Modified Droop Control for the Optimal Management of the Battery Systems in Isolated Microgrids

Luisa Frosio, Gabriele Marchegiani
EPS Elvi Energy - Electro Power System Group
Milano, Italy
luisa.frosio@eps-mail.com, gabriele.marchegiani@eps-mail.com

Alberto Bolzoni, Roberto Perini
Dip.to di Energia-Politecnico di Milano
Milano, Italy
alberto.bolzoni@polimi.it, roberto.perini@polimi.it

Abstract— **Microgrids are often made up with Hybrid Power Plants (HPPs), which include storage batteries. To enhance system efficiency, it is important to manage the batteries so as to avoid that one gets charged at other batteries' expense. To reduce costs and increase robustness, a Microgrid Controller that communicates with all the HPPs can be avoided and the droop control is often adopted for the HPPs' interface inverters. This paper proposes a method to change the droop coefficients so as to get the described target with no communication available between the HPPs. Theoretical analysis is validated through a simulation carried out on a study case.**

Keywords— Microgrids, hybrid power plant, battery management, droop control.

I. INTRODUCTION

In grid-connected or isolated microgrids, a particular importance is given to Hybrid Power Plants (HPP), which contain a storage system, or more renewable sources, or more thermal generators [1]. There are two typical configurations of the HPPs, that differ on the typology of the common parallel bus for the parallel connection of the storage systems and the generators: the AC-bus and the DC-bus configuration. The latter is used for small systems, where the sizing of the interface inverter is not prohibitive. Different control logics for the microgrids stability and internal power flows management are proposed in literature, taking into account different operation modes for the HPPs' DC/AC inverters [2], [3], [4]. This paper will analyze a HPP in the DC-bus configuration connected to a microgrid with a decentralized control, or with a hierarchical control where the optimization of the battery management is demanded to the single HPP and not to the microgrid controller, to enhance the reliability of the system and reduce the computational load of the microgrid controller. The results shown here can be extended to the control of DC/AC inverters dedicated to the batteries of HPPs in AC-bus configuration. The paper will focus on the operating losses of a battery; then it will be developed a control technique for droop controlled inverters operating in parallel on a microgrid, that allows to reduce the total energy lost in the batteries over a reference period of time (one year) without relaying in supervision of a microgrid controller. The droop control technique leaves some degrees of freedom in the control system structures, and it allows to introduce some optimization objectives in the microgrid management. It is possible to exploit this degree of freedom varying the active and reactive droop coefficients m and n of the inverters connected to the microgrid. In this paper, an optimizing algorithm that is based on local measurements inside each HPP and acts only on the active droop coefficients m will be defined, in order to reduce the losses in the storage systems of the whole microgrid.

The paper is divided as follows:

In the first part the analytical expression of the energy losses caused by the current circulating (operating losses) in the storage systems of the microgrid is defined. The optimal operating condition of the microgrid, where the batteries operating losses are minimized, is identified.

The second part describes how this microgrid optimal operating condition can be transferred in particular states of the HPPs connected to the microgrid. We develop a control logic to identify the optimal state for each HPP from the measurement of local quantities, without any communication system between hybrid units. We define the control law that is used to modify the active droop coefficients in order to push the HPPs toward the optimal operating state.

Then a simplified energetic model of the microgrid is created, starting from the energetic model of a single hybrid power plant. Through the solution of this microgrid energetic model, implemented in Matlab code, the performances of the proposed optimizing control system can be evaluated.

