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Short term energy arbitrage in PV-battery grid-connected systems

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Abstract. In this work, we show the optimization of the daily arbitrage operation of a PV-battery power generating system. Genetic algorithms (GA) metaheuristic technique is used for the optimization. A new arbitrage method is applied. An integer variable which can take one of three values (-1, 0 or 1) for each hour of the day decides the operation of the battery (charge/inactive/discharge), considering as inputs the average hourly irradiance, temperature and electricity price forecast for the day-ahead, and the state of charge (SOC) at the first hour of the day-ahead. The optimal arbitrage operation obtains the maximum net incomes, that is, incomes of selling electricity minus cost of purchasing electricity and degradation cost of the battery. The method is applied to a PV-battery power generating system near Zaragoza (Spain) for a specific day, obtaining net incomes 7% higher than using a previously published optimization method.

Key words. Grid-connected PV-battery system, arbitrage, daily operation, control strategy, optimization, genetic algorithms.

1. Introduction

Adding storage to renewable power systems can help the electrical system to enhance its functionality. Adding storage (and, specifically, batteries) the renewable power system can performance energy arbitrage and also a range of support services, including black start capability, frequency regulation, reactive support, voltage control, and strategic participation in ancillary service markets [1]. A revision of the application and integration of grid-connected batteries was shown by Zhao et al. [2].
Energy arbitrage consists of the following:

- Storing the energy produced by the renewable generator (charging the battery) when the energy prices are low (usually when there is low national demand);
- Selling energy to the grid by discharging the battery when the prices are high (high national demand).

Depending on the battery CAPEX cost and its lifetime and on the electricity price differences between peaks and valleys, grid-connected PV-battery power generating systems (Fig. 1) can have better profitability than PV-only systems by means of energy arbitrage [3]. However, the arbitrage costs due to energy purchase from the grid and due to battery degradation (due to cycle and calendar) must be considered. In energy arbitrage applications, battery degradation has a strong impact in the system profitability [4,5], concluding that it is very important to accurately calculating the battery degradation [6].

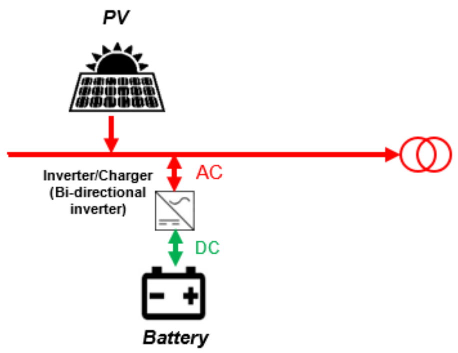

Fig.1. PV-battery power generating system.

Apart from arbitrage, batteries can also provide a range of support services [7]. Curtailment reduction or ramp rate control are other features which can be achieved using batteries in renewable power generating systems [2].
PV-battery power plants are economically viable in specific scenarios, such as improving flexibility and system performance [8].
In the last years, in systems with high penetration of PV (California, Australia, Spain in the last year), in many days the hourly electricity price turns into a "duck" shape [9], with lowest prices during noontime, when there is the peak PV generation. In these cases, depending on the electricity curve shape and on the battery CAPEX and degradation with cycles and time, the provision of energy arbitrage by batteries can improve the profitability of the PV generating unit.
In a previous work, we optimized the performance of the PV-battery system in the long term (25-years) considering arbitrge and also frequency containment reserve [7]. In that work, the optimisation of the arbitrage strategy was to find two optimal values: maximum electricity price to charge the battery and minimum electricity price to discharge the battery.
In this work, we consider the optimization of the energy management (arbitrage) of the PV-battery system in the short term (1-day ahead), trying to maximize the net

benefits (incomes from injecting electricity to the grid minus the degradation cost of the battery and the purchasing electricity cost), using a new arbitrage strategy.

