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Short term energy management in stand-alone PV-battery-diesel systems

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Abstract. In this work, the short term (daily) operation of an off-grid hybrid PV-diesel-battery system is optimized by genetic algorithms. An integer variable (0, 1 or 2) for each hour of the day decides the way the battery works. With the forecast of the hourly irradiation, temperature and load consumption for the next day, and estimating the state of charge of the battery (SOC) at the first hour of the day, we perform the optimization of the integer variables for the 24 hours of next day. To avoid inadmissible computation time, the optimization is performed by using genetic algorithms (GA) obtaining in roughly 1 hour the optimal solution or a solution near the optimal one. The optimization tries to obtain the minimal total cost of the daily operation while supplying the whole load. We compare the results of the optimization with the typical control strategies (load following, cycle charging and set point strategies), obtaining better results with the new optimized strategy. The reduction in the operational cost obtained varies from 2.5% to 62%, compared to the typical control strategies (load following or cycle charging).

Key words. PV-diesel-battery systems, off-grid, daily operation, control strategy, optimization, genetic algorithms.

1. Introduction

In places where winter irradiation is much lower than summer irradiation, off-grid PV-Diesel-battery systems can be cost-effective compared to PV-battery systems [1]. Fig. 1 shows the system.

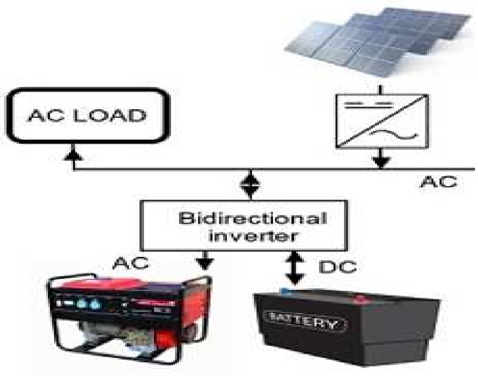

Fig. 1. Off-grid PV-Diesel-battery system.

The control of a the off-grid hybrid system is done by means of the bi-directional inverter [2], the battery bank controller and the control system. The battery management system (BMS, for Li-ion batteries) of the charge controller (for lead-acid batteries) prevents over-charge and over-discharge in order to maximise the battery lifetime. The inverter-charger controls the start/stop of the diesel generator and its management (just supplying the net load or supplying energy also for charging the battery). Typical control strategies [3] are the "load following" strategy and the "cycle charging" strategy.
Load following strategy (LF): when the energy from renewable sources is not sufficient to satisfy the demand, the batteries are responsible for supplying this deficit. In the case that the batteries are not able to supply all the energy demanded, it is the generator that must provide it.

Cycle charging strategy (CC): Differs from the previous strategy in that in the event that the generator is required to operate, it will operate at its nominal power to satisfy the demand and, in addition, to charge the batteries only during that hour. There is a variant of this cycle charging strategy, called the set point strategy (SP), in which the diesel generator continues to operate at its nominal power until the battery bank reaches a specific value of state of charge (usually 95-100%).

Some inverter-chargers fully charge the battery bank periodically, such as every 14 days or after eight nominal charge throughputs [4].

Many previous papers have studied the control of off-grid PV-Diesel-battery systems. Bajpai and Dash [5], Mohammed et al. [6] and also Nema et al. [7] presented reviews of the most relevant works of the state-of-the-art of hybrid PV-wind systems. Mohammed et al. [8] reviewed the state-of-the-art of hybrid PV-diesel-battery system control strategies. Typical LF and CC strategies were used in many prior works. Dufo-López et al. [9] demonstrated the optimisation of design and control strategies (for a whole year) for PV-diesel-battery systems using the LF strategy, the CC strategy and a combined strategy. Later, Dufo-López et al. presented a method for optimising the daily operation (minimising the total operating cost) of a hybrid photovoltaic-wind-diesel-battery system using model predictive control with actual weather forecasts of hourly values of wind speed, irradiation, temperature and load [10].

