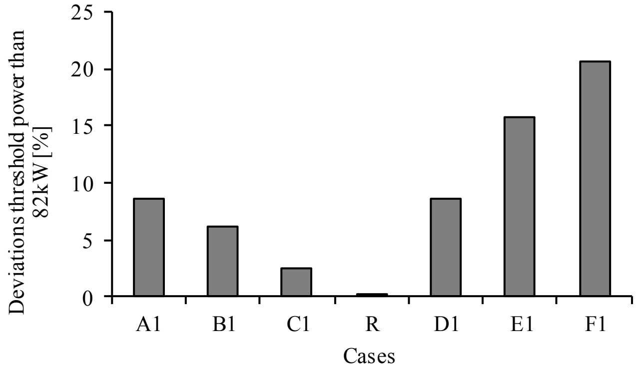

Figure 7. Deviation threshold from the reference case

Moving away from the reference state we have a higher deviation. If we mistakenly set the controller for the reference state but the production of the PV system belongs to one of the other cases, we will obtain deviation in costs. These deviations are presented in Fig. 8. It can be noticed that a block of overcast days wider than in the reference case leads to errors in the cost of more than 20 %, due to an increase in the power threshold. On the opposite, the number of overcast days less than it is in the reference case leads to an error less than 2%, because the customer can deliver surplus of their energy in the distribution network.

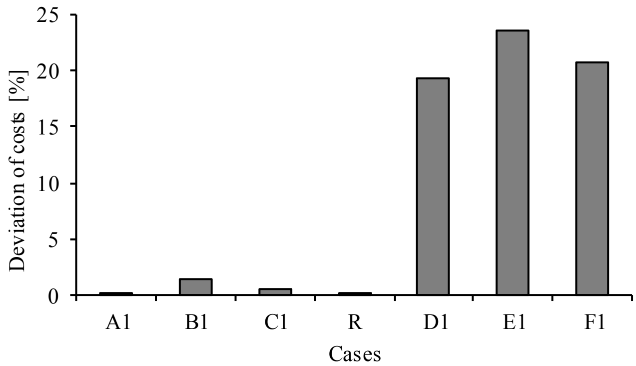

Figure 8. Deviation of energy cost from the minimum value

D. Changes in the Customer Load

Finally, the impact of load change on the cost of energy is analyzed. The load is linearly scaled by multiplying the load profile by a constant k. Table III presents the values of coefficient k, optimal threshold power and the cost related to the optimal threshold.

TABLE III. LOAD SCALING

Event	k	Optimal threshold [kW]	Cost for optimal threshold [BAM]
Case A2	0.85	60	1216
Case B2	0.90	68	1601
Case C2	0.95	75	1978
Reference case (R)	1.00	82	2338
Case D2	1.05	90	2689
Case E2	1.10	97	3032
Case F2	1.15	104	3372

Fig. 9 presents the cost of energy as the function of the coefficient k. In this figure we can notice that the optimal threshold is growing when the coefficient k tends towards 1.15.

If the controller is set for the reference case and the load belongs to one of cases defined here, we have deviations in the cost. These deviations are presented in Fig. 10. In this figure we can see that the coefficient k less than one causes the error less than 10%. However, for the coefficient k higher than one error is higher than 20%, because it leads to an increase in the grid power threshold.

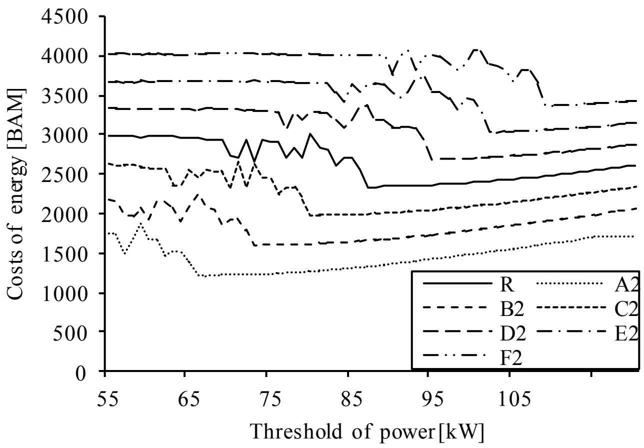

Figure 9. Cost of energy as the function of grid power threshold for considered simulation cases

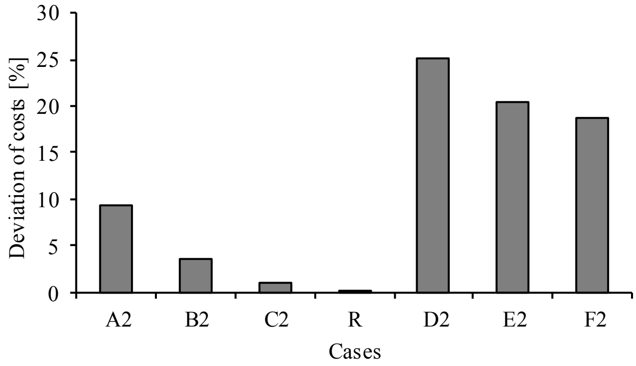

Figure 10. Deviation of energy cost from the minimum value

IV. CONCLUSIONS

The customer cost of energy is significantly sensitive on the change of the load and the number of consecutive overcast days. Our simulations show that the underestimation of number of overcast days makes the proposed control strategy less cost effective. Similarly, the control strategy performance is getting worse if the customer load is underestimated. Generally spoken, a deterministic approach is applicable to the systems where the input variables can be predicted with a solid certainty. Otherwise, if the inputs exhibit remarkable unpredictable deviations, more complex stochastic methods should be employed.

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