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# Optimal management of microgrid with renewable generation

J.A. Domínguez-Navarro[1], J.L. Bernal-Agustín[1], R. Dufo-Lopéz[1], J.S. Artal-Sevil[1], A.A. Bayod-Rújula[1], J.M. Yusta[1], and A. Coronado-Mendoza[2]

[1] Department of Electrical Engineering
E.I.N.A., University of Zaragoza
Campus Río Ebro – María de Luna, 3, 50018 Zaragoza (Spain)
Phone/Fax number:+0034 976 762401, e-mail: jadona@unizar.es

[2] Engineering Department,
Tonalá Campus, University of Guadalajara,
Nuevo Periférico 555, Ejido San José Tatepozco, 48525 Tonalá Jalisco, (Mexico)

**Abstract.** An energy management system to minimize the operation cost of a microgrid is presented in this work. The microgrid is composed of the technologies more used as renewable energies and storage systems, as well as active consumers which demand depends on price.
The proposed model is based on linear programming with the operating cost as the objective function and the operating limits as constraints. The model has two phases. The first phase does the optimal dispatch of generating units in function of the forecasting demand and the offers made by generators. The second phase minimizes the differences between the planning values obtained in the first phase and the real data, because there are differences as consequence of the uncertainties of renewable energies and the consumers' behaviour.

## Key words
Energy management system, Storage systems, Optimization, Renewable energy.

## 1. Introduction
A microgrid can significantly improve the efficiency of the balance between generation and demand. It allows reducing the emissions and increasing the quality of the energy [1].
Due to the demand variability and the unmanageable nature of the renewable sources, it needs implementing an energy management system into the microgrid. Classical controlled generators as diesel generators and new technologies as storage systems and controlled demands help to maintain the power balance.
Energy management systems aims to maximise the profit of the microgrid operation (or minimise the cost) [2-7], minimise the emissions [8], or using several objectives [9]. These systems use several optimization algorithms as linear programming or heuristic methods [10-12] as particle swarm or evolutionary algorithms.
The aim of the proposed work is doing the optimal manage of a microgrid with renewable energies and storage systems. In section 2, the mathematical model is described. In section 3, results obtained are presented and commented. Finally, we write the conclusions in the section 4.

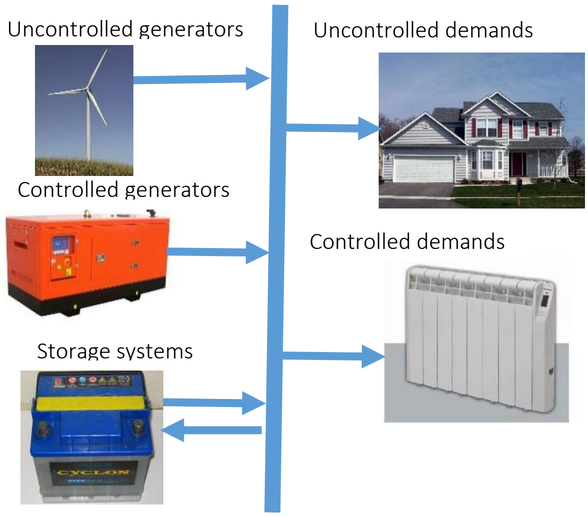


Fig. 1. Proposed migrogrid.

## 2. Mathematical model
The microgrid proposed, Fig. 1, is composed of uncontrolled generators (as wind generators and photovoltaic systems), controlled generators (as a diesel generator), a storage system (as a battery), an uncontrolled demand that has always to be satisfied and a controlled demand (as thermal loads that can move their consumption temporally).
The problem is the optimization of the dispatch of generators in the microgrid, complying the operating constraints of each actor (generators, storage systems and demands), and the economic constraints imposed by the sell and buy prices. The losses are neglected and the power balance is made with active power to simplify the problem.

The mathematical model has two phases. The first phase is made before 0:00 a.m. It optimises the operating cost of the microgrid considering as data: the selling prices and quantities offered by generators and batteries (in discharge mode), and the buying prices and quantities offered by controlled demands and batteries (in charge mode) for the next 24 hours. The quantities offered by uncontrolled generators will be provisional due to inherent uncertainty of their renewable sources. The second phase is executed every hour, and it sets the differences between the provisional quantities and the real data of uncontrolled generators and demands for the next hour. This adjustment is done minimizing the cost of penalizations for positive and negative differences into the system. The prices in this phase are bigger.