2. New control strategy

In this paper, we define a new control strategy which optimizes the operation of the day. The operation of each hour of the day is determined by a integer variable which can take 3 values:

(0): Battery unavailable for discharge, only available for charge from the net renewable generation. If there is net load, it is supplied by the diesel generator, which runs at the required power to supply the load.
(1): Same as (0) with the difference that if there is net load, it is supplied by the diesel generator, which runs at full load, supplying the load and charging the battery.
(2): Batteries available to be charged from the net renewable generation. Batteries available to supply the net load.

With the forecast of the hourly irradiation, temperature and load consumption for the next day, and estimating the battery SOC at the beginning of the day, the optimization of the integer variable for the 24 hours of next day would imply 3^{24} cases. Evaluating all the cases (considering around 100 cases per second) would take 90 years for the optimization, which is obviously inadmissible. By means of GA, in 1 h we can obtain the optimal strategy or a solution near the optimal one. The optimization tries to obtain the minimal cost of the daily operation while supplying the whole load. The cost includes the diesel fuel, the operation and maintenance of the diesel generator, the degradation cost of the diesel generator, the degradation cost of the battery and the cost assigned in the case the battery SOC at the end of the day is lower than at the beginning.

3. Case study

An off-grid hybrid PV-diesel-battery system located near Zaragoza is considered for the optimization of the control strategy of a specific day, in this case December the 7th. We will compare the operational cost considering the LF, CC and SP strategies with the optimization of the new control strategy. We will repeat for December the 10th.
The system is composed of a PV generator of 60 kW (DC) with its PV inverter, a diesel generator of 10 kVA, an inverter-charger of 10 kVA and a battery bank of 240 kWh. The AC consumption load of the day is 81.2 kWh with the profile shown in Fig. 2.

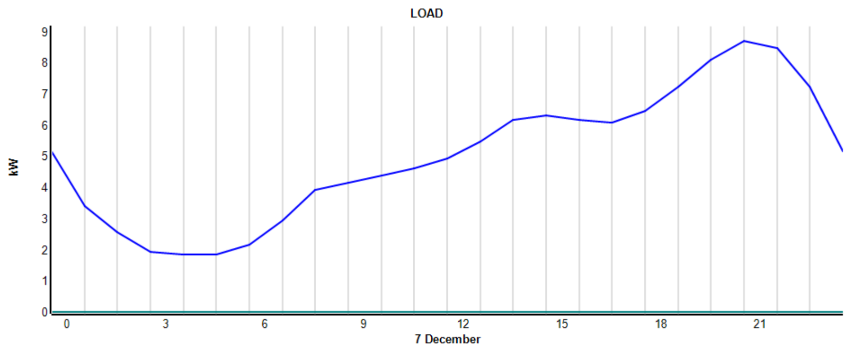

Fig. 2. Load consumption of the day December 7th.

The operational costs will be calculated considering the following data:

3.1. Diesel generator
The operation and maintenance (O&M) cost of the diesel generator is 0.2 €/h. Also, a lifespan of 20,000 h is considered. During each hour when the diesel is running, the O&M cost will be accounted, and also the proportional cost of degradation of the diesel generator (each hour will have a cost of 1/20,000 multiplied by the acquisition cost, which is 8,000 €).

The minimum output power is 3 kW (not allowed to run at lower power).
The fuel consumption during hour t is obtained by the consumption curve, with parameters A = 0.246 l/kWh and B=0.08145 l/h as shown in Eq. 1.

$$Cons_{\text{fuel}}(t) = B \cdot P_{\text{GEN, rated}} + A \cdot P_{\text{GEN}}(t) \qquad (1)$$

Where $P_{GEN,rated}$ and $P_{GEN}(t)$ are, respectively, the nominal power and the output power during time t.
Each start of the diesel generator is accounted as 5 minutes extra of lifespan.
Also, a extra factor (f_{extra_GEN}) is considered for the running time if its output power is out of the optimal range [10] (Fig. 3).