2. New arbitrage strategy in the short term

The operation of the system during each hour of the day can be defined by an integer variable which can take three different values:
(0): Supply the PV generation to the grid. Battery is inactive (not used for charge neither for discharge).
(-1): Priority to charge the battery at the maximum specific C-rate with the PV generation and/or by purchasing energy from the grid.
(+1): Priority to inject to the grid the PV generation and the battery discharge a the maximum specific C-rate.
At the end of the day-1 (day before), the electricity hourly price for the day-ahead is known. Also, we have the forecast of the hourly average irradiance and temperature of the day-ahead, and we know the battery SOC (and we can estimate this value at the end of the day-1). The optimization of the integer variable for the 24 hours of the day-ahead would imply 3^{24} cases. Considering our model can evaluate around 1,000 cases per second, it would take 9 years to consider all the possible combinations. However, by means of GA metaheuristic technique, in less than 1 h we can obtain the optimal strategy or a solution near the optimal one.
The objective of the optimization is to maximize the net incomes of the day, f(x).

$$\text{maximize}\, f(x) \qquad (1)$$

Where f(x) are the incomes of the day due to selling electricity to the grid minus the costs.

$$f(x) = \left(\sum_{t=0}^{23} P_{sell}(t) \cdot Pr_E(t)\right) - \left(\sum_{t=0}^{23} P_{buy}(t) \cdot \left(Pr_E(t) + Pr_{Access}(t)\right) + \left(SOH(t=24) - SOH(t=0)\right) C_{Bat} + \left(SOC(t=0) - SOC(t=24)\right) C_{Penalty}\right) \qquad (2)$$

Where P_{sell}(t) (kWh) is the average power sold during hour t and Pr_{E}(t) (€/kWh) is the electricity price during hour t. The cost includes the degradation cost of the battery (using advanced ageing models: Nauman et al. models for cycle [10] and calendar [11] degradation of Li-ion LFP batteries) and the penalty cost assigned in the case the battery SOC at the end of the day is lower than at the beginning (using the average electricity price of the day). *SOH(t)* is the state of health (p.u.) of the battery while *SOC(t)* is the state of charge (kWh). C_{Bat} (€) is the battery acquisition cost and C_{Penalty} (€/kWh) is the penalty cost. Also, if electricity is purchased to the grid (at valley hours) (P_{buy}(t), kWh), the cost of this energy must be considered, ant it will include the energy cost plus the access charge cost (Pr_{Access}(t), €/kWh is the price of the access charge for the electricity bought during hour t).
The decision variables (genes of the genetic algorithm) to be optimized (Eq. 3) are the 24 integer values (one for each hour) which will define the operation of each hour (each value can be 0, -1 or +1, as shown above).

$$x = (x_0, x_2, \ldots x_{23}) \qquad (3)$$

3. Genetic algorithm

The genetic algorithm will optimize the system in less than 1 hour (to be applied the previous day at 23 h; the optimization will be obtained before 0 h of the day-ahead, then the optimal parameters will be automatically set to the control of the system of the day-ahead).
The parameters of the GA are [12]:

- Maximum number of generations: 15
- Population size: 200.000
- Crossover rate: 90%
- Mutation rate: 1%

With these parameters, evaluating 1,000 combinations per second (computer with Intel i5-6500 CPU, 3.2 GHz and 16 GB RAM), in less than 1 hour the GA performs the optimization.

4. Case study

A PV-battery power generating system located near Zaragoza (Spain) is considered for the optimization of the control strategy of a specific day-ahead (February 11th). PV rated DC power is 10 kW (with its own inverter of 9 kW, 90% efficiency at rated power), south oriented and 30º tilt angle, battery capacity is 24 kWh and inverter-charger is of 6 kW (battery duration 4 h). Interconnection allowed grid power is 10 kW. Hourly purchase/sell electicity price for the day-ahead is shown in Fig. 2, while access charge (for the electricity purchased to the grid) is a fixed value of 20 €/MWh. Irradiance forecast for the day-ahead is shown in Fig. 3.
Li-ion LFP battery has been considered. Maximum rate for charge/discharge considered is C/4 (rated capacity divided 4) and roundtrip efficiency 90%. The battery CAPEX is 300 €/kWh (C_{Bat} = 7,200 €) and its lifetime vs. depth of discharge (DOD) is shown in Fig. 4, while Fig. 5 shows the inverter-charger efficiency.
The cost assigned in the case the battery SOC at the end of the day is lower than at the beginning is C_{Penalty} = 0.1 €/kWh for the SOC difference.