II. REDUCTION OF THE BATTERY LOSSES

The operating power losses $P_{pl}(t)$ of a generic battery system can be expressed as function of the battery that the power is exchanging $P_{bat}(t)$:

$$P_{pl}(t) = \left(1-\eta_l(t)\right)\cdot P_{bat}(t) \tag{1}$$

The operating efficiency η_l is calculated from the battery series equivalent resistance R_l and considering the battery voltage constant and equal to its rated value V_{nbat}:

$$\eta_l(t) = 1-\frac{R_l\cdot P_{bat}(t)}{V_{nbat}^2} = 1-K_l\cdot P_{bat}(t) \tag{2}$$

Introducing a time discretization for modelling purpose, in a generic microgrid, with several hybrid power plants connected, the total energy lost for operating losses in the battery banks of all the HPPs is:

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$$E_{plTOT}=\sum_{h=1}^{Hy}\sum_{k=1}^{N}\left(\frac{R_{l,k}}{V_{nbat,k}^{2}}\cdot P_{bat,k}^{2}(h)\right)\cdot\Delta h \tag{3}$$

where R_l, V_{nbat}, P_{bat} are the resistance, rated voltage, power flow of the generic k battery bank, Δh is the discrete time interval and H_y the global time interval (one year) $E_{pl,TOT}$ is the total energy lost in the microgrid batteries. It should be noted that in (3) the power flow through the batteries appears raised to the second power, thus, the battery energy losses do not depend on the direction of the batteries power flow (charge or discharge power) since a symmetrical resistance R_l has been considered. The minimization of $E_{pl,TOT}$ can be achieved by minimizing the absolute value of the power flow through each battery of the microgrid in every time interval h:

$$\min\left(E_{plTOT}\right)\Rightarrow\min\left(\left|\sum_{k=1}^{N}P_{bat,k}(h)\cdot\Delta h\right|\right) \tag{4}$$

From (4), the objective of the optimization technique, proposed in this chapter to reduce the battery losses, is the minimization of the total power flow $P_{bat,TOT}(h)$ through the batteries in every time interval h:

$$P_{bat,TOT}=\sum_{k=1}^{N}\left|P_{bat,k}(h)\right| \tag{5}$$

III. ENERGETIC BALANCE IN THE MICROGRID AND OPTIMIZING CONTROL

A. Energetic balance

For the study case microgrid, composed of two HPPs, the instantaneous active power balance can be analyzed looking at Fig.1, where the power flows are highlighted.

In each time interval h the active power balance of the system, neglecting the conversion losses of the power plants, can be expressed as the equilibrium of the power flows across the three surfaces S_1, S_2 and S_0 , Fig.1:

$$P_{loadt}(h)=P_{res1}(h)+P_{res2}(h)-P_{bat1}(h)-P_{bat2}(h) \tag{6}$$

where $P_{res1,2}(h)$ is the total power available from the renewable generators of a hybrid power plant, HYB$_1$ or HYB$_2$.

In each time interval h, the power required from the two battery banks is:

$$\begin{aligned}&P_{nec}(h)=\\&\left(P_{res1}(h)+P_{res2}(h)\right)-P_{loadt}(h)=P_{bat1}(h)+P_{bat2}(h)\end{aligned} \tag{7}$$

$P_{nec}(h)$ is the necessary total power flow required from the batteries to maintain the energetic balance of the microgrid, and it represents the minimum value of the total battery power flow at each time interval.

Applying the “module” operator to (7) we obtain:

$$\begin{aligned}&\left|P_{nec}(h)\right|=\\&\left|\left(P_{res1}(h)+P_{res2}(h)\right)-P_{loadt}(h)\right|=\left|P_{bat1}(h)+P_{bat2}(h)\right|\end{aligned} \tag{8}$$