Now, these optimization models are expressed mathematically.

Phase 1: Unit commitment.

Minimize:

$$\sum_{h=1}^{24}\left\{\left(\sum_{k\in\Omega} Ppk(h)\times Ck(h)\right) + Ppsd(h)\times Csd(h) - Ppsc(h)\times Csc(h) + Ppcdns(h)\times Ccdns(h) + Ppncdns(h)\times Cpncdns(h)\right\}\times dT \tag{1}$$

Where:

h time period [hours].

dT duration of time period h.

Ω set of considered generators.

Ppk(h) provisional power supplied by generator k at hour h.

Ck(h) cost of the supplied power by generator k at hour h.

Ppsd(h) provisional power for the battery in discharge mode at hour h.

Csd(h) cost of discharge for the battery at hour h.

Ppsc(h) provisional power for the battery in charge mode at hour h.

Csc(h) cost of charge for the battery at hour h.

Ppcdns(h) provisional power of the controlled demand not supplied at hour h.

Ccdns(h) incentive paid to consumers with controlled demand because this demand is not supplied at hour h.

Ppncdns(h) provisional power of the uncontrolled demand not supplied at hour h.

Cncdns(h) penalization paid to consumers with uncontrolled demand because this demand is not supplied at hour h.

Constraints:

The operation of the microgrid is subject to next constraints: energy balance in every hour (2), operating limits of generators (3), limit of the non supplied power for uncontrolled demand (4), limit of the non supplied power for controlled demand (5), max power of charge and discharge in battery (6, 7), energy balance in battery (8) and operating limits of battery (9).

$$\left(\sum_{k\in\Omega} Ppk(h) + Ppsd(h)\right)\times dT = \big(Ppncd(h) - Ppncdns(h) + Ppcd(h) - Ppcdns(h) + Ppsc(h)\big)\times dT \tag{2}$$

$$Ppmink(h) \le Ppk(h) \le Ppmaxk(h) \tag{3}$$

$$Ppncdns(h) \le Ppncd(h) \tag{4}$$

$$Ppcdns(h) \le Ppcd(h) \tag{5}$$

$$Ppsd(h) \le Psdmax \tag{6}$$

$$Ppsc(h) \le Pscmax \tag{7}$$

$$Eps(h) = Eps(h-1) + (Ppsc(h) - Ppsd(h))\times dT \tag{8}$$

$$Esmin \le Eps(h) \le Esmax \tag{9}$$

Where;

Ppncd(h) provisional power for uncontrolled demand at hour h.

Ppcd(h) provisional power for controlled demand at hour h.

Ppmink(h), Ppmaxk(h) provisional limits for the min and max generated power in the generator k at hour h.

Psdmax, Pscmax max power limits of discharge and charge in the battery.

Esmin, Esmax min and max energy limits for the battery.

Eps(h) provisional energy in the battery at hour h.

Phase 2: Differences management.

The dispatch made in phase 1 is the baseline for the adjustments done in this phase. The objective is to punish the variations respect the baseline and to encourage the flexibility of those generators and demands that help to do the energy balance of the system.

Minimize,

$$\sum_{h=1}^{24}\left\{\left(\sum_{k\in\Omega} abs(difPk(h))\times difCk(h)\right) + abs(difPsd(h))\times difCsd(h) + abs(difPsc(h))\times difCsc(h) + abs(difPcdns(h))\times difCcdns(h) + abs(difPncdns(h))\times difCncdns(h)\right\}\times dT \tag{10}$$

Where,

difPk(h) difference between provisional and real power supplied by generator k at hour h.

difCk(h) cost of difference of power supplied by generator k at hour h.

difPsd(h) difference between provisional and real power discharged by battery at hour h.

difCsd(h) cost of difference of power discharged by battery at hour h.

difPsc(h) difference between provisional and real power charged by battery at hour h.
difCsc(h) cost of difference of power charged by battery at hour h.
difPcdns(h) difference between provisional and real power non supplied in controlled demand at hour h.
difCcdns(h) cost of difference between the controlled demand provisional and real that non supplied at hour h.
difPncdns(h) difference between provisional and real power non supplied in uncontrolled demand at hour h.
difCncdns(h) cost of difference between the uncontrolled demand provisional and real that non supplied at hour h.

