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Control Room Requirements for Voltage Control in Future Power Systems

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Abstract: In future power grids, a large integration of renewable energy sources is foreseen, which will impose serious technical challenges to system operators. To mitigate some of the problems that renewable energy sources may bring, new voltage and frequency control strategies must be developed. Given the expected evolution of technologies and information systems, these new strategies will benefit from increasing system observability and resources controllability, enabling a more efficient grid operation. The ELECTRA IRP project addressed the new challenges that future power systems will face and developed new grid management and control functionalities to overcome the identified problems. This work, implemented in the framework of ELECTRA, presents an innovative functionality for the control room of the cell operator and its application in assistance with the voltage control designed for the Web-of-Cells. The voltage control method developed uses a proactive mode to calculate the set-points to be sent to the flexible resources, each minute, for a following 15-min period. This way, the voltage control method developed is able to mitigate voltage problems that may occur, while, at the same time, contributes to reduce the energy losses. To enable a straightforward utilization of this functionality, a user interface was created for system operators so they can observe the network state and control resources in a forthright manner accordingly.

Keywords: control room; future grids; system operator; voltage control

1. Introduction

The European Union and other countries around the world, concerned with environmental problems, have set a target to decrease greenhouse gas emissions by 20%, compared to the values from 1990, as a main goal for 2020 [1]. Renewable energy sources can definitely help that cause and thus a high integration of those sources in the power system is expected in the near future [2]. Despite representing an important step forward towards sustainability, high levels of renewable energy sources are bringing new technical challenges [3]. The main problems are essentially related with the high unpredictability of this type of resources (wind and solar), which will demand new strategies for real-time energy balancing and voltage control [4]. These new approaches will strongly rely on information and communication technologies, which will also be essential for control room operators. These information and communication technologies -based solutions will increase grid observability and will enable a faster and improved grid management and control [5,6].

The ELECTRA IRP project, financed by the European Commission under the FP7 program, has as main goals to design the future grid architectures that will undergo beyond 2035 and to develop new functionalities for voltage and frequency control to mitigate problems that will arise with the foreseen changes [7]. In ELECTRA, a new concept was developed, the so-called Web-of-Cells (WoC), as the representative grid architecture of the future power systems. The WoC consists of a group of interconnected substructures, the "cells". A cell is defined as a group of loads, generators and Distributed Energy Resources (DERs), within a geographical area, which can integrate different voltage levels [8]. The main characteristic of a cell is that it seeks to use local resources to solve local problems, thus requiring a certain amount of flexibility to counteract unexpected generation or load deviations [9]. The proper operation of the cells together with new mechanisms of close collaboration between them will help to make the future power system more stable and secure. A new set of functionalities were developed in ELECTRA to adapt some of the frequency and voltage control mechanisms that exist nowadays to future power systems, in particular to the WoC concept, and also to develop new ones [10].

The work presented in this paper is solely focused on the visualization of the voltage control mechanisms developed in the project, as well as on the user interface that was created for the cell operators in order to use the voltage control mechanisms in a straightforward manner.

Today's control rooms are composed by multiple monitors, varying with the complexity of the system being monitored, which display different types of information, such as distribution management systems data, networks alarms, e-mails, etc. Operators also have to get in contact with crews and other operators through radio, phone or e-mail and sometimes the procedures end up not being very efficient [11]. With the evolution of distribution networks and its growing complexity, the control room must be redefined or else the risk of operational errors may occur more frequently [12]. In [13], it was identified some sources of operator errors due to the lack of situational awareness and identified some improvements and measures to prevent design errors that provoked problems in past situations.

Given the large amount of grid measurements that are expected to be collected in the future, grid observability potential will increase significantly. Some works have dealt with the increase of renewable energy sources, which increase the complexity of the system and its uncertainty, and made recommendations concerning the way this problem should be treated [14,15]. Thus, advanced grid control rooms will be required to enable system operators to integrate in an efficient manner all the information received from grid equipment, filtering or extracting and visualizing a clear portrayal of the grid state, creating a good situational awareness of the system [16]. The information that appears to the operators must be well detailed, prioritized and presented in a simplified way, so that it facilitates their work in understanding the problems of the network and how to manage them in the best way without disregarding system safety [11]. In the ELECTRA project, this subject was also addressed, and in the view of the WoC concept, the system operator should have the responsibility to supervise a highly automated system, while having some degree of control over the system and intervene when necessary [17].

Considering this, a user interface was specifically developed in ELECTRA for the voltage control. The aim of the user interface is to provide an enhanced grid observability to system operators, so they can have some degree of control over the resources, instead of relying only in automatic Optimal Power Flow-based solutions or local voltage control approaches (e.g., droop control [4,18]).

The structure of the voltage control developed in ELECTRA as well as the detailed operation of the Post-Primary Voltage Control (PPVC) algorithm are explained in Section 2. The user interface for the control room is presented in Section 3. The case studies and results obtained are presented in Section 4. Finally, the conclusions are presented in Section 5.

2. ELECTRA Voltage Control Scheme

Two voltage control functionalities were developed in ELECTRA for the WoC: the Primary Voltage Control (PVC) and the PPVC. The PVC aims at mitigating voltage deviations in the connection point of the device while PPVC restores the voltage to their optimal values minimizing active power losses. The PVC developed for the WoC is based on the utilization of a grid impedance estimation function to calculate the necessary active or reactive power to be injected/absorbed to reduce the difference between actual voltage and the set point value. The PPVC consists in a cell-centralized voltage control method that uses a proactive algorithm, running every 15 min, to calculate the optimal set-points of the flexible resources. As the PVC is an automatic control with no real involvement of the cell operator, this paper is dedicated to the visualization and control of the PPVC resources done by the cell operator from the control room.

The PPVC [19] restores the voltages in the nodes of the cell to the set point values while minimizing the power losses in the cell. It ensures the balance between reactive power flow optimization and robust voltage set-points (within a tolerance band) that do not trigger a new set-point calculation continuously if the set-points are close to the safe band limits. It is based on the execution of an Optimal Power Flow algorithm that provides the set-points for the nodes with automatic voltage restoration capabilities and the status/position for the nodes with discrete control, such as transformers with on-load tap changers, capacitor banks, shifting transformers, or interruptible loads.

The voltage control scheme PPVC defined within ELECTRA has two operation modes: Proactive and Corrective. In the Proactive mode the window-ahead planning operations based on short-term forecasts are included while the Corrective handles the response when reacting to unscheduled events. The Proactive mode has a cyclic operation with windows lengths of 15 min.

On the basis of widespread deployment of advanced metering infrastructure in the cells, e.g., remote terminal units, the information up to the node level is collected and sent to the cell controller in real-time. This goes far beyond current practices, where Distributed System Operators rely only on the voltage measurements registered on the secondary side of the transformer for the distribution grid operation. The Corrective mode is launched if the cell controller detects any voltage out of the safe band. Otherwise, periodically (every 15 min) and automatically, new set-points are calculated and updated in the DERs controllers, directly or via an aggregator. The timeline of the PPVC operation can be seen in Figure 1.

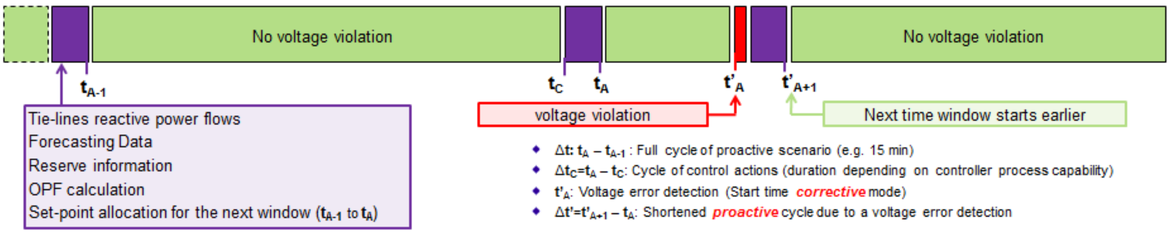

Figure 1. Timeline of PPVC voltage control.

Before the start of the time window comprised between t_{A-1} and t_A (proactive scenario cycle), the Cell Operator has received the data for the optimization of the voltage profile in the nodes for the following window. This includes the information about the availability of the resources and their location, the reactive power flows in the tie-lines that connect the different cells and the generation and load forecasts. Together with the static information about the grid components and topology, the algorithm is executed during the cycle of control actions (purple slots in Figure 1) and at t_{A-1} the set-points are sent to the resources. To find a tradeoff between accuracy and tractability, it has been considered that the sampling interval of the forecasts is 1/60 Hz = 16.7 ms. If there were no abnormal events in the grid, the Proactive operation would continue in 15-min cycles. In case the Cell Monitoring System detects the violation of the voltage at any node (t'_A), it sends a trigger signal to activate the calculation of new optimal set-points because the previous are no longer valid. The underlying principles are, in summary, the same between the Proactive and Corrective operation mode but the need of corrective actions shortens the actual proactive window and makes the following window start before (t'_{A+1} instead of t_{A+1}). In normal operation, the Proactive mode is enough to correct the imbalances coming from generation-load fluctuations and thus, the Corrective mode is only needed in case of unexpected incidents, such as the loss of a line or the failure of a big power plant . The PPVC shows an evolution over the current voltage control schemes. It gives the optimal voltage set-points to the DER units for the next operation time window, in a proactive way, thus facilitating the anticipation to future voltage events. The PPVC reduces the complexity of the traditional voltage schemes developed in three steps (primary/secondary/tertiary) and, as a consequence, improving the system efficiency. In practice, nowadays the implementation of a centralized OPF is still troublesome [3,20]. However, the PPVC could be possible in the 2030+ horizon where ELECTRA IRP focuses, thanks to the advances in grid observability and the rise of the calculation capacities, the communication systems and the data processing algorithms that are constitutive of the WoC [19].