For the study case microgrid, equation (4) becomes:

$$P_{bat,TOT}=\left|P_{bat1}(h)\right|+\left|P_{bat2}(h)\right| \tag{9}$$

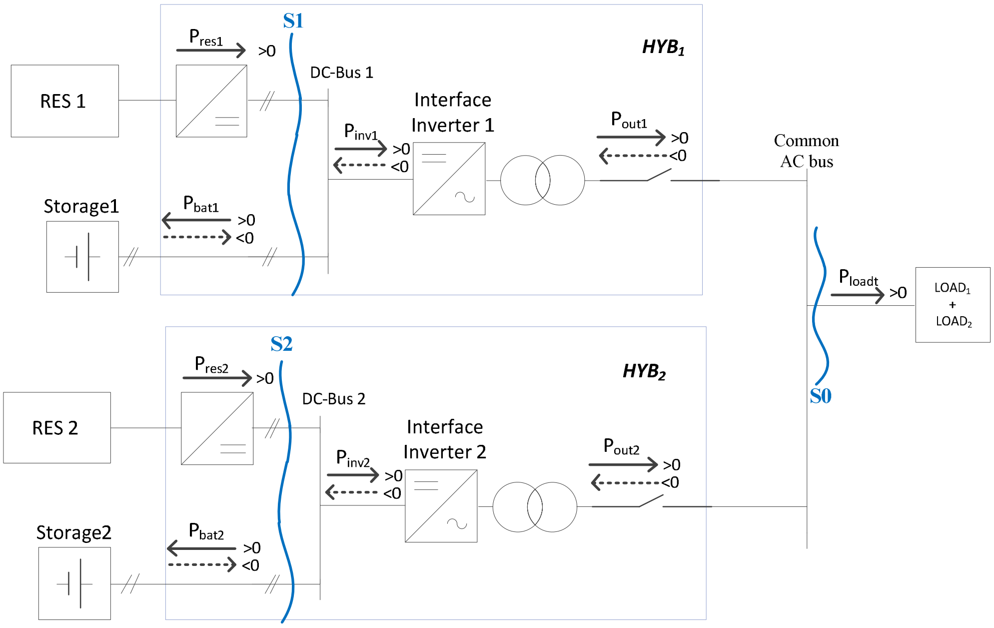

Fig. 1 – Power flows in the study case microgrid

The minimization of the total battery power flow $P_{bat,TOT}(h)$ means that its value should be maintained strictly equal to the necessary total battery power flow $P_{nec}(h)$:

$$\left|P_{bat\,1}(h)\right|+\left|P_{bat\,2}(h)\right|=\left|P_{nec}\right| \tag{10}$$

The optimizing condition (10) is satisfied if the battery power flows of the two HPPs have the same sign (both the batteries in discharge or in charge operation), as shown in (11).

$$\begin{aligned}
&if\ P_{bat1}(h)\cdot P_{bat2}(h)>0\\
&\Rightarrow\left|P_{bat1}(h)\right|+\left|P_{bat2}(h)\right|=\left|P_{bat1}(h)+P_{bat2}(h)\right|=\left|P_{nec}(h)\right|\\
&if\ P_{bat1}(h)\cdot P_{bat2}(h)<0\\
&\Rightarrow\left|P_{bat1}(h)\right|+\left|P_{bat2}(h)\right|>\left|P_{bat1}(h)+P_{bat2}(h)\right|\\
&\Rightarrow\left|P_{bat1}(h)\right|+\left|P_{bat2}(h)\right|>\left|P_{nec}(h)\right|
\end{aligned} \tag{11}$$

In conclusion, the condition that should be verified to minimize the batteries operation losses is that, in each time interval, the two battery banks should work in the same operating condition (charge or discharge):

$$P_{bat1}(h)\cdot P_{bat2}(h)>0 \tag{12}$$

B. Generalization to a case with N HPPs

A generalization of the optimizing condition (12) for a general microgrid with a number *N* of hybrid power plants, each one equipped with a battery bank, is:

$$sign\left(P_{bat\,i}(h)\right)=sign\left(P_{bat\,j}(h)\right) \qquad \forall i,j=1,\ldots N \tag{13}$$

