Resilience-oriented Schedule of Microgrids with Hybrid Energy Storage System using Model Predictive Control

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Introduction

Microgrids can be regarded as a promising solution to increase the power systems resilience in an energy paradigm based on renewable generation.

Their main advantage is given by their ability to work as islanded systems under power grid outages. Microgrids are usually integrated in electrical markets carrying out a schedule according to economic aspects while resilience criteria are neglected.

With the aim of improving the autonomy of the microgrid while achieving fast transition response, a hybrid ESS composed of hydrogen and batteries is considered. In the table below we can see the main degradation issues for this ESS

ESS	Degradation Issues
Batteries	Working Cycles, Overcharge, Undercharge, High stress current ratio
Electrolyzer and Fuel Cells	Working Hours, Fluctuations of current, Start/Stop Cycles

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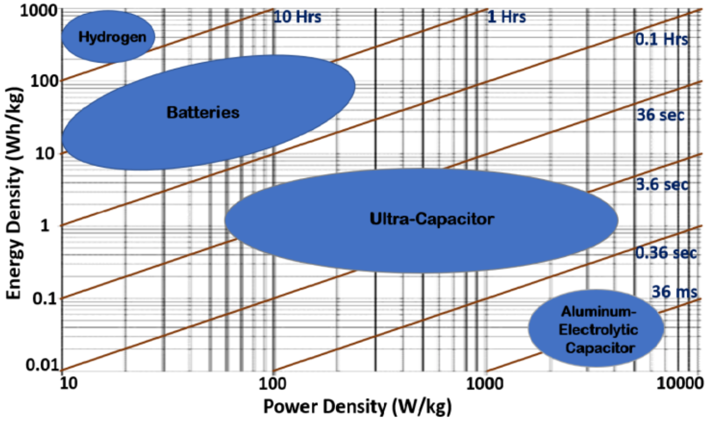
Introduction

In order to take into account possible transitions between grid-connected and islanded modes in all the sample instants of the schedule horizon (SH), the control problem is formulated using Stochastic Model Predictive Control (SMPC) techniques.

The control problem is developed considering a healthy operation of the hybrid ESS avoiding degradation issues.



Due to the presence of logic and dynamic control variables, the plant is modeled by using the Mixed Logic Dynamic (MLD) framework.

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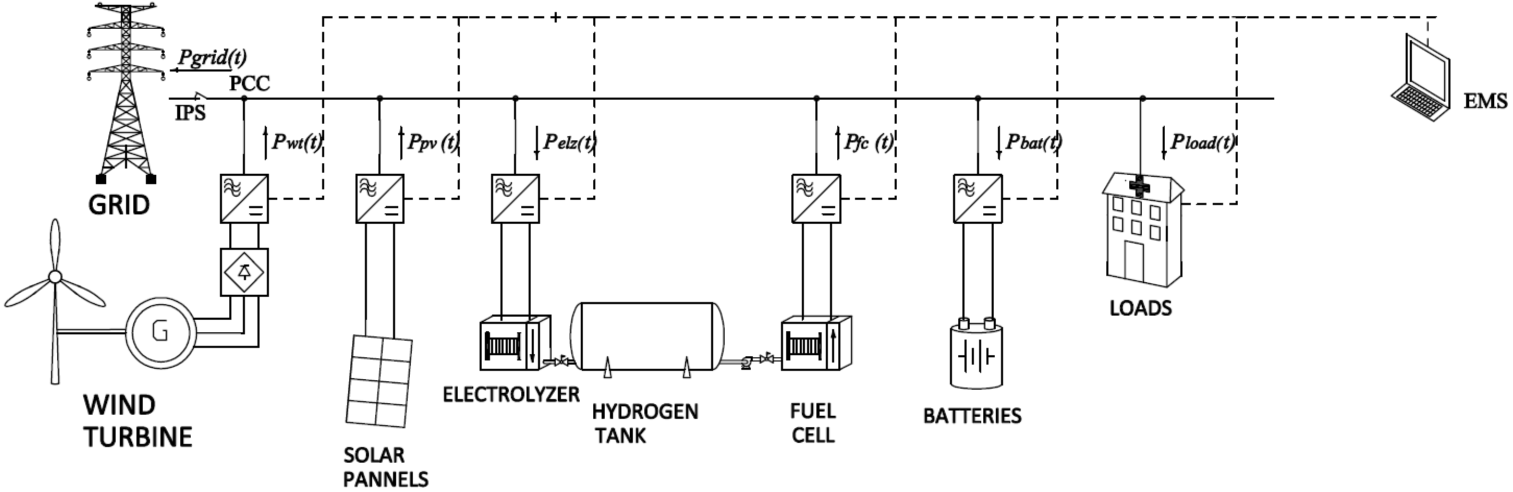
Stochastic MPC-Based Controller Design

The microgrid is composed of wind turbine and photovoltaic generators, it contains critical and non-critical loads and there are two kinds of ESS: batteries and hydrogen.