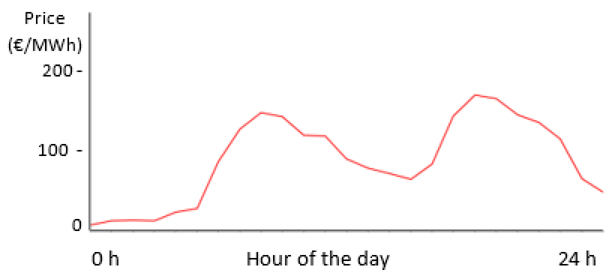

Fig. 2. Horuly sell electricity price.

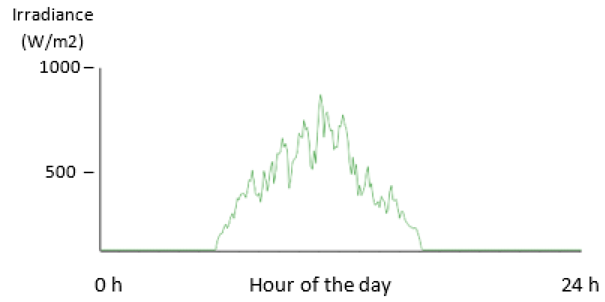

Fig. 3. Irradiance forecast.

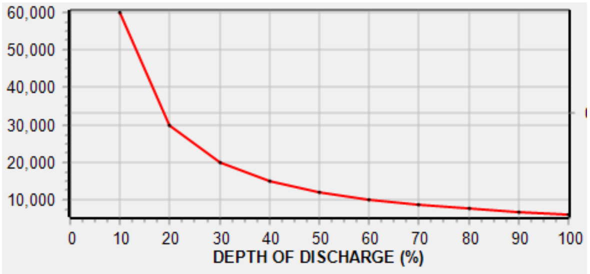

Fig. 4. Battery cycle life vs. DOD. iHOGA software [13]

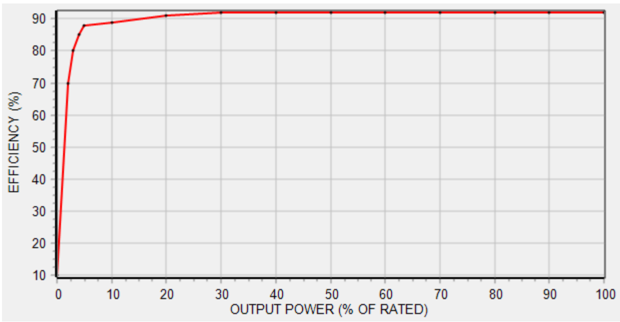

Fig. 5. Inverter-charger efficiency. iHOGA software [13]

5. Results

A. Optimisation with the new arbitrage strategy

The optimization of the new arbitrage strategy has obtained the results of the integers for all the day-ahead (24 h) shown in Table I.

Fig. 6 shows the simulation of February 11th with the optimal control strategy. Battery discharge is in blue, battery charge in light brown, PV in yellow, buy energy in turquoise (narrow line) and sell energy in purple (narrow line), all referred to left axis. SOC is in red, referred to right axis. We can see that battery is charged from 0 to 1 h and from 3 to 4 h from the grid, and from 15 to 17 h from the PV plus the rest of the power until C/4 (24kWh/4h = 6 kW) power is obtained (purchased) from the grid. Battery is discharged froom 9 to 11 h and from 19 to 21 h. Charge/discharge power is limited to C/4 (6 kW), which is also the rated power of the inverter/charger. Form 9 to 11 h, the battery discharge is added to the PV generation, and the total power is injected to the grid. We can see that, during this day, not all the battery capacity is used, as only 2 h charge are used in the morning (and then 2 h discharge), and the same in the afternoon – evening. In this day, a battery of 50% of capacity would be enough, however, in other days, the whole battery capacity is used (charging during 4 h and later discharging during 4 h).