3. User Interface

The user interface plays an essential role in the grid operation and management. The graphical design of the tool needs to be simple and clear to facilitate the systems operators' work. Although its simplicity is an important aspect, it must provide all the relevant information of the system. As emphasized in the introduction, it has to highlight the most critical information and create a good situation awareness for operators responsible for a system that is highly automated, but with some degree of control.

In the user interface developed, the available information is divided into two parts: the global information and the network scheme information (Figure 2) or the detailed information (Figures 3 and 4). The global information is always visible for the operator and represents the information of the cells under the responsibility of the Cell Operator and neighboring cells. The network scheme is visible at the beginning, but it is changed to the detailed information when the operator decides to have an in depth visualization of a given cell. All the information available in the user interface, as well as the actions that system operators can implement are presented in the following subsections.

It is important to notice that the user interface presented intends to be a complete visualization tool for system operators. This is the reason why it contains more information than the one needed for the PPVC (e.g., branches loading information).

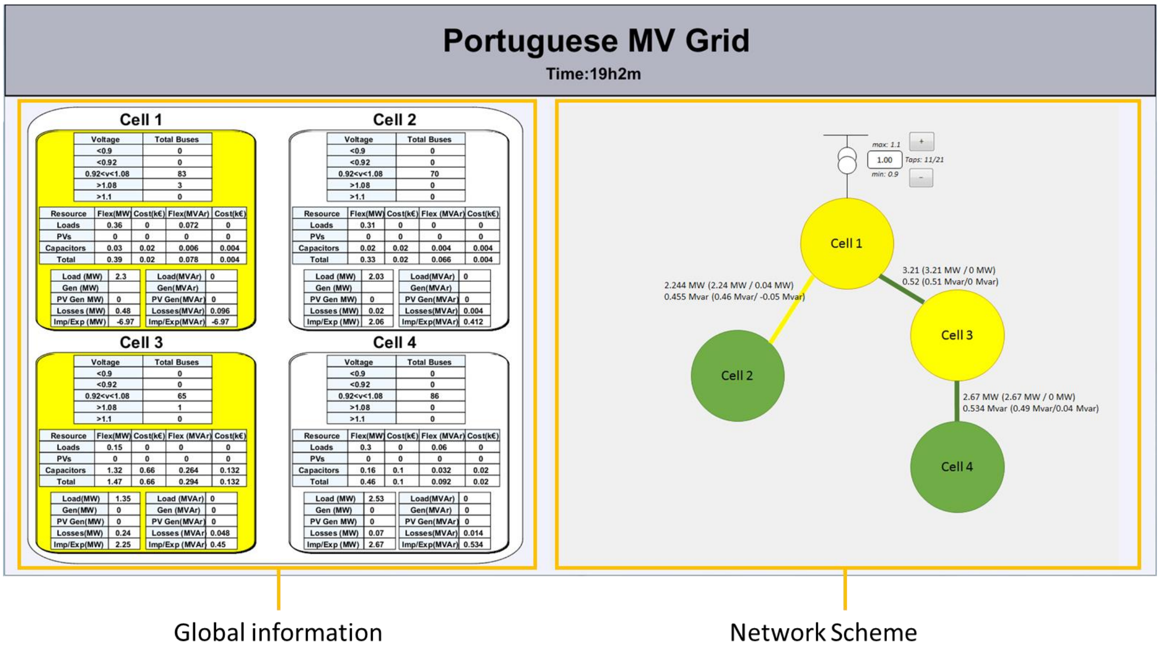

Figure 2. User interface: network scheme.

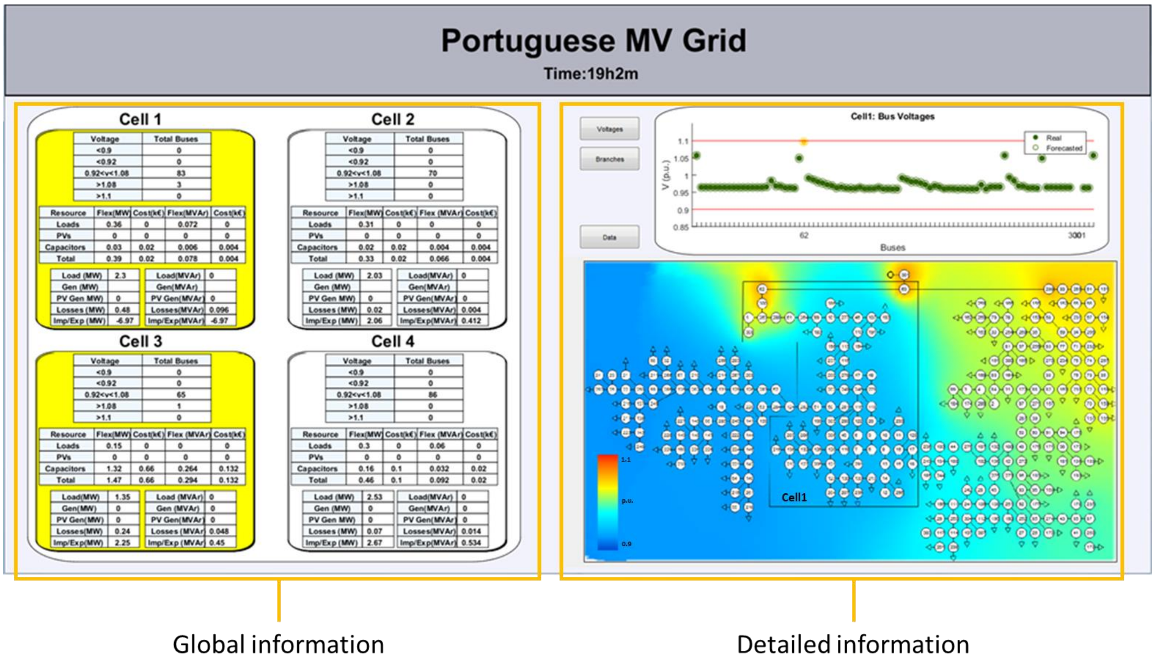

Figure 3. User interface: detailed information with map.

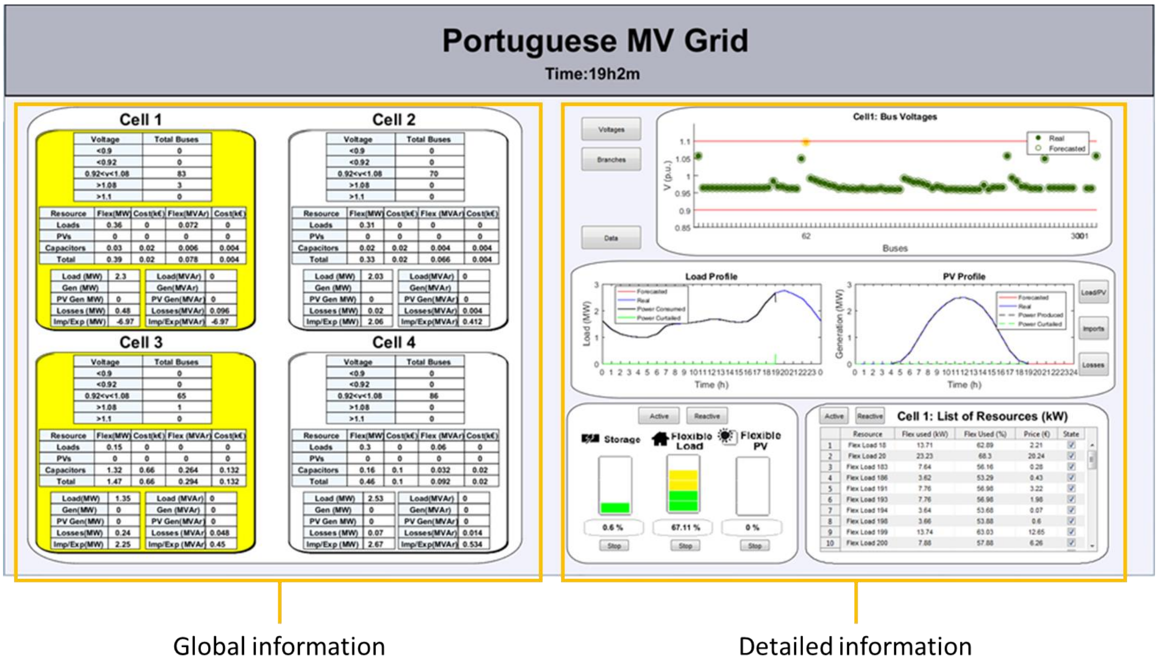

Figure 4. User interface: detailed information with other data.

3.1. Global Information Displayed

As this work is focused on voltage control, the user interface will only display information considered relevant for this type of control and for the grid operation.

For each cell, the information presented is clustered into three groups (Figure 5), detailed in the following subsections.