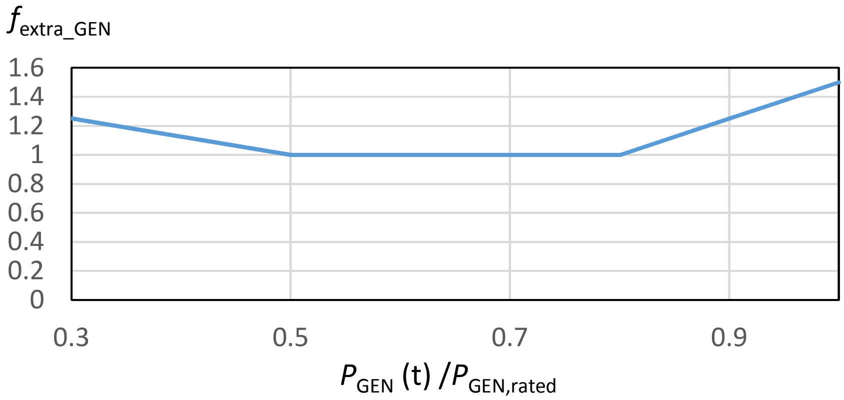

Fig. 3. Extra factor for the running time of the diesel generator [10].

3.2. Batteries

The battery considered has an acquisition cost of 37,500 € and a expected lifespan of 6,000 full equivalent cycles.
The battery degradation cost will be calculated considering the total energy cycled during the day, which will be converted to equivalent cycles and then divided by the 6,000 cycles of lifespan and multiplied by the acquisition cost.
If at the end of the day the SOC is lower than at the beginning, a penalty must be applied. The difference between the SOC at the beginning of the day (30% at the beginning of December 7^{th}) and the SOC at the end of the day will have a penalty cost of 0.1 €/kWh.

3.3. Genetic algorithm

The genetic algorithm will optimize the system in just 1 hour (to be applied the previous day at 23 h; the optimization will be obtained before 0h of the next day, then the optimal parameters will be automatically set to the inverter-charger to control the system of the next day).
The parameters of the GA are [11]:

- 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 will perform the optimization.

4. Results

The optimization of the new control strategy has obtained the results of the integers for the 24 h shown in Table I.
Fig. 4 shows the simulation of December 7^{th} with the optimal control strategy. Battery discharge is in blue, battery charge in light brown, PV in yellow and diesel generator in black, all referred to left axis. SOC is in red while SOC limits are in pink, all referred to right axis. We can see that, from 0 a.m. to 8 a.m. and from batteries must supply the load (integer 2), and the same from 17 to 24 h, except from 21 to 22, where the diesel must run at full load, supplying the load and charging the battery (integer 1). From 9 a.m. to 16, there is surplus renewable power, therefore the batteries are charged (integer 1).
The total operation cost of this day is 8.98 € with the optimized new strategy.

Table I. – Optimal control strategy for December 7th.

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

The total operation cost of this day using LF strategy is 10.32 €, same as using CC or SP strategies (as diesel is not used this day using typical strategies), simulation in Fig. 5. In Fig. 5 we can see that LF, CC or SP strategies do the same for this day, and diesel generator is off during all the day. However, at the end of the day the battery SOC is lower than with the new strategy, and the SOC difference with the beginning of the day implies a cost (0.1 €/kWh), therefore the total cost for this day is lower with the new optimized strategy.

Optimal new strategy obtained a cost of 13% lower than typical strategies for the day of December 7th.
We have optimized the new control strategy for another day, December the 10th, starting with a SOC of 10%.
The optimal new strategy gives a total cost of 20.1 € (Fig. 6) while for LF the cost is 27.6 € (Fig. 7), for CC 20.6 € (Fig. 8) and for SP 53.6 € (Fig. 9).

Optimal new strategy obtained a cost of 27% lower than LF, 2.5% lower than CC and 62% lower than SP strategy for the day of December 10th.
Fig. 6 shows the optimal new strategy for December the 10th. We can see in the hour of 1-2 a.m. and from 3 to 8 a.m. the optimal integer is 2: battery tries to supply the load, and, when it is at minimum SOC, diesel generator runs at maximum load, charging the batteries. The hours 0-1 and 2-3 a.m. the optimal integer is 1, diesel runs at full load supplying the load and charging the battery. The rest of the hours the optimal integer is 2.