In this day, with the optimal arbitrage, the total incomes due to selling electricity to the grid this day are 7.82, while electricity costs are 1.11 € and cost of battery degradation 1.01 €. Net incomes are 7.82 - 1.11 - 1.01 = 5.69 €.

Table I. – Optimal control strategy for February 11th.

Hour	Integer	Hour	Integer
0	-1	12	0
1	0	13	0
2	0	14	0
3	-1	15	-1
4	0	16	-1
5	0	17	0
6	0	18	0
7	0	19	1
8	0	20	1
9	1	21	0
10	1	22	0
11	0	23	0

B. Optimisation with two variables (previously published method)

We have also obtianed the optimal result with the method shown in the previous work (applied to the short term) [7] of two price setpoint variables. The optimal maximum electricity price to charge the battery was 20 €/MWh while the optimal minimum electricity price to discharge the battery was 160 €/MWh. The simulation of the optimal arbitrage is shown in Fig. 7, where we can see that the battery is charged with the grid in the morning, during 4 hours when electicity price is lower than 20 €/MWh, and battery is discharged from 19 to 21 h, when electricity price is higher than 160 €/MWh. At the end of the day, the battery SOC is higher than at the beginning, therefore a bonus of the average electicity price of the day is applied to the difference.

In this case, all the battery capacity is used the day considered.

With these results, the net incomes are 5.31 €, lower than in the optimal case of the new arbitrage control.

7. Conclusions

In this paper, we show the optimization of a new control strategy for the energy arbitrage in a PV-battery grid-connected system. Using genetic algorithms metaheuristic technique, the optimisation of the operation of each hour of the day-ahead is performed in a reasonable computation time (less than 1 h). The method is applied to a system with 10 kW DC rated power PV, 24 kWh battery and 6 kW inverter-charger, obtaining for the day considered (February 11th) an optimal arbitrage management with net incomes of 5.69 €. This value is higher in 7% than the net incomes obtained with the

optimal system found with the previous published method, where the optimisation was to find the optimal values of the maximum electricity price to charge the battery and of the minimum electricity price to discharge the battery.
This work demonstrates that the optimization of the hourly operation in PV-battery grid-connected systems can lead to better economic results than just considering price setpoints to charge or discharge the battery.
The potential real-world applications are grid-connected PV-battery systems and also PV power generating systems which want to improve their profitabilty adding battery storage.

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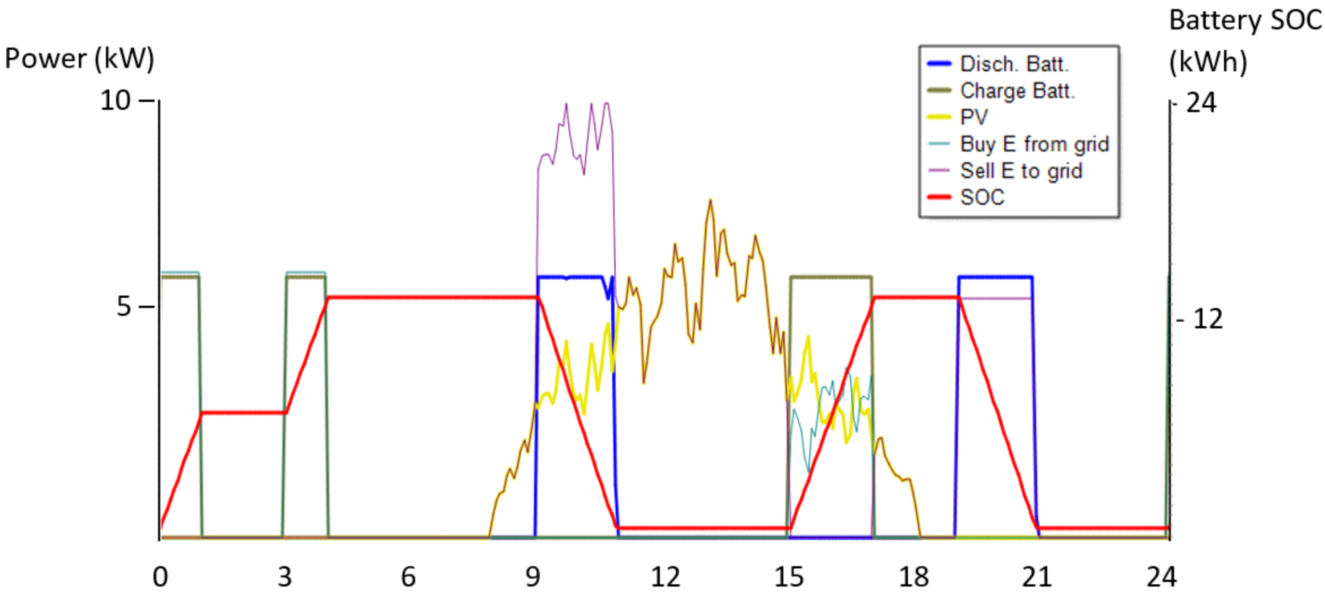