The controller is designed for the microgrid participation in the Day-Ahead Market, for this reason the considered sample time is Ts=1 hour. The controller is designed according to:

- Feasible Islanding/critically criteria
- Survivability criteria
- Healthy Operation



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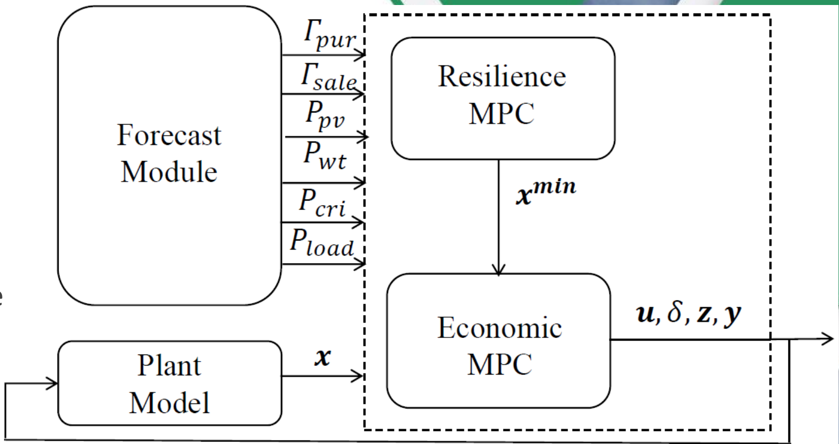
Stochastic MPC-Based Controller Design

A different optimization scenario is considered for each sample instant of the SH, considering a transition between the grid-connected to the islanded mode. These scenarios are defined as ’critical scenarios’ and are solved in the ’Resilience MPC’ module of the Block Diagram.

Finally, one ’normal’ scenario is included in order to optimize the participation of the microgrid in the day-ahead market when it is working in the grid-connected mode for all the sample instants of the SH.

This is optimized in the ’Economic MPC’ module of the controller. The control problem can be formulated as a Stochastic Multi-Scenario MPC controller by employing the sum of a multi-objective cost function for each scenario.



$$\min J = \sum_{s=1}^{N_s} J^{[s]}(\mathbf{u}^{[s]}, \delta^{[s]})$$

$$J^{[s]} = \sum_{k=1}^{SH} f(\mathbf{u}^{[s]}(t+k), \delta^{[s]}(t+k))$$

subject to:

$$\mathbf{u}^{min} \le \mathbf{u}^{[s]}(t) \le \mathbf{u}^{max}$$
$$0 \le \delta^{[s]}(t) \le 1$$
$$0 \le \mathbf{z}^{[s]}(t) \le \mathbf{z}^{max}$$
$$\mathbf{x}^{min} \le \mathbf{x}^{[s]}(t) \le \mathbf{x}^{max}$$
$$\mathbf{y}^{min} \le \mathbf{y}^{[s]}(t) \le \mathbf{y}^{max}$$

$$\mathbf{x}^{[s]}(t+1) = \mathbf{A}\mathbf{x}^{[s]}(t) + \mathbf{B}_u\mathbf{u}^{[s]}(t) + \mathbf{B}_\delta\delta^{[s]}(t) + \mathbf{B}_z\mathbf{z}^{[s]}(t) + \mathbf{B}_d\mathbf{d}(t)$$

$$\mathbf{y}^{[s]}(t) = \mathbf{C}\mathbf{x}^{[s]}(t) + \mathbf{D}_u\mathbf{u}^{[s]}(t) + \mathbf{D}_\delta\delta^{[s]}(t) + \mathbf{D}_z\mathbf{z}^{[s]}(t) + \mathbf{D}_d\mathbf{d}(t)$$

$$\mathbf{E}_\delta\delta^{[s]}(t) + \mathbf{E}_z\mathbf{z}^{[s]}(t) \le \mathbf{F}\mathbf{x}^{[s]}(t) + \mathbf{E}_u\mathbf{u}^{[s]}(t) + \mathbf{E}_d\mathbf{d}(t)$$

Stochastic MPC-Based Controller Design

The different control variables and system outputs are related to a physical model of the plant, which is modeled using the space state representation of the plant by introducing a set of state variables

$$\boldsymbol{u}^{[s]} = \left[P_{ch}^{[s]}, P_{dis}^{[s]}, P_{elz}^{[s]}, P_{fc}^{[s]}, P_{pur}^{[s]}, P_{sale}^{[s]}, \alpha_{cur,gen}^{[s]}\right]^T$$
$$\boldsymbol{\delta}^{[s]} = [\delta_{elz}^{[s]}, \delta_{fc}^{[s]}, \sigma_{elz}^{[s]}, \sigma_{fc}^{[s]}, \chi_{elz}^{[s]}, \chi_{fc}^{[s]}, \delta_{cur,1}^{[s]}, \delta_{cur,2}^{[s]}, \ldots \delta_{cur,10}^{[s]}, ,]^T$$
$$\mathbf{z}^{[s]} = \left[z_{elz}^{[s]}, z_{fc}^{[s]}, \vartheta_{elz}^{[s]}, \vartheta_{fc}^{[s]}\right]^T$$
$$\mathbf{x}^{[s]} = \left[SOC^{[s]}, LOH^{[s]}\right]^T$$
$$\mathbf{y}^{[s]} = \left[P_{grid}^{[s]}\right]^T$$
$$\mathbf{d} = \left[\hat{P}_{pv}, \hat{P}_{wt}, \hat{P}_{load}, \hat{P}_{cri}\right]^T$$