We can see that, in these hours analysed, integer 0 is not chosen by the optimal new control strategy, as it is better to use the diesel at full power during few hours (to supply the load and charge the batteries) than using the diesel more hours at minimum power.
Fig. 7 shows the simulation of December the 10th for LF strategy. We see that the diesel genset runs at minimum power to supply the load (and charge the battery if minimum power is higher than the load). Fig. 8 shows the simulation for CC strategy, where the diesel generator runs at full power during the time steps the battery cannot supply the load. Fig. 9 shows the SP strategy, where the diesel runs at full load until the SOC setpoint (100%) is reached (or renewable power is enough to supply the load and charge the battery).

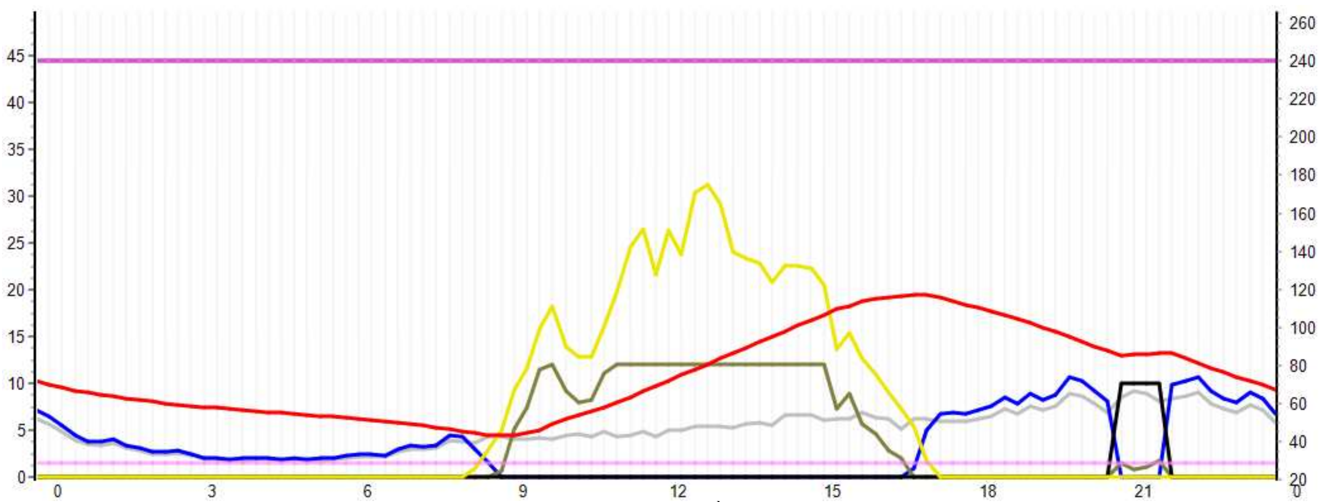

Fig. 4. Simulation of December 7th, optimal new strategy.