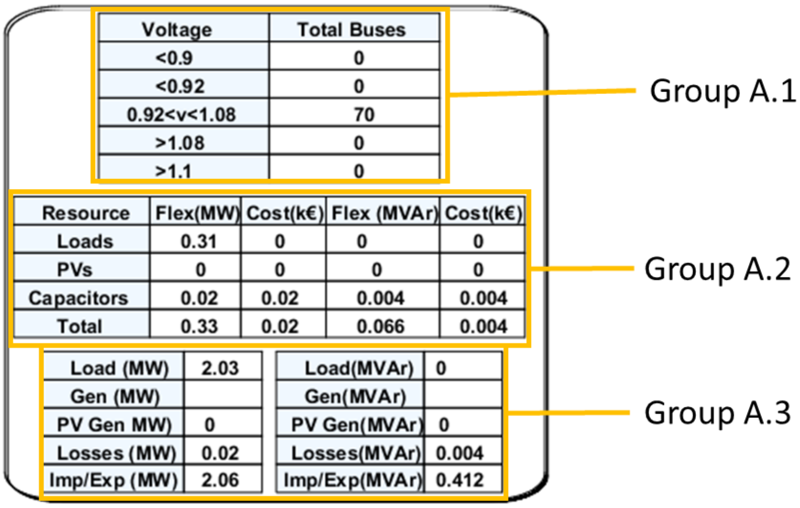

Figure 5. Global information groups.

- Group A.1: Voltage-related information

Table 1 shows the number of buses that are in each range of voltage values presented in the left column. Five ranges were considered:

Table 1. Voltage information.

Voltage	Total Buses (no.)
<0.9	-
<0.92	-
0.92 < V < 1.08	-
>1.08	-
>1.1	-

- In the range (0.92 < V < 1.08), the cell is in "normal situation" and there should not be any cause for concern;
- other two ranges (<0.92 and >1.08), called "abnormal situation", are to show the buses that are within the safe band but close to the limits. This situation is for the operator to be alert that a more serious situation may occur in the following moments;
- two of them (<0.9 and >1.1), called "emergency situation", are to show the buses that already exceeded the voltage predefined limits and, in this case, the PPVC control is triggered. These limits are defined following the standard EN 50160 [21].

- Group A.2: Flexibility provided by the resources and associated cost

Table 2 presents the total flexibility being used by each type of resource (flexible loads, PVs and storage/capacitors) and the costs of the reserves being used. The totals of flexibility are presented in MW for active power and MVAr for reactive power and the costs for providing active power or reactive power are presented in thousands of euros. The section "Capacitors" includes storage systems and capacitors.

Table 2. Resources information.

Resources	Flex (MW)	Cost (k€)	Flex (MVAr)	Cost (k€)
Loads	-	-	-	-
PVs	-	-	-	-
Capacitors	-	-	-	-
Total	-	-	-	-

It is important to notice that other flexible resources, e.g., wind farms, may be added to the visualization tool. The case presented only includes information about the resources available in the network used as test case (see Section 4).

- Group A.3: Global cell information

Table 3 presents the total load, the total generation, the total PV generation, the losses in the cell and the energy imports/exports (positive for imports and negative for exports). All the information is presented in MW.

Table 3. Other information for active power.

Load (MW)	**-**
Gen (MW)	-
PV Gen (MW)	-
Losses (MW)	-
Imp/Exp (MW)	-

Table 4 has the same information as Table 3 but for reactive power resources. All the information is presented in MVAr.

Table 4. Other information for reactive power.

Load (MVAr)	**-**
Gen (MVAr)	-
PV Gen (MVAr)	-
Losses (MVAr)	-
Imp/Exp (MVAr)	-

3.2. Network Scheme

In Figure 6, it is possible to observe the network scheme that is initially visible to the operators. In this scheme, it is possible to see how the cells are connected and the state of the cells and their tie-lines: if the voltages are in the "normal situation", the color will be green; if they are in the "abnormal situation", the color will be yellow; if they are in the "emergency situation", the color will be red. The same principle is applied to the branches. It is also possible to see the active power flow and the reactive power flow in each tie line as well as their scheduled value (the first value in brackets) and the difference between the real and the scheduled power flow (the second value in brackets).

The tap position of the transformer is also visible in a screen right next to the transformer (in p.u.). The operator is able to change the tap position in this scheme by clicking on the buttons "+" or "−". The maximum value possible for the tap in p.u. is presented above screen ("max: 1.1") as well as the minimum value presented below the screen ("min: 0.9"). The actual tap position is presented right next to the tap value screen ("Taps: 11/21"), so that the operator can know how many positions the transformer has.

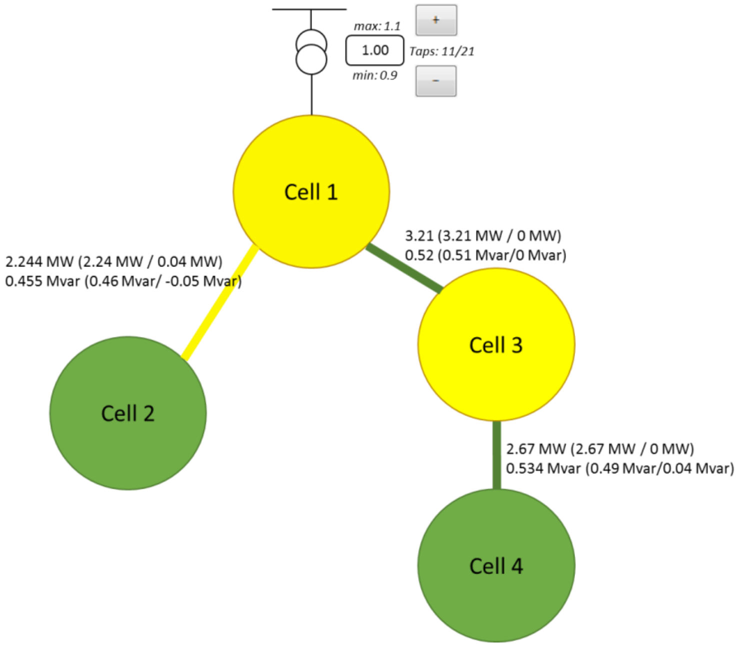

Figure 6. Network scheme visible to operators.

3.3. Detailed Information Displayed

If the operators want to have a better knowledge of a specific cell, they can have access to further information provided in the form of charts. The information that can be accessed for each cell is described in the following subsections. In this case, the information presented is also clustered into five groups. First, the operator can observe the voltage information or branch information in a graphic (group B.1) or in a map (group B.2), as seen in Figure 7. If the operators wants to observe data related with load, PV, imports or losses profiles (group B.3), the individual state (group B.4) or aggregated state of flexible resources (group B.5), he can click in the button "Data", as seen in Figure 8.

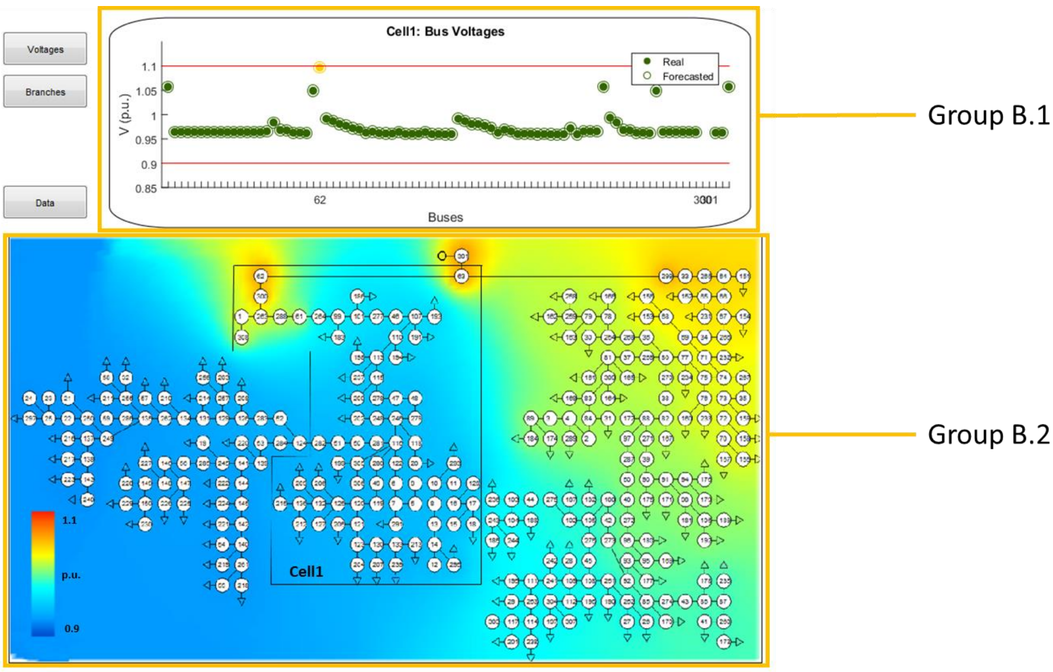

Figure 7. Detailed information groups with map.

