# Primary Frequency Control in Future Power Systems

## The ELECTRA Project Approach under the Web-of-Cells Concept

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***Abstract*—This paper presents a new approach for primary frequency control in interconnected power systems. This new approach is built upon the traditional control, but explores the capabilities that future network components may have, like faster communications and improved computing capacity. Specific control functions were developed aiming at solving frequency deviation problems generated in a control area by using locally available resources. The work presented in this paper is integrated in the FP7 ELECTRA project, where a new power system architecture – the Web-of-Cells concept – is being developed, together with innovative management and control functionalities to explore the full potential of distributed energy resources.**

***Keywords—Primary Frequency Control, Frequency Containment Control, Power-Frequency Characteristic, Web-of-cells***

## I. Introduction

Future power systems are expected to be significantly different from todays' reality. The main drivers for this change are European Union's goals to reduce the $CO_2$ emissions and to increase the integration of Distributed Generation (DG) based on Renewable Energy Sources (RES) [1]. As the integration of RES increases, the traditional centralized generation will become less frequent imposing more complexity to the operation of power systems. Additionally, DG has frequently a high variability that drives the need to forecast its day-ahead production in order to operate the system in a secure manner.

These problems are being addressed in the FP7 ELECTRA project, whose main goal is to foresee the changes that electric power systems will undergo, anticipate the problems that may arise from and find solutions to mitigate them [2].

This work, integrated in the FP7 ELECTRA project, presents a new approach for primary frequency control in future power systems that aims at solving frequency deviation problems generated in a control area by using locally available resources. The main objective of the project is to develop enhanced functionalities for balancing and voltage control purposes, considering the real time operation of the power systems of 2030 and beyond.

The control functions that have been developed will be presented as discussed in the paper, together with the results obtained from their implementation in a test system.

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## II. The Web-of-Cells Concept

The main concept underlying the ELECTRA project is the Web-Of-Cells (WOC). The WOC is an innovative conceptual framework where power systems are composed of a set of interconnected cells with the purpose of making the whole system stable and secure. A cell is defined as a group of loads, generators and Distributed Energy Resources (DER), within a geographical area, and with a control center that always seeks to solve balance and voltage problems locally, using local resources [3]. In order to achieve this purpose, a cell must aggregate sufficient flexibility among its resources. In the cases where a cell does not have enough resources to solve the problem locally, it will have temporary support from neighbor cells [4]. The cells can be integrated in different voltage levels and the operator of each cell is called Cell Operator (CO). An example of a WOC power system is presented in Fig. 1.

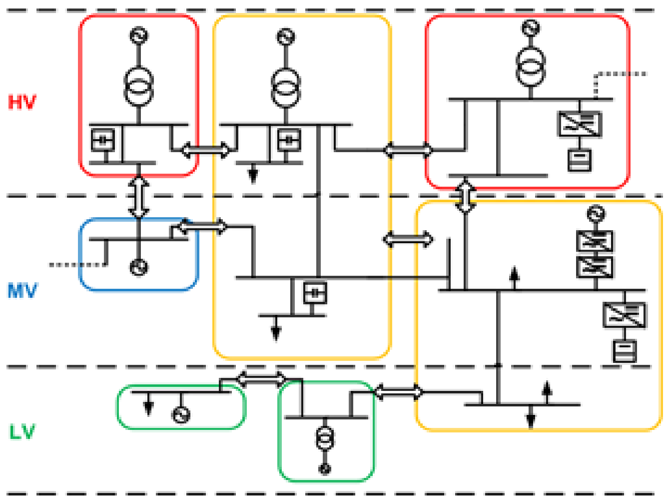


Fig. 1 – Example of a Web-of-Cells power system [3]

### A. *Balance Control in the Web-of-Cells*

The purpose of balance control (or frequency control) is to keep the frequency within admissible limits when an imbalance between load and generation occurs. If a disturbance occurs, the frequency will suffer a deviation and the balance control functions will be activated in a hierarchical way.