Constraints:

$$\left(\sum_{k\in\Omega} difPk(h) + difPsd(h)\right) \times dT = (difPncd(h) - difPncdns(h) + difPpcd(h) - difPcdns(h) + difPsc(h)) \times dT \quad (11)$$

$$Ppk(h) + difPk(h) = Pk(h) \quad (12)$$
$$Prmin(h) \leq Pk(h) \leq Prmaxk(h) \quad (13)$$

$$Ppncdns(h) + difPncdns(h) = Pncdns(h) \quad (14)$$
$$Pncdns(h) \leq Prncd(h) \quad (15)$$
$$Ppcdns(h) + difPcdns(h) = Pcdns(h) \quad (16)$$
$$Pcdns(h) \leq Prcd(h) \quad (17)$$

$$Ppsd(h) + difPsd(h) = Psd(h) \quad (18)$$
$$Psd(h) \leq Psdmax \quad (19)$$
$$Ppsc(h) + difPsc(h) = Psc(h) \quad (20)$$
$$Psc(h) \leq Pscmax \quad (21)$$
$$Ers(h) = Ers(h-1) + (Psc(h) - Psd(h)) \times dT \quad (22)$$
$$Esmin \leq Ers(h) \leq Esmax \quad (23)$$

Where,
difPncd(h) difference between the provisional and real uncontrolled demand at hour h.
difPcd(h) difference between the provisional and real controlled demand at hour h.
Prmink(h), Prmaxk(h) real limits for the min and max generated power in the generator k at hour h.
Ers(h) real energy in the battery at hour h.

## 3. Results

**Description of the case**

The used microgrid [13] is composed by two uncontrolled renewable generators (one wind and other photovoltaic), a controlled generator (a diesel), a storage system (a battery), and two demands (one controlled and other uncontrolled). Table I shows the specifications of each generator of the proposed microgrid and Table II the prices offered by microgrid actors. For simplify, these prices have been considered the same in all hours and the cost of differences are double.

Fig. 2-4 shows the forecasting power for uncontrolled demand, and for wind and photovoltaic generators respectively.

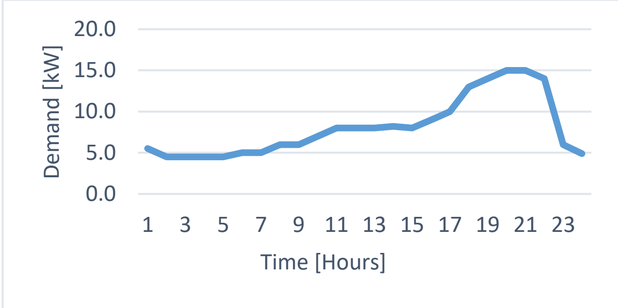

Fig. 2. Forecasting of the provisional uncontrolled demand.

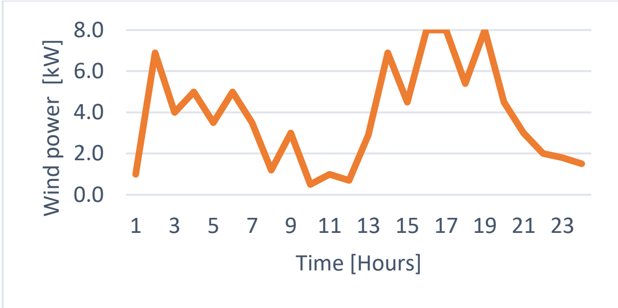

Fig. 3. Forecasting of provisional wind power.