For a generic hybrid power plant *k*, the power balance on the DC bus requires that:

$$P_{bat\,k}(h)=P_{res\,k}(h)-P_{inv\,k}(h) \tag{14}$$

The power absorbed or injected in the DC bus by the interface inverter of the HPP, $P_{inv\ k}(h)$, should be calculated from the required power at the a.c. interface of the hybrid power plant $P_{out\,k}(h)$, considering the a.c. interface stage efficiency, $\eta_{out\,k}$:

when the inverter supplies the load

$$P_{inv\,k}(h)=\frac{P_{out\,k}(h)}{\eta_{out\,k}(h)} \qquad if \quad P_{out\,k}(h)>0 \tag{15}$$

when the inverter absorbs power from the microgrid

$$P_{inv\,k}(h)=P_{out\,k}(h)\cdot\eta_{out\,k}(h) \quad if \quad P_{out\,k}(h)<0 \tag{16}$$

Neglecting the a.c. interface stage losses, we can consider:

$$P_{inv\,k}(h)\cong P_{out\,k}(h) \tag{17}$$

C. Application to a case with droop-controlled HPPs

The active power sharing between parallel inverters controlled with the droop algorithm depends on the relation between the active droop coefficients of the hybrid power plants *m*. For the study case microgrid, the droop active equation for each HPP is:

$$\omega=\omega^{*}-m_iP_{out\ i} \qquad i=1,2 \tag{18}$$

and the power balance yields:

$$\textstyle\sum_{i=1}^{2}P_{out\ i}=P_{load\ t} \qquad 19)$$

The active powers delivered by the two inverters are determined by the following relations:

$$\begin{aligned}
P_{out\ 1}(h)&=P_{load\ t}(h)\cdot\frac{m_2}{m_1+m_2}\\
P_{out\,2}(h)&=P_{load\ t}(h)\cdot\frac{m_1}{m_1+m_2}
\end{aligned} \tag{20}$$

Introducing (14), (17) and (20) in the optimizing condition (12) we obtain the following minimum losses condition:

$$\begin{aligned}
&\left(P_{res1}(h)-\frac{m_2}{m_1+m_2}\cdot P_{load\,t}(h)\right)\cdot\\
&\cdot\left(P_{res\,2}(h)-\frac{m_1}{m_1+m_2}\cdot P_{load\,t}(h)\right)>0
\end{aligned} \tag{21}$$

that can be developed as:

$$\begin{aligned}
&P_{res1}(h)\cdot P_{res\,2}(h)-P_{load\,t}(h)\cdot\\
&\cdot\left(\frac{m_1}{m_1+m_2}\cdot P_{res1}(h)+\frac{m_2}{m_1+m_2}\cdot P_{res\,2}(h)\right)+\\
&+P_{load\,t}^{2}(h)\cdot\frac{m_1\cdot m_2}{\left(m_1+m_2\right)^2}>0
\end{aligned} \tag{22}$$

The load demand $P_{load\,t}(h)$ and the power available from the renewable sources $P_{res1,2}(h)$ are forced by the external conditions and cannot be controlled. Thus, the only way to satisfy the optimizing condition (22) is to modify the ratio between the droop coefficients m_1 and m_2.

Using the droop control strategy allows to regulate the power sharing between paralleled HPPs without any communication system between the HPPs and without any microgrid supervision and control system. In the following, a method to implement the optimizing condition (22) using only the local measurements of each HPP is described

For each HPP the control variable to minimize the battery operating losses of the entire microgrid is the active droop coefficient *m*, and the control is implemented without any information on the active droop coefficient of the other HPPs nor on the total power absorbed from the load.

For each HPP, the sign of the battery power flow depends on the RES availability and on the power demand at the hybrid power plant a.c. output. From equations (14), (15) and (17), we obtain (Fig. 2):

$$\begin{array}{llll} state\ A & if & P_{res\,k}(h) > P_{out\,k}(h) & \Rightarrow P_{bat\,k}(h) > 0 \\ state\ B & if & P_{res\,k}(h) < P_{out\,k}(h) & \Rightarrow P_{bat\,k}(h) < 0 \end{array} \qquad (23)$$