$$SOC^{[s]}(t+1) = SOC^{[s]}(t) + \frac{P_{ch}^{[s]}(t) \cdot \eta_{ch}}{C_{bat}} - \frac{P_{dis}^{[s]}(t)/\eta_{dis}}{C_{bat}}$$

$$LOH^{[s]}(t+1) = LOH^{[s]}(t) + z_{elz}^{[s]}(t) \cdot \eta_{elz} - \frac{z_{fc}^{[s]}(t)}{\eta_{fc}}$$

$$\begin{aligned}
z_\alpha^{[s]}(t) &= P_\alpha^{[s]}(t) \cdot \delta_\alpha^{[s]}(t) \\
m \le z_\alpha(t) - P_\alpha^{max}\delta_\alpha^{[s]}(t) &\le 0 \\
0 \le z_\alpha^{[s]}(t) - P_\alpha^{min}\delta_\alpha^{[s]}(t) &\le M \\
P_\beta^{[s]}(t) - P_\alpha^{max}(1 - \delta_\alpha^{[s]}(t)) - z_\alpha^{[s]}(t) &\le 0 \\
0 \le P_\alpha^{[s]}(t) - P_\alpha^{min}(1 - \delta_\alpha^{[s]}(t)) - z_\alpha^{[s]}(t)
\end{aligned}$$

$$\begin{aligned}
&P_{pur}^{[s]}(t) - P_{sale}^{[s]}(t) + \hat{P}_{pv}(t) + \hat{P}_{wt}(t) + P_{bat}^{[s]}(t) \\
&+ z_{fc}^{[s]}(t) - \hat{P}_{load}(t) - z_{elz}(t) + \sum_{n=1}^{10}(\delta_{cur,n}^{[s]}(t)\hat{P}_{load,n}(t)) \\
&- \alpha_{cur,gen}^{[s]}(t) \cdot (\hat{P}_{pv}(t) + \hat{P}_{wt}(t)) = 0 \\
&-P_{grid}^{[s]}(t) + P_{pur}^{[s]}(t) - P_{sale}^{[s]}(t) = 0
\end{aligned}$$

$$\begin{aligned}
\chi_\alpha^{[s]}(t) = \delta_\alpha^{[s]}(t) \wedge \delta^{[s]} a_\alpha(t-1)&|_{\alpha=elz,fc} \\
m \le -\delta_\alpha^{[s]}(t) + \chi_\alpha^{[s]}(t) \le 0&|_{\alpha=elz,fc} \\
m \le -\delta_\alpha^{[s]}(t-1) + \chi_\alpha^{[s]}(t) \le 0&|_{\alpha=elz,fc} \\
m \le \delta_\alpha^{[s]}(t) + \delta_\alpha^{[s]}(t-1) - \chi_\alpha^{[s]}(t) \le 1&|_{\alpha=elz,fc}
\end{aligned}$$

$$\begin{aligned}
\vartheta_\alpha(t) &= (P_\alpha(t) - P_\alpha(t-1)) \cdot \chi_\alpha(t) \\
m \le \vartheta_\alpha(t) - \Delta P_\alpha^{max}\chi_\alpha(t) &\le 0 \\
0 \le \vartheta_\alpha(t) - \Delta P_\alpha^{min}\chi_\alpha(t) &\le M \\
m \le \vartheta_\alpha(t) - \Delta P_\alpha(t) + \Delta P_\alpha^{min}(1 - \chi_\alpha(t)) &\le 0 \\
0 \le \vartheta_\alpha(t) - \Delta P_\alpha(t) + \Delta P_\alpha^{max}(1 - \chi_\alpha(t)) &\le M
\end{aligned}$$

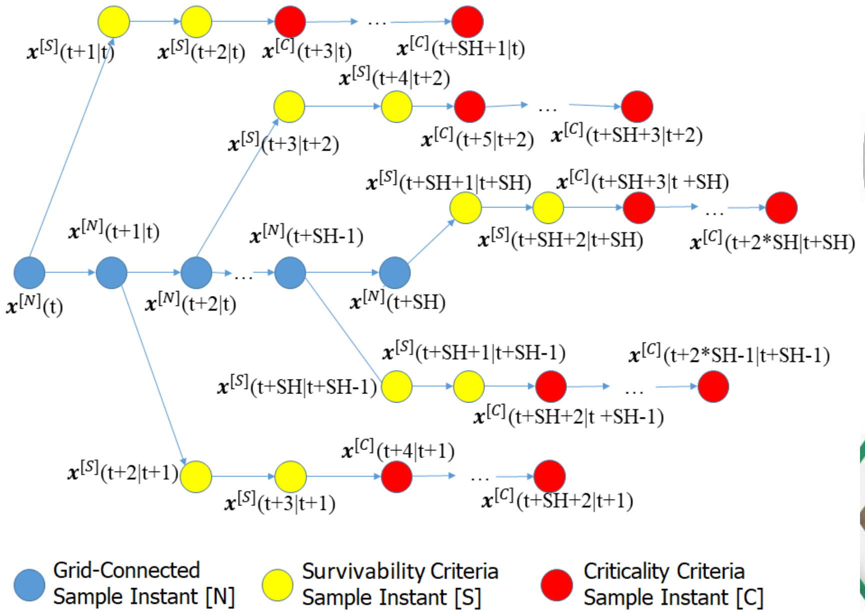
$$\begin{aligned}
\sigma_\alpha^{[s]}(t) = \delta_\alpha^{[s]}(t) \wedge \sim \delta_\alpha^{[s]}(t-1)&|_{\alpha=elz,fc} \\
m \le -\delta_\alpha^{[s]}(t) + \sigma_\alpha^{[s]}(t) \le 0&|_{\alpha=elz,fc} \\
m \le -(1 - \delta_\alpha^{[s]}(t-1)) + \sigma_\alpha^{[s]}(t) \le 0&|_{\alpha=elz,fc} \\
m \le \delta_\alpha^{[s]}(t) + (1 - \delta_\alpha^{[s]}(t-1) - \sigma_\alpha^{[s]}(t) \le 1&|_{\alpha=elz,fc}
\end{aligned}$$