In current power systems that control is made at three levels:

- Primary Frequency Control - when a frequency deviation occurs, the primary control is the first to react to that deviation in order to avoid the frequency to go beyond the predefined limit;
- Secondary Frequency Control - activated afterwards, usually 1-5 s after the disturbance, aiming at restoring the frequency and tie-lines power flows to their scheduled values;
- Tertiary Frequency Control - the tertiary control is activated in order to relieve the secondary control for other needs.

Within this conceptual framework, different grid codes have been developed, where it is foreseen the possibility of some DG to actively participate on the provision of some control reserves [5]. However, nowadays the reserves provision comes essentially from synchronous generators.

In ELECTRA, the balance control is performed using four control functions: Inertia Response Power Control (IRPC), Frequency Containment Control (FCC), Balance Restoration Control (BRC) and Balancing Steering Control (BSC). The last three functions are equivalent to the primary frequency control, secondary frequency control and tertiary frequency control, respectively, but with some adaptations to fit the WOC purposes.

Nowadays, power systems can rely on traditional generators for the provision of inertia, which is intrinsic to those machines. However, the majority of the generators are likely to be replaced by DG in the future and these new resources do not provide inertia. This would create problems to the system stability, as it is already being observed in grids with a large integration of DG [6]. To counteract this problem, the solution being considered in ELECTRA is the development of the IRPC function, which will emulate inertia in DG units, particularly on those connected to the grid through power electronic interfaces. In addition to DG units, resources like storage devices can also provide synthetic inertia to the grid [7].

Within this overall concept, the work presented in this paper is focused on the FCC. The control functions developed for this purpose will be presented together with the results obtained from their implementation in a test system. A comparison between the FCC performance and todays' traditional primary frequency control will also be made.

## III. Primary Frequency Control in Current Power Systems

This section presents an overview of the primary frequency control that exists nowadays in electric power systems. The objective of primary control, as previously mentioned, is to contain the frequency deviation within admissible limits when an imbalance problem occurs.

Interconnected power systems have usually several control areas and each one has a responsible Transmission System Operator (TSO). As frequency is a global variable, all the TSOs must combine efforts to maintain it close to the predefined value. Thus, it is necessary to calculate the power that a certain control area needs to autonomously provide in order to solve the global power-frequency control problem. This is typically done by using the concept of Network Power Frequency Characteristic (NPFC).

The TSO of each control area is responsible for assuring that there is sufficient reserve to respond to the problem according to the NPFC defined. The resources that participate in this control are automatically activated and respond to frequency deviations according to the droop control implemented at each unit level. Further details about the droop control are provided in subsection III B.

### *A. Network Power Frequency Characteristic*

The NPFC ($\lambda_u$) defines the sensitivity of a synchronous system to the impairment between scheduled and actual frequency and the energy that is needed to correct that deviation. This value is defined annually by ENTSO-E and is calculated with the following equation [8]:

$$\lambda_u = \frac{\Delta P_u}{\Delta f} \text{ [MW/Hz]} \tag{1}$$

Where:

- $\Delta P_u$ – variation in power causing a disturbance [MW];
- $\Delta f$ – quasi-steady-state frequency deviation in response to a disturbance [Hz].

In ENTSO-E, the reference incident $\Delta P_u$ is considered to be 3000MW, based on the simultaneous loss of two nuclear power plants, and the absolute frequency deviation of 200mHz [9].

Next equation is then used to calculate how much should be the power contribution of an area i to the NPFC ($\lambda_i$) [8]:

$$\lambda_i = C_i . \lambda_u \text{ [MW/Hz]} \tag{2}$$

Where:

- $C_i$ – contribution of area i.

The contribution of each area is calculated by the following equation [8]:

$$C_i = \frac{E_i}{E_T} \tag{3}$$

Where:

- $E_i$ – electricity generated in the area I [MW];
- $E_T$ – sum of the electricity generated in the entire interconnected system [MW].