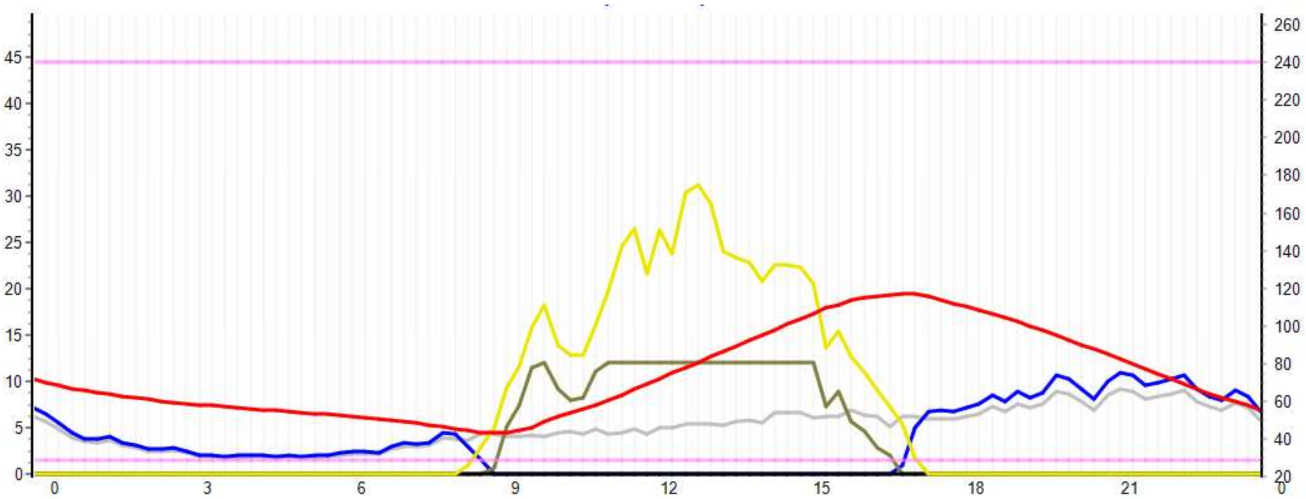

Fig. 5. Simulation of December 7th, LF,CC or SP strategies.

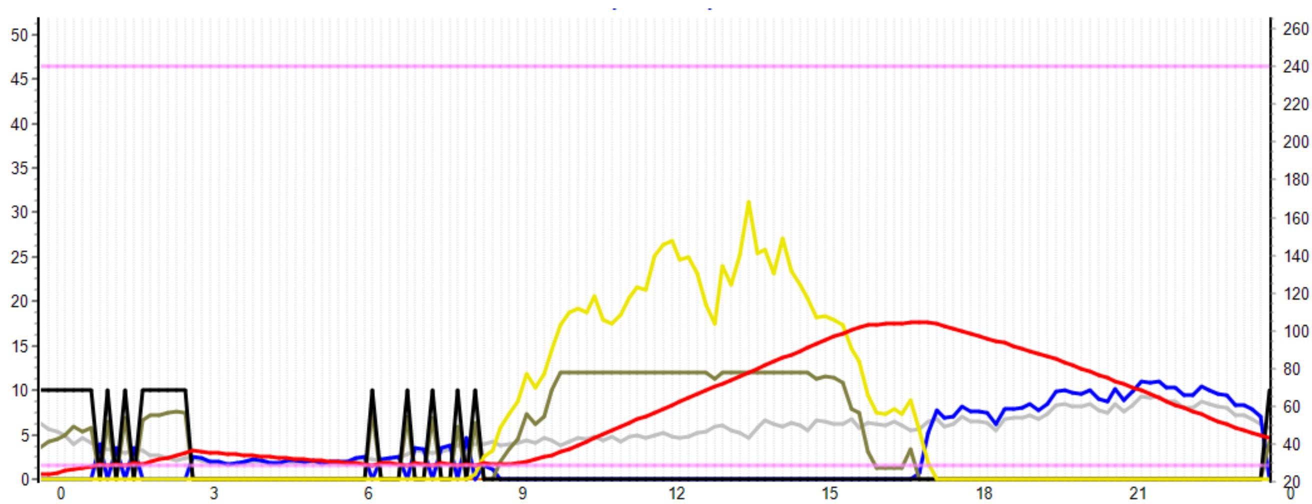

Fig. 6. Simulation of December 10th, optimal new strategy.

Fig. 7. Simulation of December 10th, LF strategy.