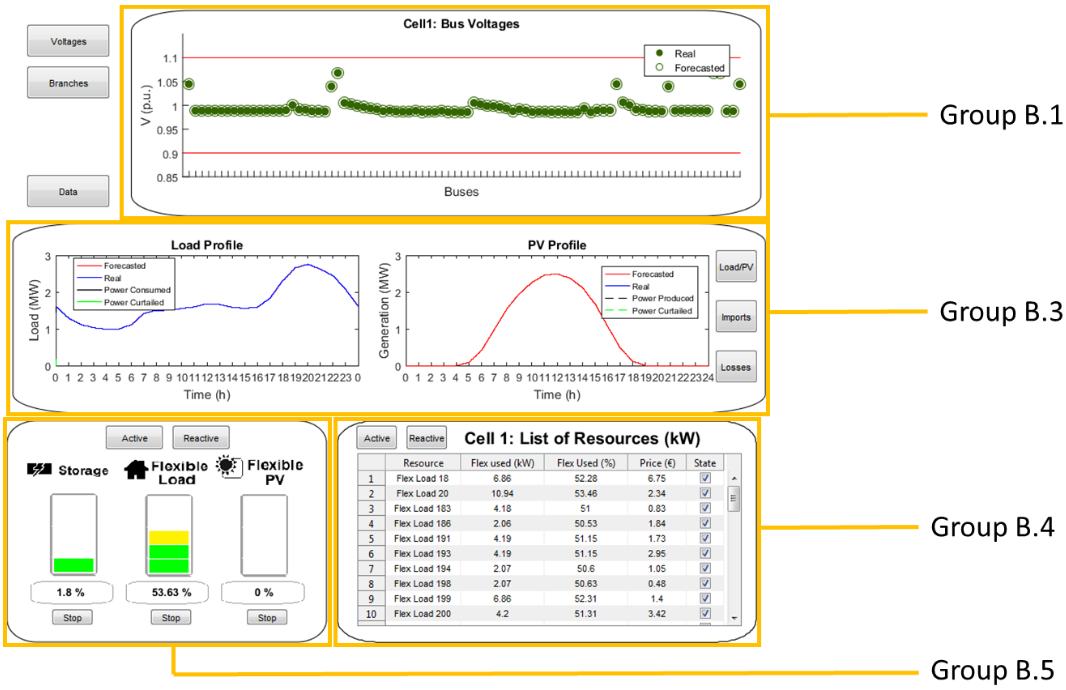

Figure 8. Detailed information groups with other data.

- Group B.1: Buses voltage chart and branches loading chart

This chart presents the voltage in each bus. In case any bus gets in the "abnormal situation" or "emergency situation", its number will appear in the x-axis (Figure 9).

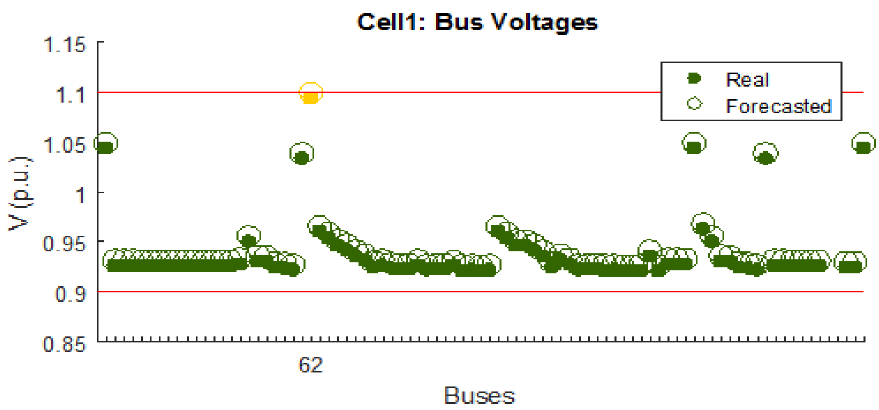

Figure 9. Buses voltage chart.

Figure 10 presents the state of the grid branches in relation to their capacity. If any of the lines gets above 80% of their capacity, they will be identified in the x-axis. This value has been defined by the authors, so that the operator is alerted that the branches are getting closer to their capacity limits, with the aim of avoiding regulatory voltage violations. [21].

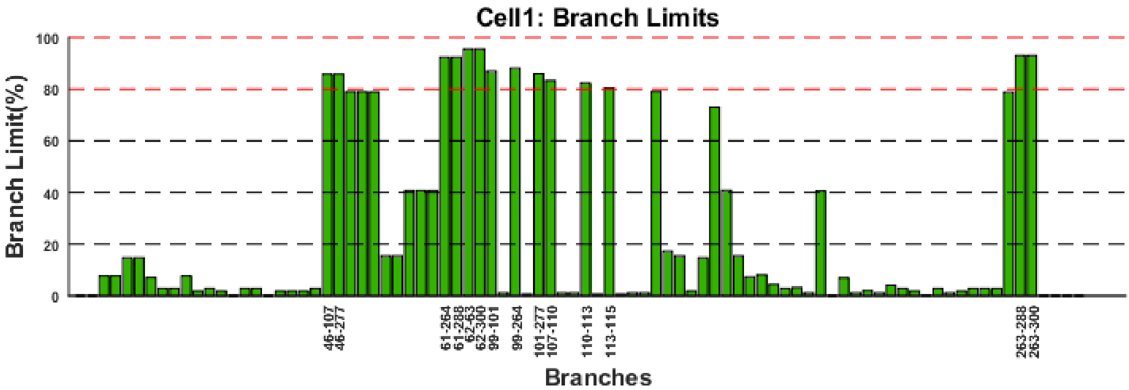

Figure 10. Branches loading chart.

- Group B.2: Buses voltage network map and branches loading network map

Figure 11 presents the map of the network representing the state of the voltages in the buses. A shape within the map will identify the cell selected for visualization. In this example, it is represented Cell 1. The color grading between dark blue and red represent increasing voltage values, from 0.9 to 1.1 p.u.

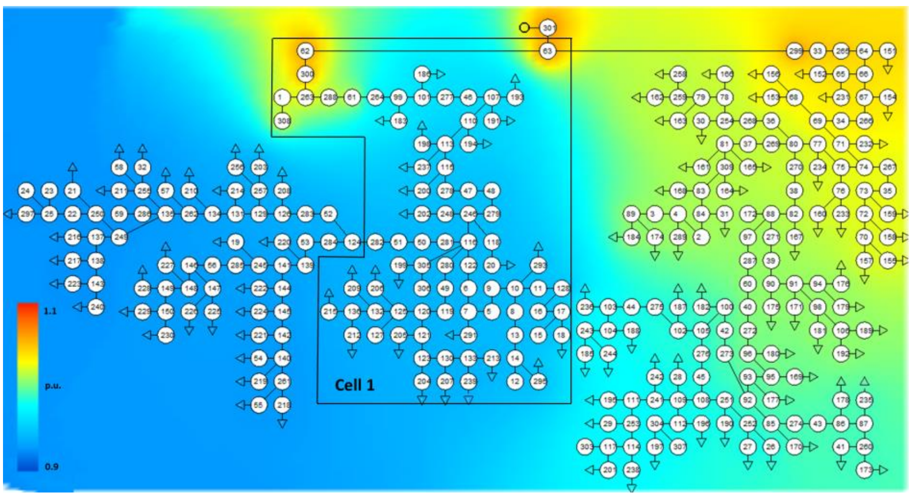

Figure 11. Map with the voltages contour.

Figure 12 also presents a map of the network but now representing the state of the branches. The color grading between dark blue and red represent increasing branches loading values, from 0 to 100%.

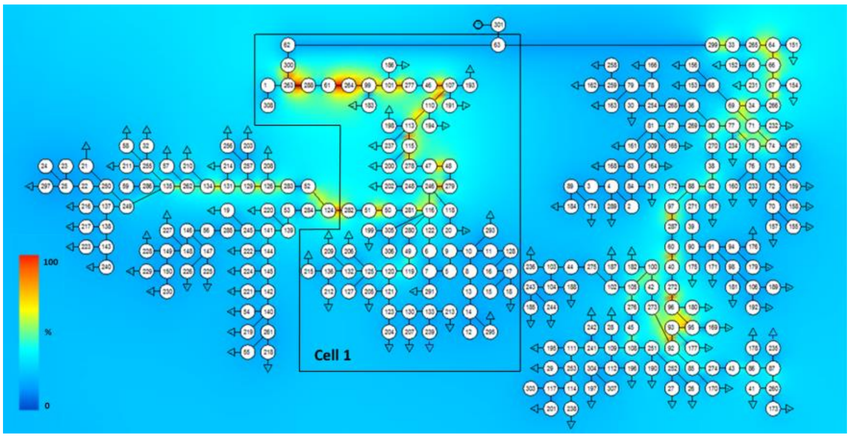

Figure 12. Map with the branches contour.

- Group B.3: Load, PV, import/export profiles and losses

The real load profile is also presented, together with the forecasted profile (Figure 13). This helps the operators understand if there are deviations from the forecasted load or anomalies that may jeopardize system operation. The profile of the flexible loads is also presented to show the amount of load flexibility that is being used in each moment of the day (power curtailed) as well as the power that is being consumed by the loads from the grid (power consumed). In our study, the cell operator receives measurements every minute, but it is possible to adjust the sampling rates (ex. each second).

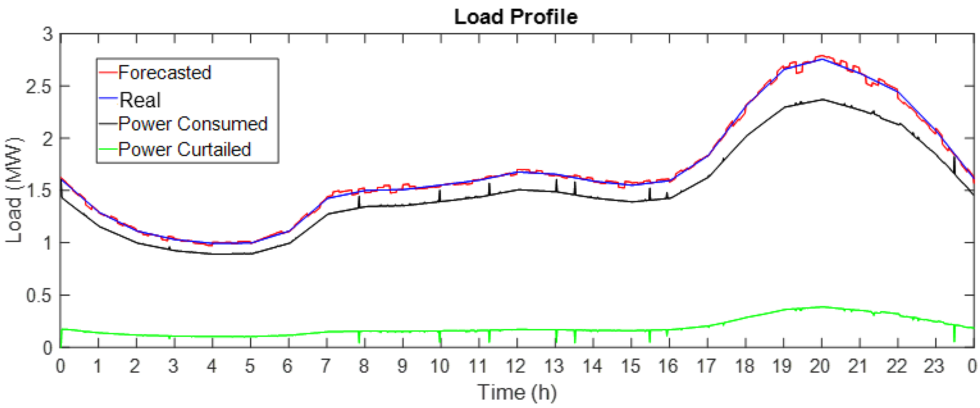

Figure 13. Load profile.