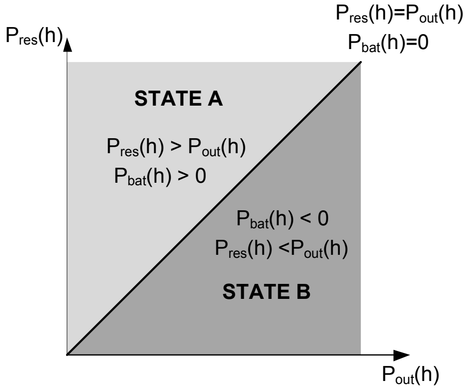

Fig. 2: DC bus power balance graphical representation for a hybrid power plant.

The active droop coefficient m_k of the HPP is regulated in order to move the operation point of the hybrid power plant in the plane $P_{out}(h)$-$P_{res}(h)$ (Fig. 2) toward the line separating the two states A (battery in discharge) and B (battery in charge), corresponding to the ideal condition $P_{bat}(h)=0$; (thus no load-losses for battery operation in the microgrid).

The variation of the active droop coefficient implies a variation of the HPP's required output power $P_{out\_k}(h)$, according to (20), thus, the operation point of the HPP is moved along a horizontal trajectory in the plane $P_{out}(h)$-$P_{res}(h)$ of Fig. 2, as shown if Fig. 3.

The regulation operated on the coefficient m_k of an HPP causes the migration of the operation point of all the other HPPs connected to the microgrid, in their specific $P_{out}(h)$-$P_{res}(h)$ plane, because of the power balance constraint on the common AC bus:

$$\sum_{k=1}^{N} P_{out\,k}(h) = P_{load\ t}(h) \qquad (24)$$

Because of (24) and considering that the regulation m_k is implemented in all the HPPs of the microgrid, the result obtained with the proposed regulation is that the microgrid equilibrium point is reached in a condition where all the HPPs are in the same region of the plane (A or B). This means that there is no indirect power exchange between the battery banks of the microgrid. In this condition, all the battery banks are in the same operation mode, charge or discharge, and the global battery power flow is minimized (12). Obviously, the regulated active droop coefficients must satisfy the stability conditions, that will be described later on.

We consider, as an example, an initial configuration where the two hybrid power plants are operating in two different states: state B for HYB$_1$ and state A for HYB$_2$, as shown in Fig. 3**Error! Reference source not found.**. In this case the optimizing condition (12) is not respected. The proposed control technique can change the minigrid equilibrium point and bring the two battery bank in the same operating condition.

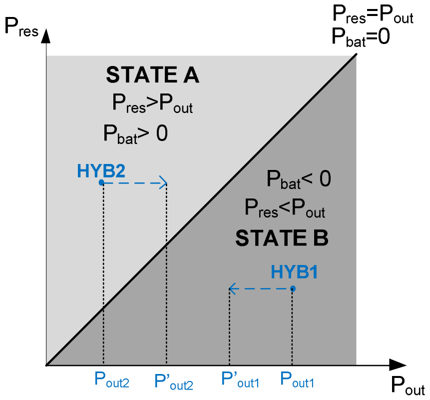

Fig. 3: DC Two HPPs are operating in non-optimized conditions. Through the proposed solution, they move towards the diagonal line, where no power exchange between the batteries happen.

If the hybrid power plant HYB$_1$ is in the state B (battery discharge), the optimization control increases the active droop coefficient m_1 to reduce the required output power (from P_{out1} to P'_{out1}), in order to move the operation point of HYB$_1$ toward the line separating the two states. At the same time, if the hybrid power plant HYB$_2$ is in the state A (battery charge), the optimization control decreases the active droop coefficient m_2 to increase the required output power (from P_{out1} to P'_{out1}), in order to move the operation point of HYB$_2$ toward the line separating the two states. The operation of the optimizing regulation in this case is shown graphically in Fig. 3 .