Resilience MPC-Controller Block

The main aim of this block is to optimize the minimum level of energy stored in order to achieve the criteria regarding survivability and criticality.

As can be seen in the figure, depending on the considered scenario each sample instant can be categorized as:

1. **'Normal'** where it is possible to exchange energy with the main grid,
2. **'Survivability'** at this sample instant the criteria of survivability and criticality have to be integrated in the control problem
3. **'Criticality'** there is not a connection with the main grid, but only the critical loads have to be fed.



Resilience MPC-Controller Block

$$
\begin{aligned}
J^{[s=j]} = T_s \Big(& \underbrace{w_{SOC} \cdot SOC^{[j]}(t_j) + w_{LOH} \cdot LOH^{[j]}(t_j)}_{Minimum\ Storage\ Level\ Calculus} + \\
& \sum_{k=1}^{k=SH+j} \underbrace{\left(-\Gamma^{DM}_{sale}(t_k) \cdot z^{[j]}_{sale}(t_k) + \Gamma^{DM}_{pur}(t_k) \cdot z^{[j]}_{pur}(t_k) \right.}_{Grid\ Exchange\ Revenue\&Cost(J_{grid})} \\
& + \underbrace{10 \cdot \max(\Gamma^{DM}_{sale}(t_k \le t_j)) \cdot \alpha^{[j]}_{cur,gen}(t_k)}_{Generation\ Curtailment\ Cost} \\
& + \underbrace{\sum_{i=1}^{i=10} \Big((10+i) \cdot \max(\Gamma^{DM}_{pur}(t_k \le t_j)) \cdot \delta^{[j]}_{cur,load\_i}(t_k) \Big)}_{Load\ Curtailment\ Cost} \\
& + \underbrace{\frac{CC_{bat}}{2 \cdot Cycles_{bat}} \sum_{\alpha=ch,dis} \left(z^{[j]}_{bat,\alpha}(t_k) \right)}_{Batteries\ Cycling\ Cost} \\
& + \underbrace{\sum_{\alpha=ch,dis} (Cost_{degr,\alpha} \cdot (z^{[j]}_{bat,\alpha}(t_k))^2)}_{Batteries\ ESS\ Degradation} \\
& + \underbrace{\sum_{\alpha=elz,fc} \left(\left(\frac{CC_\alpha}{Hours_\alpha} + Cost_{o\&m,\alpha} \right) \delta^{[j]}_\alpha(t_k) \right.}_{Hydrogen\ ESS\ Hourly\ Cost\ Use} \\
& \underbrace{\left. + Cost_{startup,\alpha} \cdot \sigma^{[j]}_\alpha(t_k) + Cost_{degr,\alpha} \cdot (\vartheta^{[j]}_\alpha(t_k))^2 \right) \Big) \Big)}_{Hydrogen\ ESS\ Degradation}
\end{aligned}
$$

There will be a cost function will be calculated for the scenario which considers that the grid outage happens, at the sample instant j.

This cost function, there are different expressions referred to optimization objectives.

Subject to:

$$
\begin{aligned}
& P^{[j]}_{grid}(t_k) = 0 \ \forall k > j \\
& \alpha^{[j]}_{cur,gen\_i}(t_k) = 0 \ \forall k \le j \\
& \delta^{[j]}_{cur,load\_i}(t_k) = 0 \ \forall k \le j \\
& \delta^{[j]}_{cur,load\_i}(t_k) = 1 \ \forall k > j+2
\end{aligned}
$$

Economic MPC-Controller Block

Once the previous block has obtained the results, these values are used to calculate the minimum values for the state variables by the Economic MPC block

$$LOH_{const} = \begin{bmatrix} LOH_1^{[1]} & LOH_1^{[2]} & \dots & LOH_1^{[SH]} \\ LOH_2^{[1]} & LOH_2^{[2]} & \dots & LOH_2^{[SH]} \\ \dots & \dots & & \dots \\ LOH_{SH}^{[1]} & LOH_{SH}^{[2]} & \dots & LOH_{SH}^{[SH]} \end{bmatrix} \quad (40)$$