In Figure 14, it is depicted information about the PV profile. It is possible to observe: the forecasted generation, which is the generation forecasted at the beginning of each day and updated each 15 min; the real power is the power that all PV panels are able to produce in the cell; the power produced is the power that is actually being produced by the PV panels and injected into the grid; the power curtailed is the PV power that is flexibility that is not exploited to maintain voltage within the predefined limits.

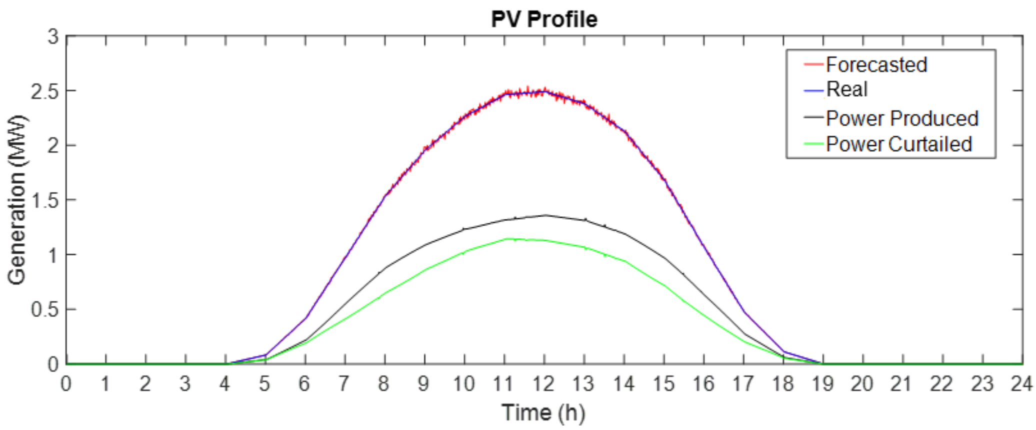

Figure 14. PV profile.

The active power losses profiles calculated for the cell are presented in Figure 15.

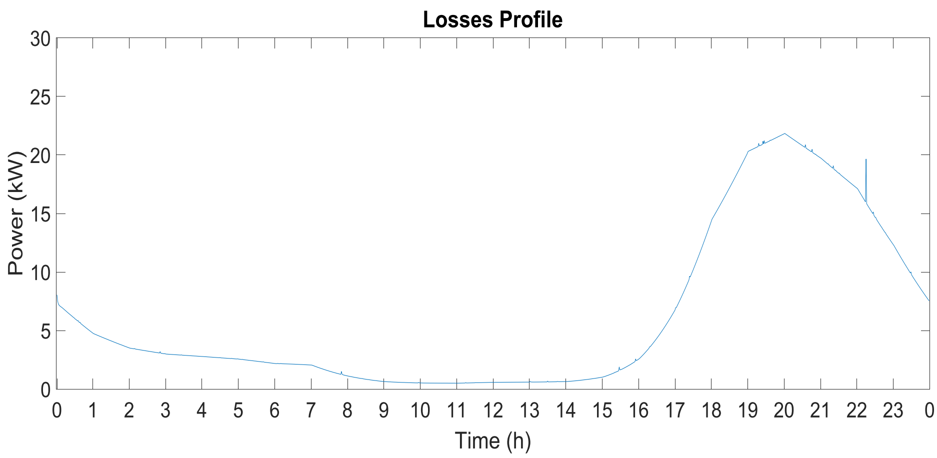

Figure 15. Generator profile.

The profile of the real imports/exports of active and reactive power of the cell with the neighboring cells are shown in Figures 16 and 17, respectively, as well as their forecasted value. If the value is negative, it means that the cell is exporting; otherwise, the cell is importing.

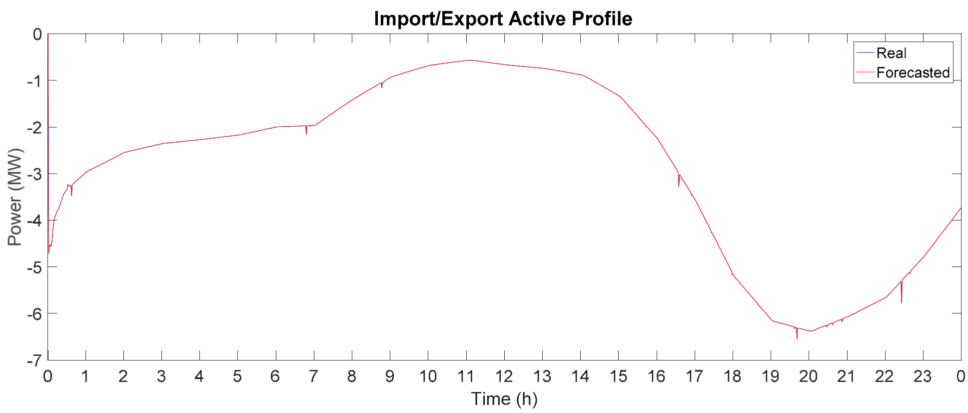

Figure 16. Import/Export active power profile.

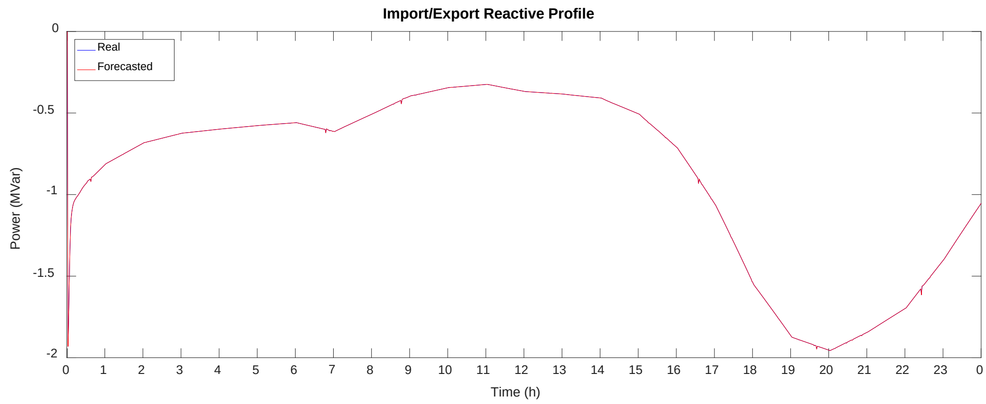

Figure 17. Import/Export reactive power profile.

- Group B.4: State of flexible resources—individual flexibility

The operator is able to visualize the resources related with active power flexibility and reactive power flexibility.

Figure 18 shows a table with information of each resource providing flexibility. The first column is the identification of the resource; the second column is the flexibility being provided by a certain resource in kW; the third column is the flexibility being used in percentage; the fourth column is the cost of the flexibility being provided; the fifth column indicates if the resource is being considered as a flexibility provider or not. The operator can use the fifth column to decide to stop or start using a certain resource.

Cell 1: List of Resources (kW)

	Resource	Flex used (kW)	Flex Used (%)	Price (k€)	State
1	Flex Load 18	13.34	62.2	0.79	☑
2	Flex Load 20	22.58	67.43	15.47	☑
3	Flex Load 183	7.48	55.79	1.97	☑
4	Flex Load 186	3.55	53.09	3.21	☑
5	Flex Load 191	7.58	56.57	7.38	☑
6	Flex Load 193	7.58	56.57	1.24	☑
7	Flex Load 194	3.57	53.46	2.99	☑
8	Flex Load 198	3.58	53.64	0.24	☑
9	Flex Load 199	13.37	62.34	4.91	☑
10	Flex Load 200	7.69	57.42	1.12	☑

Figure 18. Table with the state of active power flexible resources—individual resources.

Figure 19 shows the same information as the one presented in Figure 18 but for the reactive power resources.

Cell 1: List of Resources (kVAr)

	Resource	Flex used (kVAr)	Flex Used (%)	Price (k€)	State
1	Flex PV 18	2.67	55.98	3.66	☑
2	Flex PV 20	4.52	60.69	12.35	☑
3	Flex PV 183	1.5	50.21	1.32	☑
4	Flex PV 186	0.71	47.78	1.76	☑
5	Flex PV 191	1.52	50.91	1.81	☑
6	Flex PV 193	1.52	50.91	0.92	☑
7	Flex PV 194	0.71	48.11	2.11	☑
8	Flex PV 198	0.72	48.28	2.65	☑
9	Flex PV 199	2.67	56.1	3.1	☑
10	Flex PV 200	1.54	51.68	2.63	☑

Figure 19. Table with the state of reactive power flexible resources—individual resources.

- Group B.5: State of flexible resources—aggregated per type of resource

The operator is again able to visualize the resources related with active power flexibility and reactive power flexibility. In Figure 20 it is possible to observe the state of the flexible resources in the grid that provide active power flexibility. If the actual capacity of the flexible resources is between 0% and 40%, the color will be green; if the capacity is between 40% and 80%, the color will be yellow; if the capacity is above 80% the color will be red. The "Stop" button can be used by system operators to curtail the flexibility provided by some type of resource. Further details about the utilization of flexible resources will be provided in Section 3.3.