D. Regulation rule

The regulation rules described above for the active droop coefficients are implemented, using an incremental control with variable step. The incremental step is calculated considering the battery power flow weighted for the maximum power that we expect the battery would be required, that is the maximum power available from the renewable generators (P_{resMAX}).The control equations for a generic time step i are:

$$\begin{aligned} m_k(i) &= m_k(i-1) + \Delta m_k(i) \\ \Delta m_k(i) &= -\Delta m_{k\,\max} \cdot \frac{P_{bat\,k}(i-1)}{P_{resMAX\,k}} \end{aligned} \qquad (25)$$

where: k=1,2, for the hybrid power plants of the study case microgrid;

i is the time interval at which the optimizing regulation is implemented. It represents the dynamic of the chosen incremental regulator.

In this paper, we do not investigate further the issue of the sizing of the two regulation coefficients Δm_{max} and i, except for some general considerations. The regulator parameters Δm_{max} should be calculated considering the maximum and minimum value of the droop coefficient, the dynamic of the droop coefficient regulation (amplitude of time step i) and the expected dynamic of the external quantities ($P_{load\ t}$, and $P_{res1,2}$) variation. The higher the value of Δm_{max} is, the faster the regulation is, but the higher is the oscillation around the optimum point when the regulation transient is finished. Similarly, the amplitude of the discrete interval at which the regulation is actuated, *i*, should be defined considering that the faster is the regulation and the faster the microgrid moves toward the optimal operating point after a variation in the external quantities, but the faster are the oscillation around this point. Moreover, the droop coefficient regulation dynamic should not overlap with the droop control dynamic, to avoid perturbations in the system stability.

Finally, we define the exceeding battery power flow, $P_{exc}(h)$, as the difference between the absolute instantaneous battery power flow and the absolute value of the minimum needed battery power flow:

$$\begin{aligned} P_{exc}(h) &= P_{bat,TOT}(h) - \left|P_{nec}(h)\right| = \\ &= \left(\left|P_{bat1}(h)\right| + \left|P_{bat2}(h)\right|\right) - \left(\left|\left(P_{res1}(h) + P_{res2}(h)\right) - P_{load\,t}(h)\right|\right) \end{aligned} \tag{26}$$

$P_{exc}(h)$ represents an indirect power exchange between the batteries of the HPPs connected to the microgrid, that is not required for the system operation but it causes additional losses and is minimized by the optimizing control technique proposed here.

IV. SIMULATION RESULTS

To evaluate the proposed optimizing control technique, an energetic model of a study case microgrid is created using Matlab software.

The study case microgrid is composed of two HPPs with DC bus configuration [6] with the features shown in Table I. The method followed to design the control parameters is reported in [5].

The regulated active droop coefficients must never over go the stability limit curve calculated for the active droop coefficients m_1 and m_2 as a function of the selected values of the reactive droop coefficients n_1 and n_2. These boundary values can be obtained from the analysis of the eigenvalues. The results are reported in Fig. 4.

The input variables of the simulation are the load profile ($P_{load\ t}$) and the total power available from the renewables ($P_{res\ t}$), with the profile shown in Fig. 5: it can be seen that $P_{res\ t} > P_{load\ t}$ for some parts of the day.

TABLE I

MAIN DATA OF THE STUDY CASE MICROGRID.

	HPP1	HPP2
Rated output voltage V_n [V], power [kVA]	400; 20	400; 10
PV and wind turbine rated power [kW]	30; 10	15; 0
Battery rated energy [kWh] and minimum SOC [%]	520; 70	162.5; 70
Reactive droop coefficients n_1, n_2 [p.u.]	0.02	0.04
Minimum and maximum active droop coefficients [rad/(s·W)] and Δm_{max} [rad/(s·W)]	$1\cdot10^{-4}$; $5\cdot10^{-4}$; $0.6\cdot10^{-4}$	$1\cdot10^{-4}$; $1\cdot10^{-3}$; $0.15\cdot10^{-3}$