This LOH and SOC matrix obtained will be the key to obtaining the desired prediction in this part of the algorithm.

$$SOC_{const} = \begin{bmatrix} SOC_1^{[1]} & SOC_1^{[2]} & \dots & SOC_1^{[SH]} \\ SOC_2^{[1]} & SOC_2^{[2]} & \dots & SOC_2^{[SH]} \\ \dots & \dots & & \dots \\ SOC_{SH}^{[1]} & SOC_{SH}^{[2]} & \dots & SOC_{SH}^{[SH]} \end{bmatrix}$$

The most restrictive values of the SOC and LOH for each sample instant of all the values obtained for each of the scenarios are selected and imposed on the controller

That is, the maximum value of each hour of all scenario, will be set as the minimum value of SOC and LOH for that hour in the economic MPC algorithm.

$$SOC^E(t_k) \leq SOC^N(t_k) \leq SOC^{max}$$
$$LOH^E(t_k) \leq LOH^N(t_k) \leq LOH^{max}$$

Where $SOC^E(tk)$ is the maximum value of the k row from the SOC matrix. The same procedure is followed to obtain $LOH^E(tk)$

$$SOC^E(t_k) = \max\left(\left[SOC_k^{[1]} \quad SOC_k^{[2]} \quad \dots \quad SOC_k^{[SH]}\right]\right)$$

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Economic MPC-Controller Block

The cost function in this control block includes the possibility to purchase or sale energy through the energy exchange with the main grid in all the sample instants and its main aim is to optimize the economic revenue of exchanging energy with the main grid minimizing the operation cost of the hybrid ESS.

The state space constraints developed in the Resilience MPC Block are similar to the ones used in this controller. In order to guarantee the criticality and survivability criteria only the lower bounds of SOC and LOH for each sample instant have to be modified

$$
\begin{aligned}
J =\ & T_s \sum_{k=1}^{k=SH} \underbrace{\left(-\Gamma_{sale}^{DM}(t_k) \cdot z_{sale}(t_k) + \Gamma_{pur}^{DM}(t_k) \cdot z_{pur}(t_k)\right)}_{Grid\ Exchange\ Revenue\&Cost(J_{grid})} \\
& + \underbrace{\frac{CC_{bat}}{2 \cdot \mathrm{Cycles}_{bat}} \sum_{\alpha=ch,dis} \left(z_{bat,\alpha}(t_k)\right)}_{Batteries\ Cycling\ Cost} \\
& + \underbrace{\sum_{\alpha=ch,dis} \left(\mathrm{Cost}_{degr,\alpha} \cdot \left(z_{bat,\alpha}(t_k)\right)^2\right)}_{Batteries\ ESS\ Degradation} \\
& + \underbrace{\sum_{\alpha=elz,fc} \left(\left(\frac{CC_{\alpha}}{\mathrm{Hours}_{\alpha}} + \mathrm{Cost}_{o\&m,\alpha}\right)\delta_{\alpha}(t_k)\right.}_{Hydrogen\ ESS\ Hourly\ Cost\ Use} \\
& \underbrace{\left. + \mathrm{Cost}_{startup,\alpha} \cdot \sigma_{\alpha}(t_k) + \mathrm{Cost}_{degr,\alpha} \cdot \left(\vartheta_{\alpha}(t_k)\right)^2\right)}_{Hydrogen\ ESS\ Degradation} \\
& + \underbrace{w_{SOC} \cdot \left(SOC(SH) - SOC^{[ref]}\right)}_{Future\ Uncertainties} \\
& + \underbrace{w_{LOH} \cdot \left(LOH(SH) - LOH^{[ref]}\right)}_{Future\ Uncertainties}
\end{aligned}
$$

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Results

The controller is developed and validated through numerical simulations using the software MATLAB® and TOMLAB®

The simulations have been performed with a sample time Ts = 1 hour and during a complete day, what means SH = 24 Hours

The energy prices predicted and used in the forecast algorithm have been based on the Iberian Market Operator history data at 05/04/20

The parameters and values integrated in the controller are shown in the table

Grid parameters	
P_{grid_min}: -40 kW	P_{grid_max}: 40 kW
Renewable Energy parameters	
PV Pannels: 30kWp	Wind Turbine: 10 kW
Hydrogen ESS parameters	
Electrolyzer: 50kW, Tank: 35Nm^3	Fuel Cell: 20 kW
LOH_{max}: 35Nm^3	LOH_{min}: 5Nm^3
$Cost_{deg,elz}$: 0.0577€/W, Hour = 10000 h	$Cost_{startup,elz}$ = 0.123€
ς: 0.23Nm^3/kW h, CC = 8.22 €/kW h	$Cost_{o\&m,elz}$ = 0.002€/h
$Cost_{deg,fc}$: 0.0018€/W, Hour = 10000 h	$Cost_{startup,fc}$ = 0.01€
ς: 1.320Nm^3/kW h, CC = 30 €/kW h	$Cost_{o\&m,fc}$ = 0.001€/h
w_{LOH} = 10	
Batteries ESS parameters	
Battery: ±15 kW; ±55 kWh	w_{SOC} = 0.1
$Cost_{deg,ch}$: 10^{-9}€/W^{2}h	$Cost_{deg,dis}$: 10^{-9}€/W^{2}h
η_{ch}: 0.90	η_{dis}: 0.95
SOC_{max} = 100%	SOC_{min} = 25%