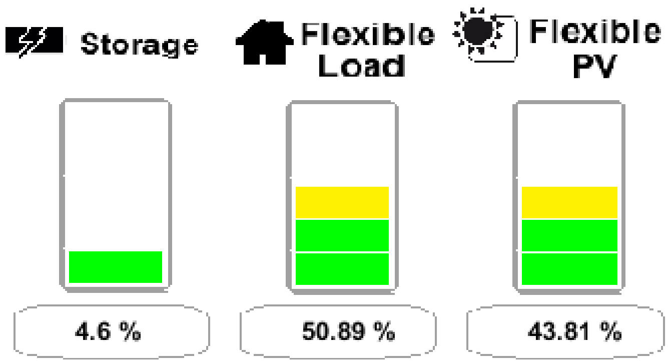

Figure 20. State of active flexible resources—aggregated per type of resource.

In Figure 21 it is possible to observe the same information as in Figure 20, but for the resources providing reactive power flexibility.

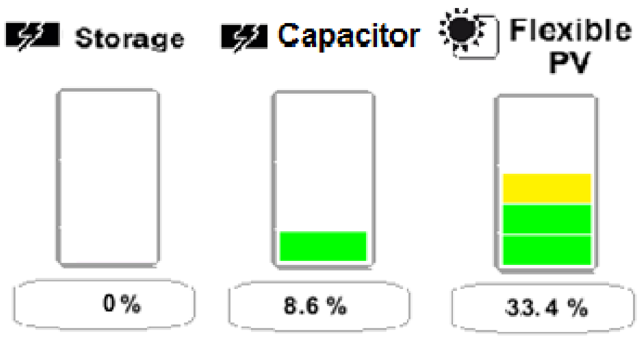

Figure 21. State of reactive flexible resources—aggregated per type of resource.

3.4. Possible Actions Implemented by System Operators through the User Interface

The first action that operators can take is to choose if they want to see more information about one cell. To do this, they just have to click on the cell they want to see. As an example, Figure 2 has four cells: if the operator clicks on cell 4, more information about this cell will appear in the right ("Detailed information").

In the "Detailed information" window, a chart of the voltages is presented by default as well as its contour map. The power flows in the branches can also be visualized. For this, the operator has to click on the "Branches" button. The operator can also decide to visualize other data and for that, he can click in the button "Data". As previously explained, different type of data is now available to the operator. Initially, the load and PV profiles are presented, but he can change to the active and reactive power profiles or to the losses profile. The individual and aggregated state of resources will also appear and by default, only the resources providing active power will be shown. Nonetheless, the operator is also able to visualize the resources providing reactive power.

As previously explained, the tool developed has been oriented to the visualization and if needed, manual operation of the PPVC algorithm. When a problem occurs, the operator has the possibility to change manually the tap position of the transformer. If changing the tap position does not solve the problem or if the operator decides that he should not change the actual operation of the transformer, the PPVC algorithm will be run. This algorithm provides a feasible solution for the system in the form of set-points that will be sent to the flexible resources. The algorithm's objective is to minimize active power losses in the cell. The limits to the voltages in the buses and power flows in the branches are constraints of the problem. Through this user interface, the operators have the opportunity to modify the initial solution and they can decide if some specific resource (individual or aggregated) should be or not activated. In case the operator interferes with the solution found, the PPVC algorithm will find a new feasible solution taking into account the resources utilization restrictions imposed by the operator. If the algorithm is unable to find a new feasible solution, a warning is displayed and the operator will be informed that the algorithm will override its restrictions. To stop using the flexibility provided by a certain resource, the operator has to check the "State" column of the table presented in Figures 18 and 19. To stop using all the resources of one kind (flexible load, PV, storage or capacitors), the operator has to click on the "Stop" button below the selected resources, as shown in Figures 20 and 21. The actions that the operators can implement for the user interface are summarized in the following bullets:

- Change the tap position of the transformer;
- Visualize detailed information about a specific cell;
- Visualize the voltages in the buses or the power flows in the branches;
- Stop or start the utilization of the flexibility provided by an individual resource;
- Stop or start the utilization of the flexibility provided by an aggregated set of resources (flexible load, PV or storage).

4. Simulation Results

4.1. Case Studies

The network used in this study to test the voltage controls developed is a typical MV grid from a rural area in Portugal (15 kV) (Figure 22) that was later divided into four cells. This division was made taking into account the criteria established by the WoC concept, as previously explained, which states that each cell should have enough flexibility to solve local problems using local resources. The specified voltage in the feeding point is 1.05 p.u. Each cell is composed by one storage system and several loads and PV generators; Cell 1 and 4 also have a capacitor. The resources that are able to provide active power flexibility are storage systems, flexible loads and PV generators; the resources that are able to provide reactive power flexibility are the storage systems, capacitors and PV generators. In these case studies, it was assumed that storage systems did not provide any reactive power. The total flexibility that the loads are able to provide is 20% of the power consumed, and in the case of the PV generators, it is 100% of the power generated. The storage systems are also able to provide flexibility, as they are owned and managed by the cell operator. Some additional details about the cells are presented in Table 5.

Table 5. Network resources.

Resource	Cell 1	Cell 2	Cell 3	Cell 4
No. loads	23	29	27	33
No. generators	23	29	27	33
No. storage	1	1	1	1
No. Capacitors	1	0	0	1
Peak load (MW)	2.76	3.44	1.55	2.93
Peak generation (MW)	2.49	2.19	1.4	2.65
Storage capacity (MW)	5	5	5	5
Capacitor capacity (MVAr)	2	0	0	2

The results were obtained using the Matpower OPF algorithm in Matlab. It was used a typical daily load diagram for this network as well as a typical PV generation diagram.

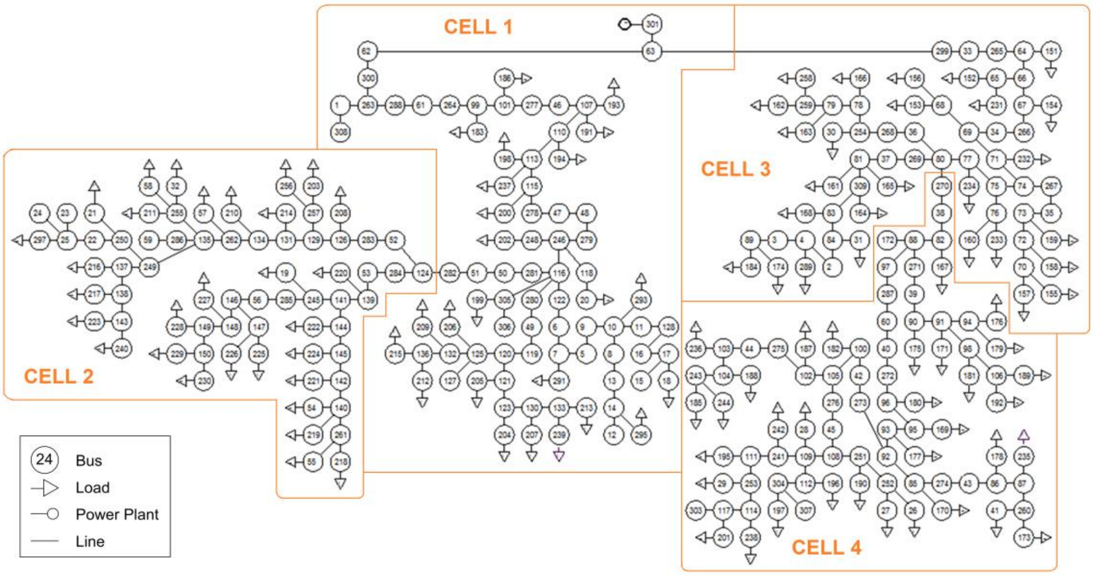

Figure 22. MV grid with four cells.

In order to test the algorithm developed for voltage control, three case studies were created:

- *Case study 0*: This is the base case where no voltage control mechanism is implemented in the network. The purpose is solely to serve as basis of comparison with the remaining scenarios.
- *Case study 1*: The voltage control algorithm developed, with the corrective and proactive controls, is assumed to be active in the network.
- *Case study 2*: The voltage control approach is the same as in case study 1. The difference is that a big forecast error is assumed to exist in the time step between 21h00 and 21h10. The forecast error is a 50% increase of the load in cell 2 in those instants and its purpose is to simulate a situation that triggers the corrective control or makes the operator change the tap position. In this case, the operator will only change the tap position and the corrective mode of the PPVC will not be used.
- *Case study 3*: Same situation as case 2, but now the operator will not change the tap position and the corrective mode of the PPVC will be triggered.

4.2. Results

The most important results obtained for each case study are presented in this section. As this work is focused on the visualization of a voltage control method in a control room of a cell operator, it is important to know the state of the voltages in the buses and to check if any limit is exceeded. As the objective of the voltage control algorithm is the minimization of power losses, the profile of the total losses is also presented, together with the flexibility used by the loads and PV generators during the day. As results are similar for all cells, only cell 2 results are presented, with the aim of balancing the clearness and the level of detail. The graphics presented in this section are for validation purposes and they are not included in the user interface for system operators described above.

- Voltages
  - Case 0

In Figure 23, it is possible to observe the voltages in some of the buses of case study 0. The voltages exceed the predefined limits during the night. From hour 17 to hour 0, the voltages in some buses fall below 0.9. The problem is not solved because no voltage control strategy is implemented.