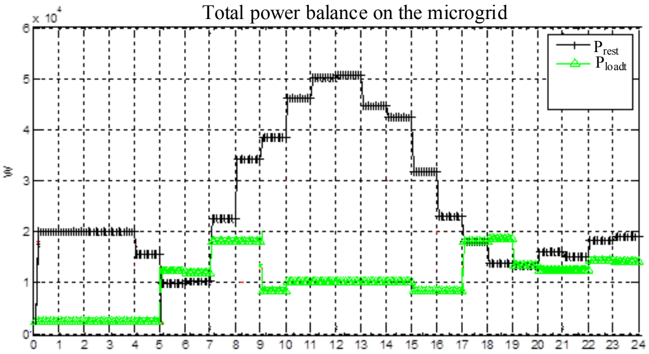

Fig. 5: Study case microgrid – Daily load profile ($P_{load\ t}$) and the total power available from the renewables ($P_{res\ t}$)

Some results of the simulations are shown in the following figures. Fig. 6 shows the exchange power P_{exc} when the droop coefficients are kept constant and equal to their minimum value: a large energy is exchanged during the time intervals 0 – 5h, 6h – 8h, 17h – 19h. By regulating the active coefficients m_1, m_2 (Fig. 7), a large reduction of P_{exc} is obtained (Fig. 8).

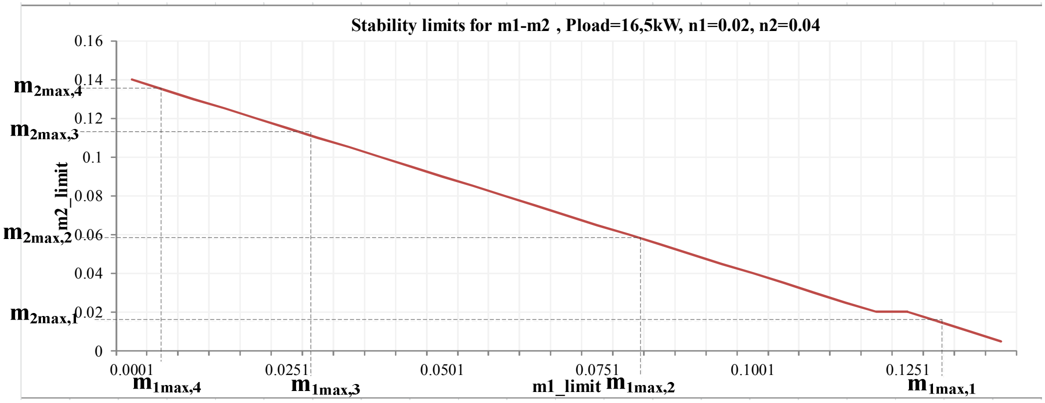

Fig. 4: Example of the graphical definition of the maximum active droop coefficients for the study case microgrid.

The indirect battery power exchange, P_{exc}, is forced to zero for almost all the day, except for some peaks caused by sudden changes in the external conditions. In the first hours of the day, from 00:00 to 5:00, the regulation cannot force to zero the controlled variable P_{exc}, because of the initial condition imposed for the simulation: in fact, the initial values of the active droop coefficients have been set to their maximum admitted values. At the beginning of the simulation, with these maximum coefficients the two HPPs are in different operating conditions: HYB1 is in state A with the battery in charge, and HYB2 is in state B discharging its battery.

The active droop coefficient m_1 should be reduced, to increase the output power of HYB_1 (P_{out1}), while m_2 should be increased. The regulation operates correctly for HYB_1, and the coefficient m_1 is brought rapidly to its minimum value between 0:00 and 1:00 (Fig. 7). On the contrary, on HYB_2 the regulation cannot operate because the droop coefficient m_2 is already at its maximum value and it cannot be increased further (see Fig. 7, between 0:00 and 5:00). Because of the maximum and minimum droop limit values, the proposed regulation cannot force to zero P_{exc} in the time period from 0:00 to 5:00 (Fig. 8), but it can reduce its value with respect to the same period of the day in the case with no regulation of the droop coefficients (Fig. 6).