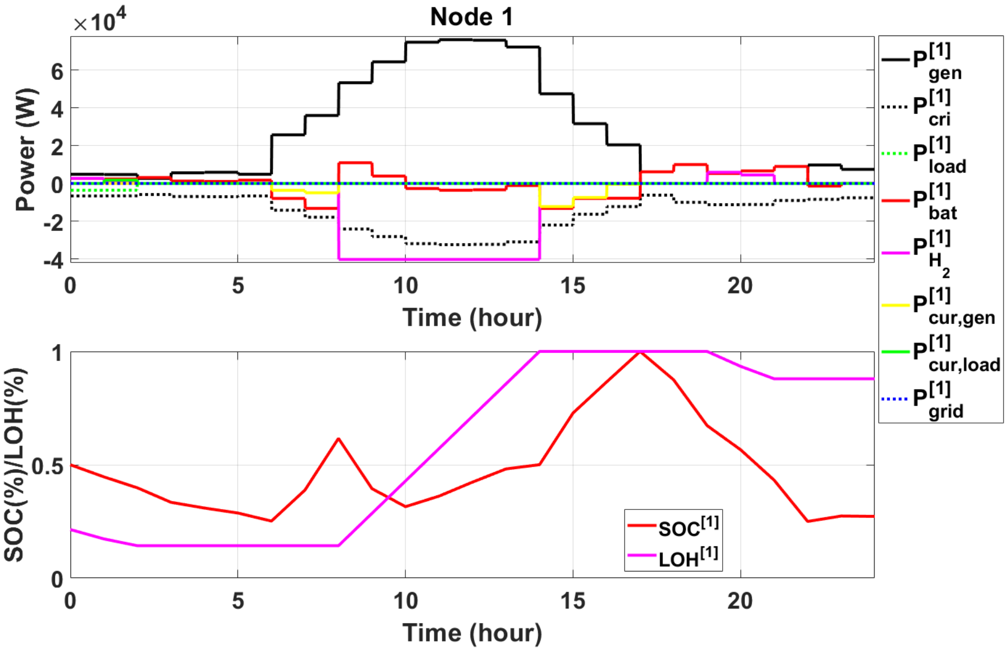
Results

The energy generated by the photovoltaic panels and the wind turbine are integrated into a common term $P_{gen} = P_{wt} + P_{pv}$ in the graphs.

Node 1 shows that the microgrid is able to feed all the loads for the first hour, but in the second hour, the system has to cut some of the non-critical loads because the stored energy is needed to feed the critical loads.

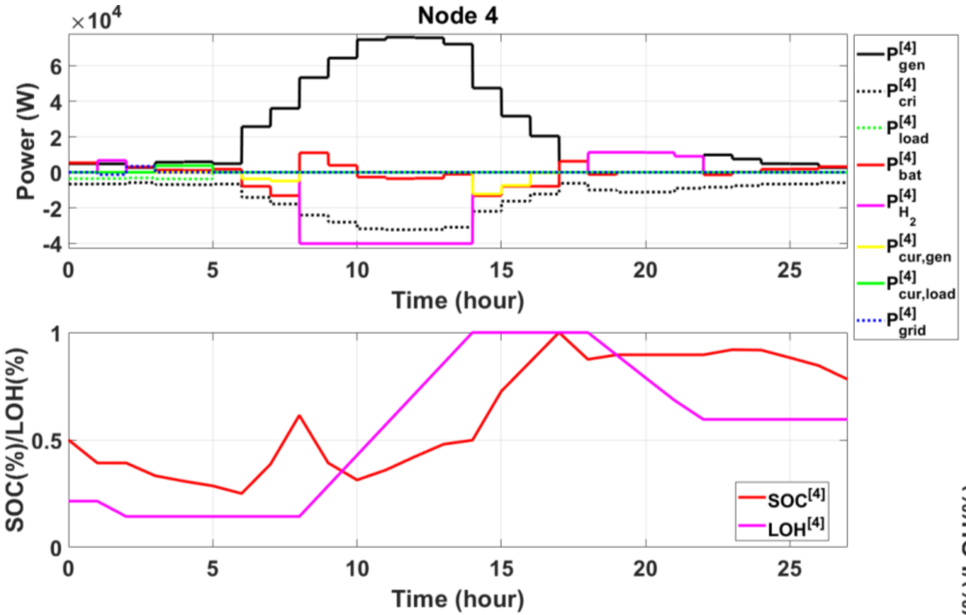
Once the first two hours have elapsed, the system enters resilience mode and feeds only the critical loads. In the following hours, the system will store generated energy in the ESS in order to confront the load requirement when generation is not available.