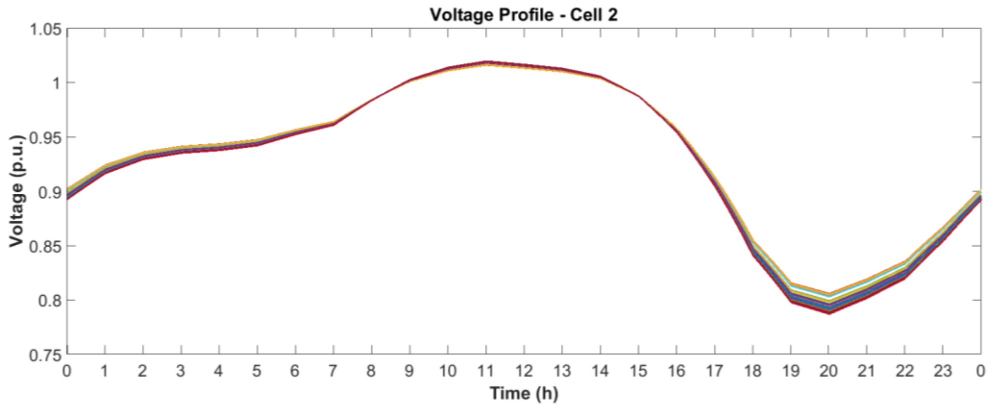

Figure 23. Voltage profile of cell 2 for case 0.

- Case 1

In Figure 24, it is possible to observe that with the voltage control implemented, using the proactive scenario at each 15 min, there are no voltage problems. This means that the voltage control implemented succeeds in controlling the voltages.

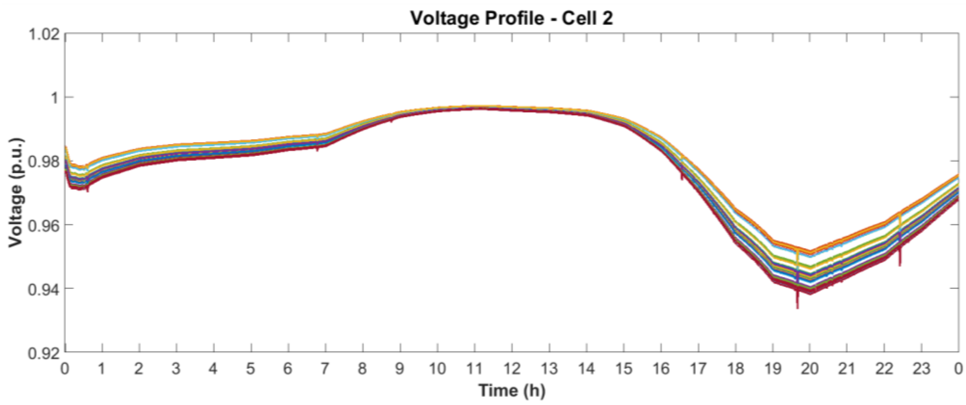

Figure 24. Voltage profile of cell 2 for case 1.

- Case 2

In Figure 25, it is possible to observe a sudden voltage decrease due to a big load forecast error. This error lead voltage below 0.9 p.u. Nonetheless, by increasing the tap position by one step, the problem is rectified and it does not occur again.

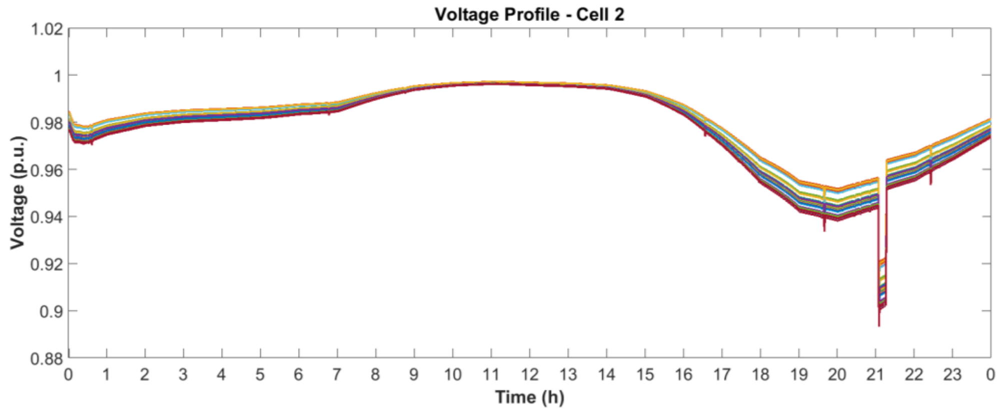

Figure 25. Voltage profile of cell 2 for case 2.

In Figure 26, it is also possible to observe how the operator could visualize the tool when the error occurred. As can be seen by the central message, the operator has the possibility to choose between modifying the taps of the transformer or the corrective mode.

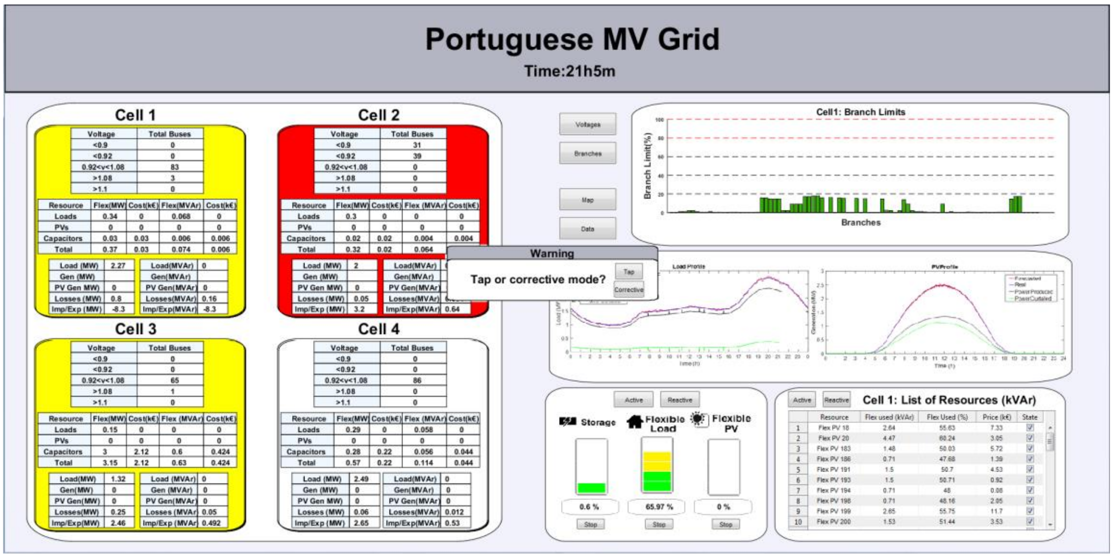

Figure 26. Visualization of the tool when the problem occurs.

○ Case 3

In Figure 27, it is also possible to observe a sudden voltage. In this case, the corrective mode is used and it is able to rectify this deviation.

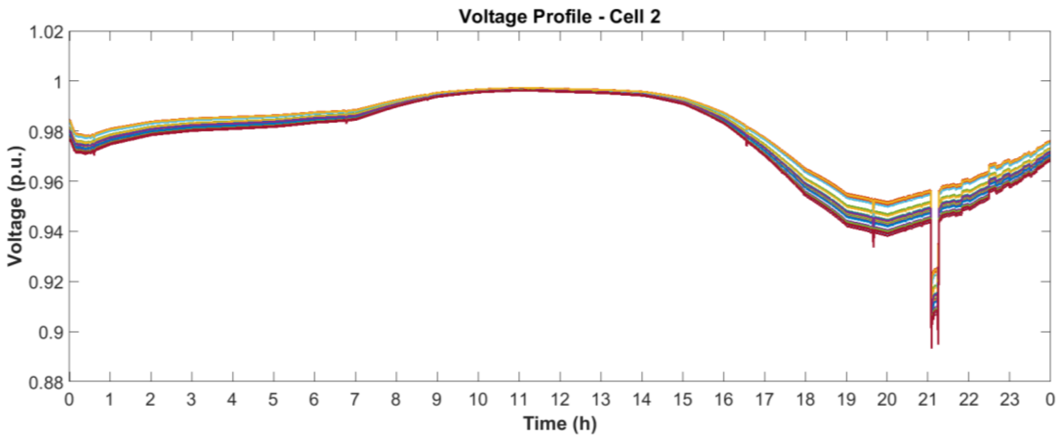

Figure 27. Voltage profile of cell 2 for case 3.

○ Case comparison

It is possible to observe in Figure 28, the decrease in the voltage in the cases 2 and 3 due to the occurrence of the problem. In both cases the voltage was corrected but, in case 2, as the tap position was increased, the voltage after the occurrence of the problem is higher than the case 3, when the corrective mode is used.

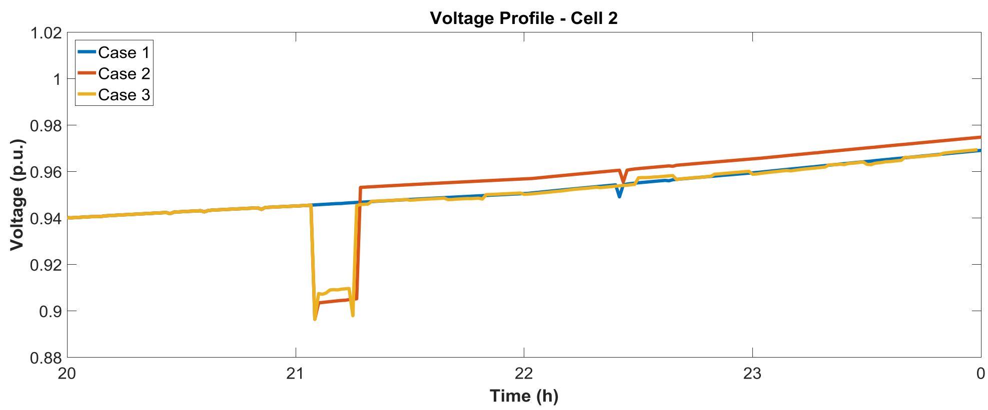

Figure 28. Zoom to the voltage profile of cell 2 (bus 134) for case 1, 2 and 3.