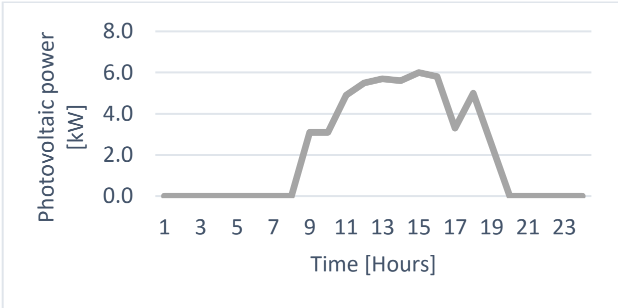

Fig. 4. Forecasting of provisional photovoltaic power.

Table I: Specifications of the proposed microgrid [13].

| **Parameter** | **Simbol** | **Value** |
|---|---|---|
| *Storage system (battery)* | | |
| Max power in discharge mode (kW) | Psdmax | 3.84 |
| Max power in charge mode (kW) | Pscmax | 0.816 |
| Max stored energy (kWh) | Esmax | 1.6 |
| Min stored energy (kWh) | Eesmin | 0.403 |
| Initial stored energy (kW) | Esinit | 1 |
| *Photovoltaic (pv)* | | |
| Max photovoltaic power (kW) | Ppvmax | 6 |
| Min photovoltaic power (kW) | Ppvmin | 0 |
| *Wind power (wt)* | | |
| Max wind power (kW) | Pwtmax | 8 |
| Min wind power (kW) | Pwtmin | 0.45 |
| *Microturbine (mt)* | | |
| Max microturbine power (kW) | Pmtmax | 12 |
| Min microturbine power (kW) | Pmtmin | 3.6 |
| *Controlled demand (cd)* | | |
| Max power (kW) | Pcdmax | 6 |

Table II: Prices (€) offered by actors in microgrid [13].

| Cpv | Cwt | Csd | Csc | Cmt | Cncdns | Ccdns |
|---|---|---|---|---|---|---|
| 0.1 | 0.083 | 0.145 | 0.125 | 0.15 | 1.5 | 0.105 |

**Results of Phase 1.**

The optimization of the cost objective function in the first phase give the power that must generate each generator according to the prices offered and its operating limits, Fig. 5, as well as the demand satisfied with the available generation, Fig. 6.

The use of the microturbine is constant, so it is the generator in charge of the system synchronisation. However, it is supplying the min allowed power and is complemented the renewable energies during the period from 20h to 24h. The uncontrolled generators of renewable energy with offered prices cheaper supply the rest of the energy.

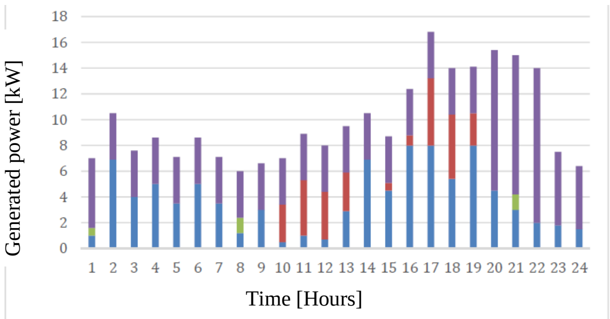


Fig. 5. Provisional power supplied by each generator. (dark blue-Pwt, red-Ppv, green-Psd, violet-Pmt, blue-Ppucdns)

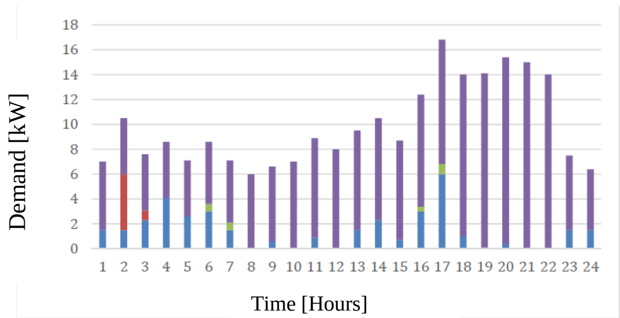


Fig. 6. Provisional power consumed by each demand. (dark blue-Ppcd, red-Ppcd, green-Psc, violet-Ppucd)

First, it is supplied the power required by the uncontrolled demand, so the price of not supplying this energy is the highest. Then, the rest of the available power is used to meet the controlled demand, Fig. 7, and to charge the battery, Fig. 8. The priority order is determined by the offered prices of each actor.