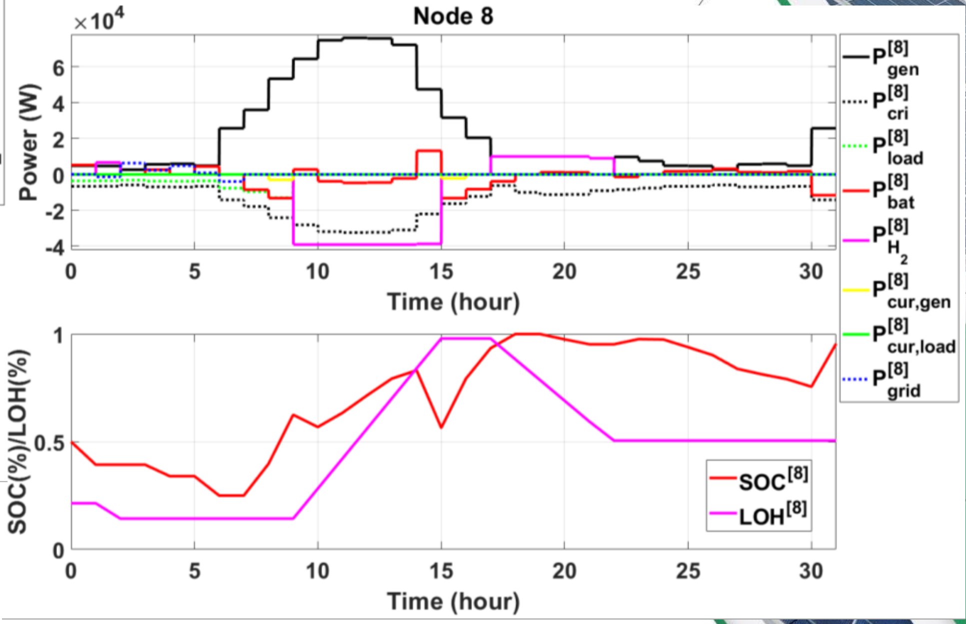
Moreover, if the connection with the grid is interrupted, the microgrid cannot sell the excess of generated energy to the grid and it is consequently necessary to perform a generation curtailment



Results

Now, we can see the result of Resilient block for nodes 4 and 8





Results

In the node 16, the system operates during 15 hours in grid connected mode and from here on, the system experiences a blackout.

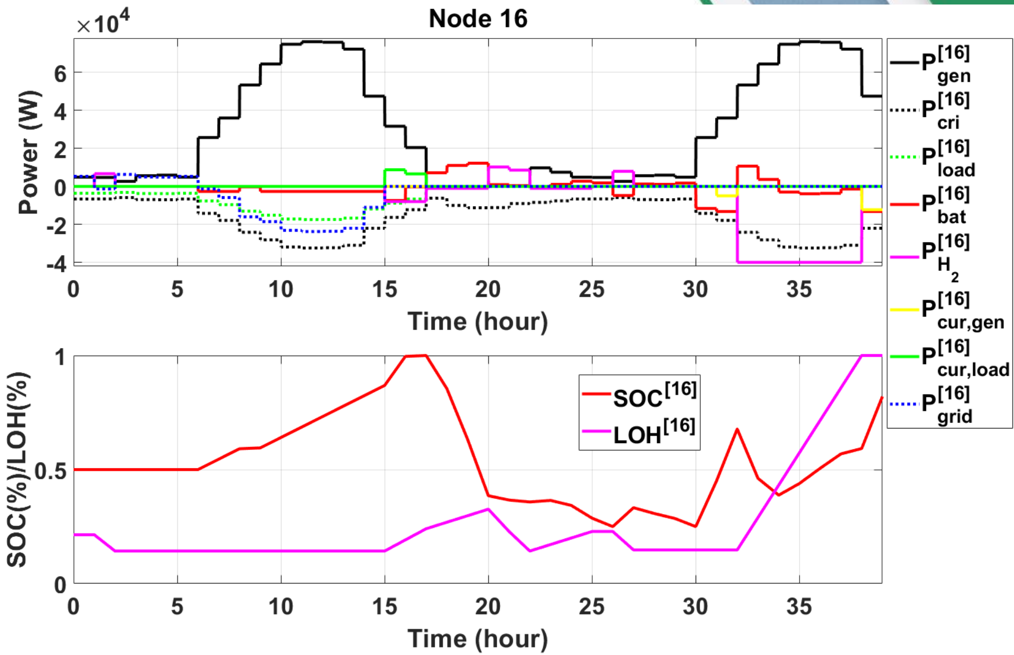
During the first 15 hours, the system buys energy from the grid and uses it to charge the ESS or to feed the loads.

After survivability, the system enters in resilience mode and only feeds the critical loads.

During the following hours, the system will store generated energy into the ESS in order to face the load requirement when generation is not available.