Fig. 6. Simulation of the new optimal arbitrage estrategy.

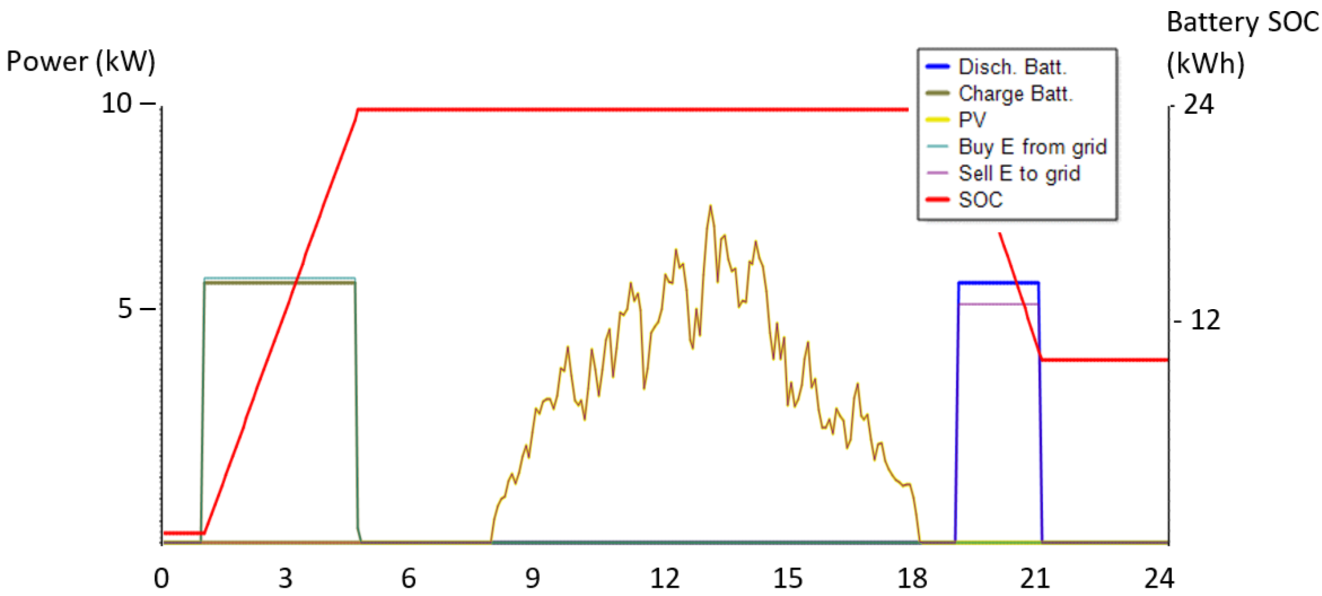

Fig. 7. Simulation of the optimal arbitrage estrategy obtained with two variables method [7].