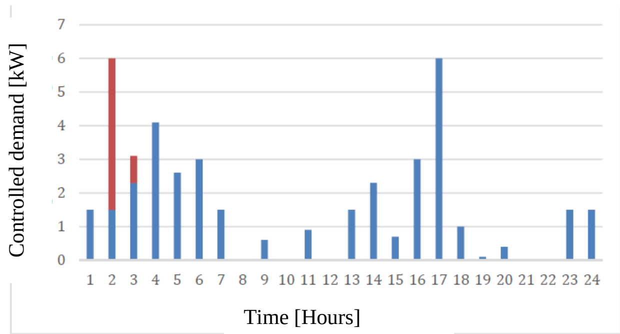


Fig. 7. Provisional controlled demands satisfied. (blue and red-Ppcd)

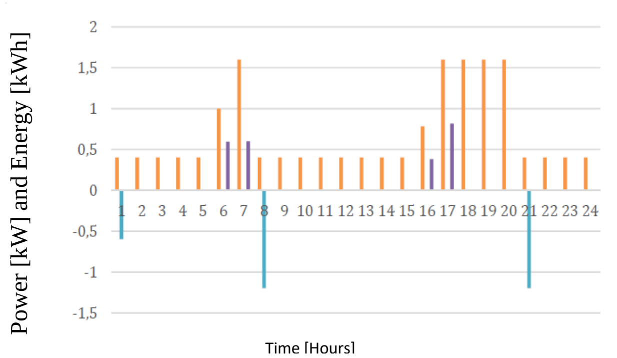


Fig. 8. Stored energy and flows of charge and discharge in each hour. (yellow-Es, blue-Psd, violet-Psc)

Besides the charging and discharging process of the battery, Fig. 8 shows the stored energy in it. As can be seen, the battery charges when there is an energy excess and it discharges when there is a generation deficit in the system. The state of charge of the battery is maintained above 20%, to extend the life of the battery.

**Results of Phase 2.**

The result of phase 1 is considered the baseline for the next 24 hours. Due to the uncertainty of the demand and generation, there are differences that must be adjusted throughout the day.

In Fig. 9-11, we can observe the differences in the uncontrolled demand and in the wind and photovoltaic generators, respectively.

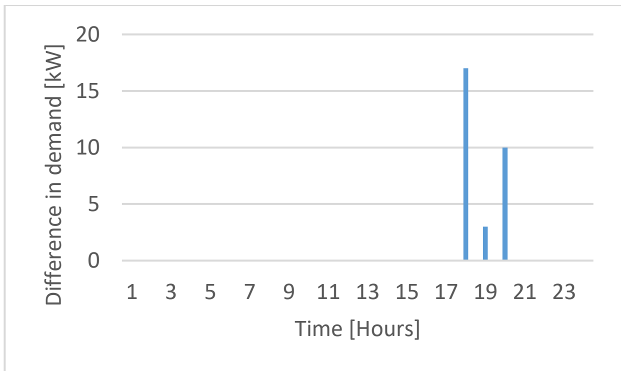


Fig. 9. Difference in uncontrolled demand.

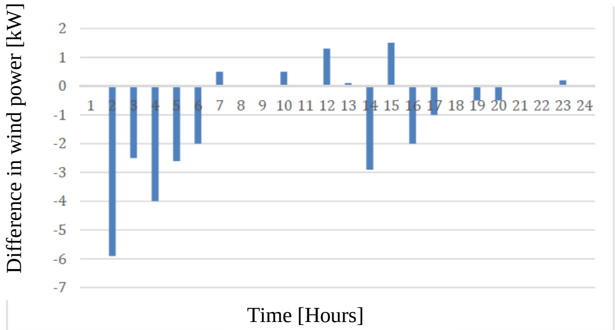

Fig. 10. Difference in wind power.

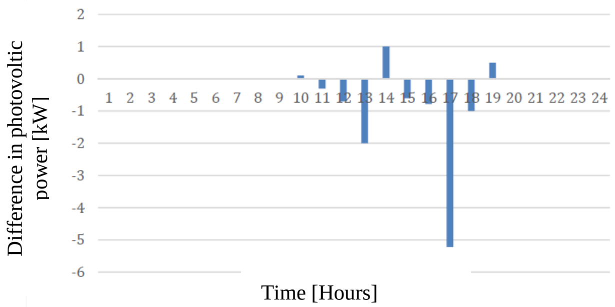

Fig. 11. Difference in photovoltaic power.