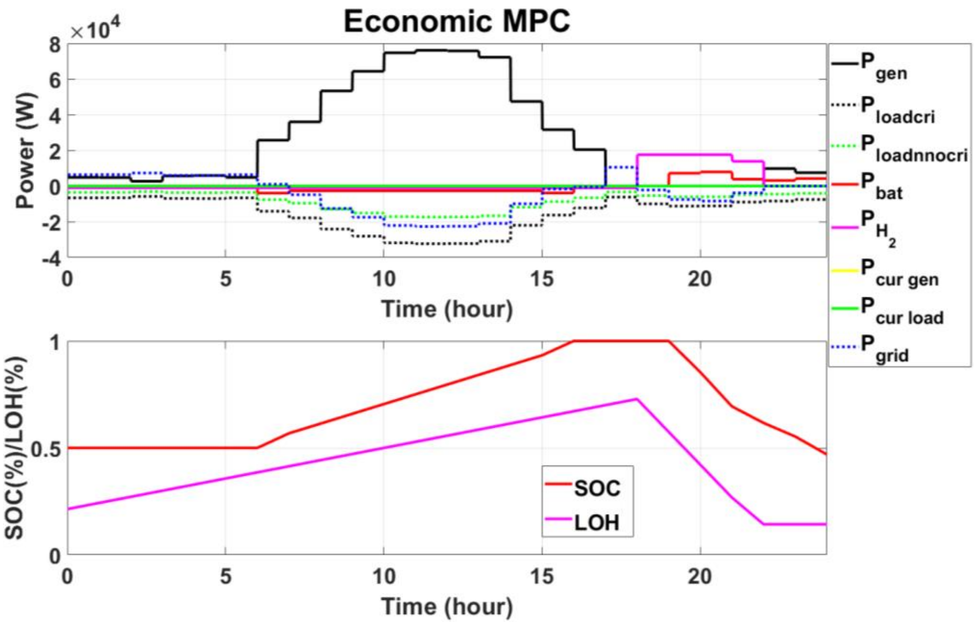
Besides, considering that the connection with the grid is interrupted, the microgrid cannot sell the excess of generated energy to the grid.

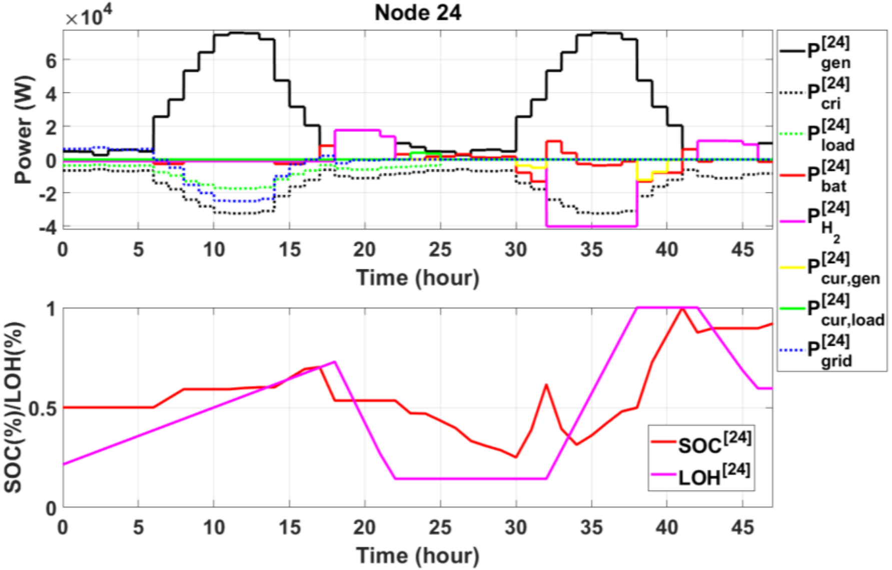
Consequently, it becomes necessary to perform a generation curtailment.



Results

Once the SH=24 scenarios are carried out by the Resilience MPC control block, the Economic MPC block is calculated. In this case, there will be critical and non-critical loads during the whole span of the test.





Conclusions

The numerical results show that the proposed methodology guarantees the supply of electricity to the internal loads of the microgrids after a power outage event in the main power grid at any sample instant without reserving a specific level of stored energy.

The developed control strategy allows to maximize the capacity of each ESS.

In order to improve the flexibility of the microgrid operation in case of a transition from the grid-connected mode to the islanded mode, two levels of resilience are proposed: **criticality and survivability**.

Hour	$LOH_{cri(s)}$	LOH_{min}	$SOC_{cri(s)}$	SOC_{min}
1	24.29%	24.29%	50%	50%
2	27.14%	27.14%	50%	50%
3	30%	30%	50%	50%
4	32.86%	32.86%	50%	50%
5	35.71%	35.71%	50%	50%
6	38.57%	38.57%	50%	50%
7	41.43%	41.43%	56.82%	56.82%
8	44.29%	44.29%	61.38%	61.38%
9	47.14%	47.14%	65.94%	65.94%
10	50%	50%	70.5%	70.5%
11	52.86%	52.86%	75.06%	75.06%
12	55.71%	55.71%	79.62%	79.62%
13	58.57%	58.57%	84.18%	84.18%
14	61.43%	61.43%	88.74%	88.74%
15	64.29%	64.29%	93.3%	93.3%
16	67.14%	67.14%	100%	100%
17	70%	70%	100%	100%
18	72.29%	72.86%	100%	100%
19	57.51%	57.51%	97.84%	100%
20	42.16%	42.16%	85.41%	85.41%
21	26.82%	26.82%	62.91%	69.41%
22	14.3%	14.3%	53.44%	61.88%
23	14.3%	14.3%	47.1%	55.34%
24	14.3%	14.3%	46.93%	46.93%

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