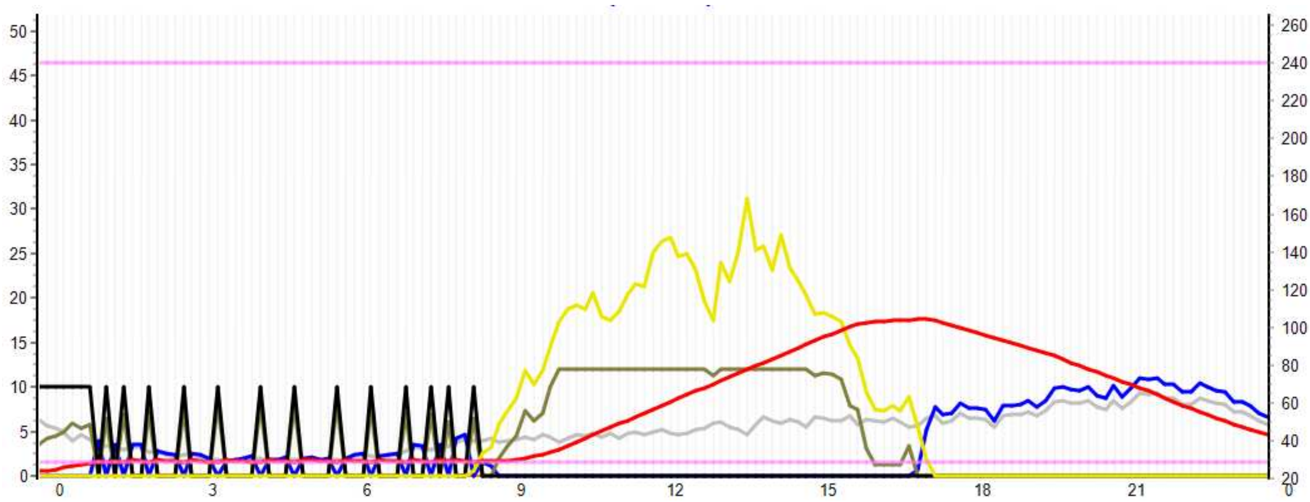

Fig. 8. Simulation of December 10th, CC strategy.

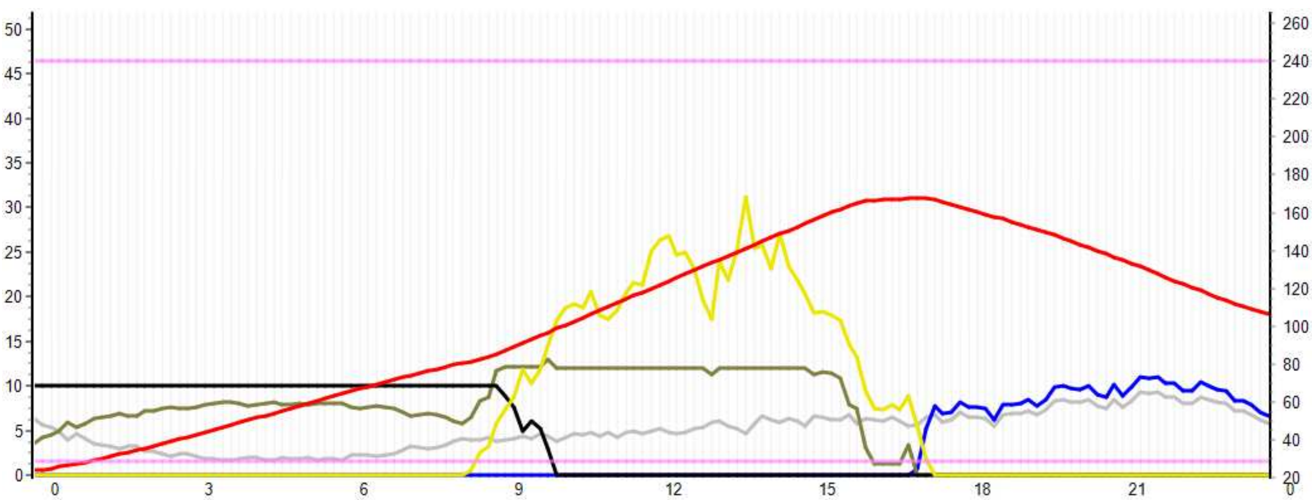

Fig. 9. Simulation of December 10th, SP strategy.

5. Conclusion

A new control strategy for the short term (1 day) energy management of off-grid PV-Diesel-battery systems have been developed. The control strategy is optimized by genetic algorithms, obtaining in 1 h the optimal or a near optimal solution. As shown in an example of application, the optimization of this new control strategy obtains better results (lower total operational cost) than the typical load following, cycle charging or set point strategies. The reduction in operational cost obtained varies from 2.5% to 62% compared to typical load following and cycle charging control strategies.

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