- Losses

In Figure 29, it is represented the sum of the losses profile during the day for each case. In case 0, the losses are higher than in the other cases. The objective of the algorithm implemented in case 1, 2 and 3 is to minimize losses and that is why the losses decrease in those cases. Between 9 and 14 h, the losses are almost zero due to the PV generators, whose generation is enough to feed the loads. Thus, power flows in the lines are minimal, generating few energy losses.

After hour 16, the losses increase because PV generation decreases and demand increases. In case 2 and 3, there is an increase in the losses due to the difference between the forecasted load and the real load. In cases 1, 2 and 3, although the losses increase after 16 h, they are lower than in case 0. Case 2, has the highest losses value, due to the manner the problem was corrected when it occurred.

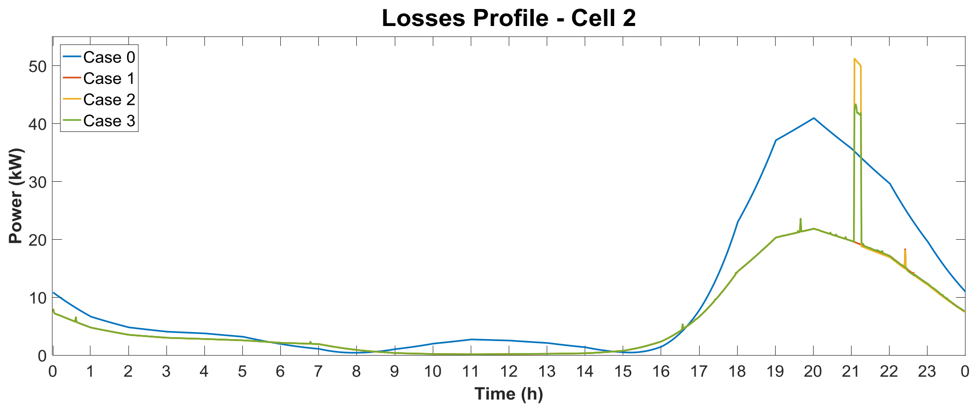

Figure 29. Losses profile of cell 2.

In Figure 30, a comparison of the sum of the losses for the three study cases is presented. It can be seen that the losses are lower in case 1 compared with the base case (Case 0) due to the increase of voltages in the grid as a consequence of the PPVC; in case 2 and 3, they have a small increase comparing with case 1, due to the load forecast error; case 3 has lower losses than case 2, due to the manner the problem was rectified

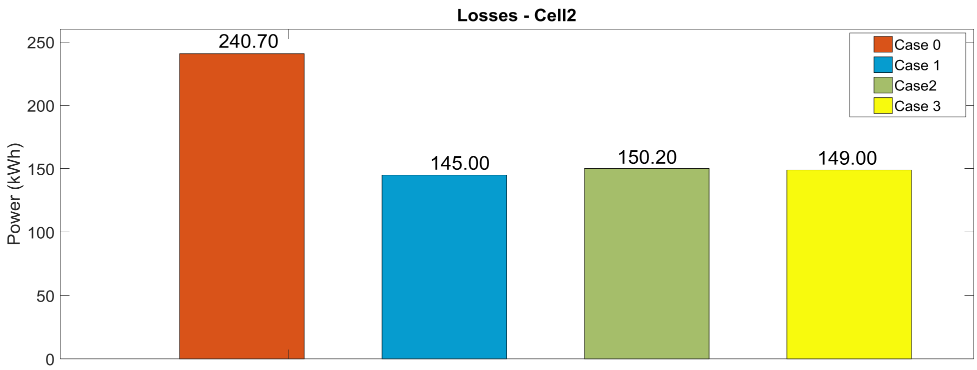

Figure 30. Total losses of cell 2.

- Load and PV Generation curtailment

In Figure 31, it is possible to observe the PV generation curtailed in cases 1, 2 and 3 (it is the same in all cases). Part of the PV generation must be shed because otherwise the generation surpasses the load. Case 0 is not represented in the figure because there is no voltage control algorithm implemented and so, there is no PV generation shed. The excess power generated by PV is exported to other networks.

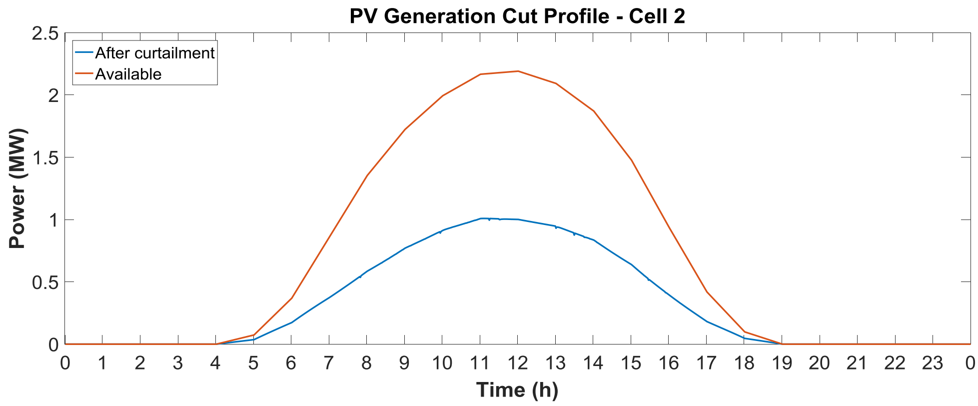

Figure 31. PV generation curtailed in cell 2.

In Figure 32, it is possible to observe that the load flexibility is used during all day and it is very similar for cases 1, 2 and 3 until hour 21. Case 1 and case 2 have the same set-points, because the operator only used the option of changing the tap positon of the transformer and it was not needed to change the flexible load set-points. In case 3, it was used the corrective mode of the PPVC and thus, the flexible load set-points were changed.

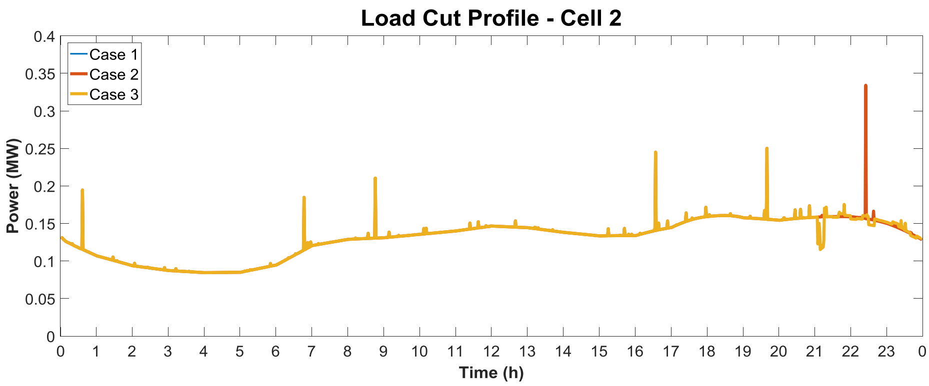

Figure 32. Load flexibility utilization in cell 2.

5. Conclusions

In this work the integration of the new voltage control algorithm, developed under the ELECTRA framework, in an operating tool for the cell operators has been developed. The work is part of the ELECTRA IRP project, which aims at developing new frequency and voltage functions considering the expected DER integration in power systems from 2035 on. The voltage control method developed runs a proactive algorithm each 15 min to calculate the optimal set-points of the reserves and a corrective mechanism to overcome unexpected grid events.

Before the implementation of the method, several voltage problems were detected during the simulations. After implementing the voltage control algorithm, no problems are detected, proving the efficacy of the method. Moreover, it is possible to observe a significant reduction in the system losses (ca. 60%). The algorithm has been also tested when there is a big error in the forecasts. Due to this error, the voltages in some buses surpasses the admissible limits. When this error occurs, two methods can be used: changing the tap positions of the transformers or using the corrective mode. Both methods are able to solve all the detected voltage problems. The difference between the two methods are that when the corrective mode is used, the voltage values are lower as well as the losses.

This method has been integrated in an operating and visualization tool developed in order to enhance grid observability and provide all the relevant data in a friendly way to the cell operators.

It also allows system operators to control some of the flexible resources in the grid in case they do not want to use them, becoming a perfect complement to visualize the voltage control strategy in the WoC and to manage cells in an effective way. The algorithm developed only focus on minimization of losses, but by being integrated in this operating tool, it is possible for operators to take into account the costs of the actual operation of the system. As operators have the ability to stop resources that are activated, they can decrease operational costs and assure that the network is operated in a safe mode. However, as shown by the results obtained from the test cases, different actions taken by operators will lead to different operating conditions of the network and available resources.

Author Contributions: A.C. implemented the PPVC control in Matlab, developed the user interface for system operators also in Matlab and contributed to the several chapters in the paper. F.S. and J.P.L. contributed for the user interface development, for the analysis of results and in the refinement of the text. J.M. conceived the PPVC control scheme and has collaborated writing the parts related with the voltage control as well as in the analysis of the results. S.R. participated in the alignment of the visualization design with the PPVC requisites and the refinement of the text.

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