Because of these differences, increased demand and decreases in wind and photovoltaic generation, the microturbine has had to increase its contribution to the system, Fig.12.

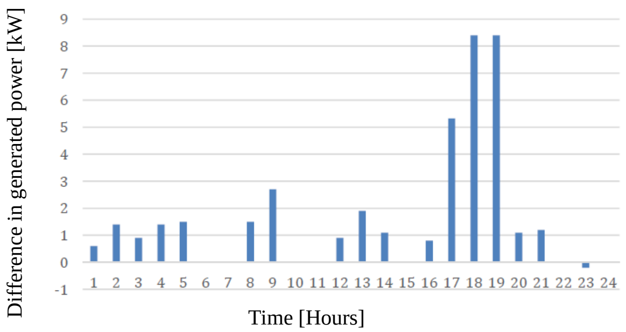

Fig. 12. Difference in power generated by microturbine.

The supply to the controlled demand has been reduced, Fig. 13, and also the charging and discharging of the battery, Fig. 14-15.

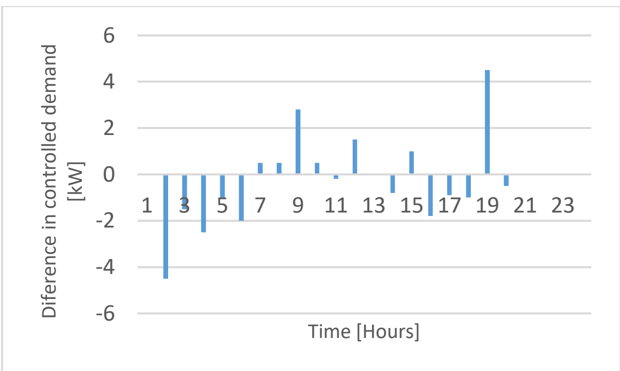

Fig. 13. Difference in controlled demand.

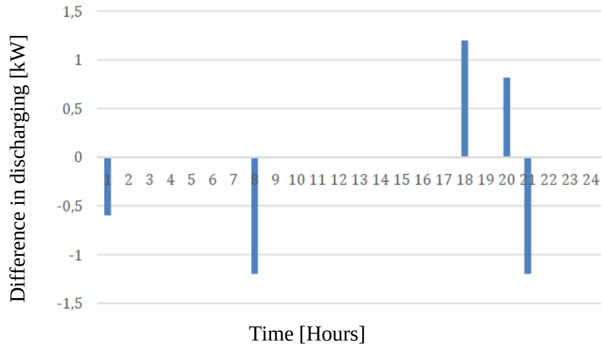

Fig. 14. Difference in discharging mode.

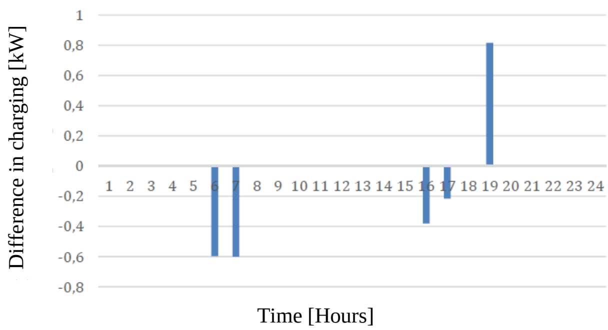

Fig. 15. Difference in charging mode.

## 4. Conclusion

The presented algorithm based on linear programming allows managing optimally a microgrid with generators and demands both controllable and uncontrollable. The results obtained confirm that microgrids with a high penetration of uncontrollable energies need storage systems and controllable demands that allow the balance between generation and demand.

The optimization model developed for the management of a microgrid aims to combine a relative simplicity in the modeling with a great versatility in the possibilities of analysis that the model allows.

The penalization of deviations and the encouragement of flexibility should help the microgrid actors themselves to adapt their behavior towards positions that facilitate the management of the microgrid.

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