If the simulation is extended to a whole month, a reduction of 70% on the total indirect energy exchange between the batteries of the microgrid is obtained.

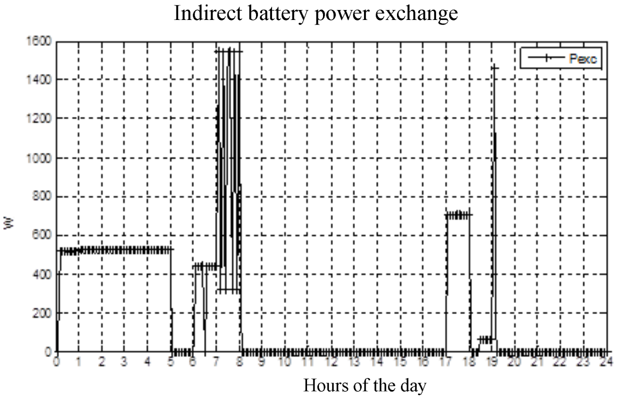

Fig. 6: Simulation results – Exceeding battery power flow (P_{exc})(indirect power exchange between the batteries) with constant active droop coefficients, m_{1min}, m_{2min}.

V. CONCLUSION

The paper has analyzed the operation of a droop-controlled microgrid supplied by two hybrid power plants (HPP). At first the optimal operating condition of the microgrid is identified so as to minimize the battery losses.

Then a control logic to find the optimal state of each HPP, measuring the local quantities, has been identified. Non communication exists between the hybrid units.

A control law to modify the active droop coefficients is proposed, so as to push the Hybrid Power Plants towards a condition that reduces the power exchanged between the two batteries. Some simulation results show the feasibility and the positive results of the proposed technique.

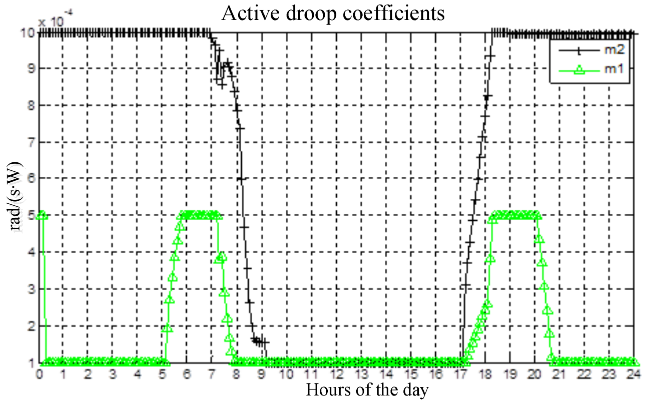

Fig. 7 - Simulation with variable inputs, regulated active droop coefficients m_1 and m_2.

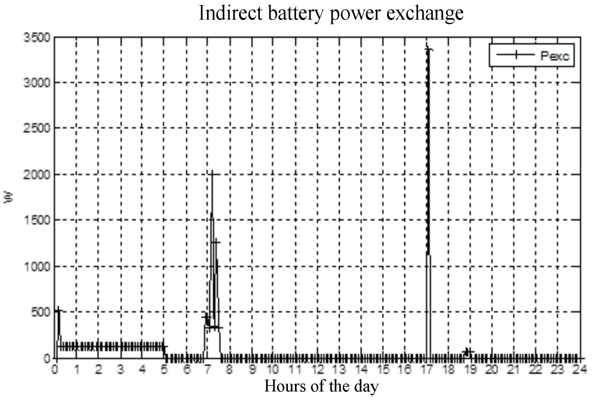

Fig. 8: Simulation results – Exceeding battery power flow (P_{exc}) with the proposed optimizing control technique. A reduction of the exchange power between the batteries is observed.

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