After receiving the information from ENTSO-E, each control area must assure that the required reserve power is always available to keep the system secure.

*B. The Droop Approach*

When a frequency deviation occurs, governors change their output proportionally to the value of that deviation. This approach uses a droop slope ($s_G$) which is defined using the following equation:

$$s_G(\%) = \frac{-\Delta f / f_n}{\Delta P_G / P_{Gn}} \quad (4)$$

Where:

- $\Delta f$ – frequency deviation [Hz];
- $f_n$ – nominal frequency [Hz];
- $\Delta P_G$ – Generated Power deviation [MW];
- $P_{Gn}$ – nominal Generated Power [MW].

The governors response can be controlled using different droop slopes for different frequency deviations. Fig. 2 shows how different droop slopes influence the power output of a generator. As it is possible to observe, with different droops and for the same frequency the generated power will be different, despite having the same capacity.

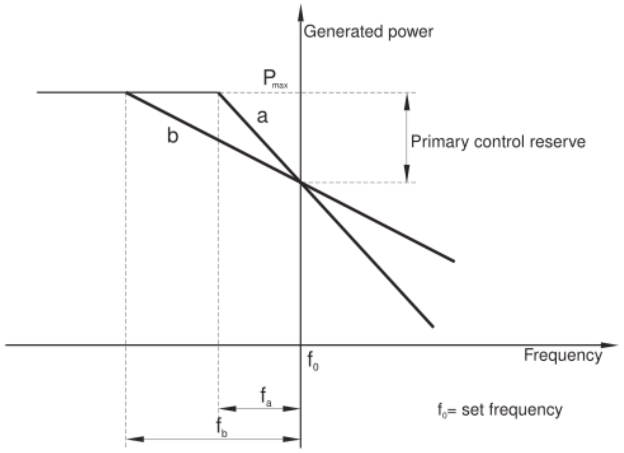


Fig. 2 - Different droop slopes [8]

## IV. Primary Frequency Control in the Web-of-Cells: the Frequency Containment Control Approach

This section describes the adaptations made to the actual primary frequency control in order to achieve the FCC concept of the WOC. The FCC approach aims at locally observing and responding to frequency changes by modifying active power to support the containment of frequency under normal operation or after incidents.

The core idea of this control scheme is originated from the classic droop control function described in the previous section, which can be extended and applied to various other resources, including DER and loads. Regardless of the underlying technology of the device that is used for the provision of FCC, the controller should always interact with higher level functions at cell level for contributing and managing the overall Cell Power Frequency Characteristic (CPFC), which is a WOC related concept similar to the NPFC.

The novelty of the proposed FCC approach is that the CPFC can be adjusted in the moments subsequent to a disturbance affecting the power-frequency control mechanism, depending if the incident occurred inside or outside a given cell. If the incident that lead to the FCC activation occurred outside a give cell, the CPFC is adjusted on those cells such that they stop contributing to the mitigation of the power imbalance. In other words, the CPFC can be adjusted in such way that only the disturbed cell is responsible for mitigating the power balance. This adjustment can be regarded as an intermediate step between the traditional primary and secondary frequency control.

The concept of FCC was developed using the Smart Grid Architecture Model (SGAM) [10], together with the associated use case. The use case control diagram is shown in Fig. 3:

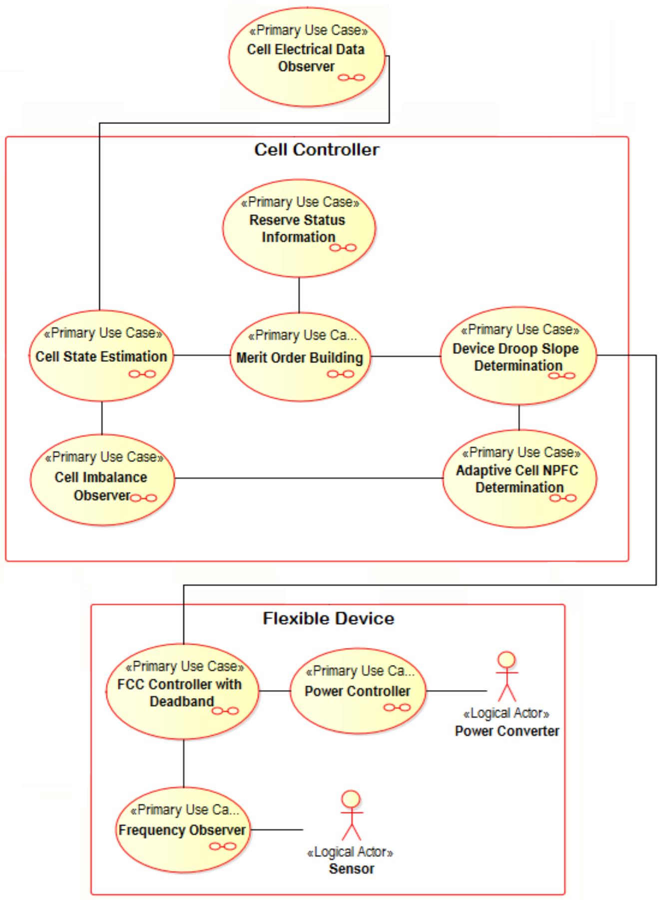


Fig. 3 - Control Diagram of the FCC use case

As previously mentioned, the resources that are able to provide reserves for primary control are automatically mobilized when there is a frequency deviation through the local droop control functionalities. Therefore, these resources have a function (FCC controller with dead-band) that, based on a frequency error signal and on its droop slope, it increases or decreases active power generation/consumption in a proportional manner to counter the system imbalance. The frequency error signal is continuously calculated by the

Frequency Observer installed in the device while the droop slope is updated each 15 min or when a frequency deviation occurs and the steady-state is reached.

The update of the droop slope at each 15 min is done by the Device Droop Slope Determination function. It is determined for the devices participating in FCC by decomposing the CFPC into device droop slopes in such a manner that its aggregated value is equal (or larger) to the CPFC calculated, taking into account activation cost and grid security. The update of the CPFC is also done by this function each 15 min using (2) and (3).

The activation cost and grid security is assured by ordering the devices that are chosen to provide primary frequency control, which is calculated by the Merit Order Building function. This function takes into account the updated state of the cell, provided by the Cell State Estimator, and the reserves availability and their associated cost, provided by the Reserves Status Information function.

The Cell State Estimator estimates the cell's grid state (bus voltages and line power flows) according to the information received by Cell Electrical Data Observer. The function of Cell Electrical Data Observer is to aggregate all the measurements of interest within the cell so that they are available to other functions.

The update of the droop slope after a disturbance is also performed by the Device Droop Slope Determination. But, in this case, the value of the CPFC is updated and calculated immediately by the Adaptive Cell NPFC Determination based on the imbalance error signal and the previous CPFC. If the imbalance error signal indicates that the problem occurred in this cell, the new value of the CPFC is the previous one; otherwise, the CPFC is zero and the cell stops contributing to solve the problem.

$$CPFC = \begin{cases} \text{CPFC, disturbance occured in this cell} \\ \text{0, disturbance occured in another cell} \end{cases} \quad (5)$$

The Cell Imbalance Observer is responsible for the calculation of the cell balance error signal. First, it must collect and aggregate the tie-line power flows, provided by the Cell State Estimator. Then, to calculate the cell balance error signal, it is necessary to calculate the deviation in the tie-lines by subtracting the sum of the programmed active power ( $P_{set}$ ) by the sum of the real active power ( $P_{act}$ ) in each interconnection area:

$$P_{error i} = \sum Pset_{ik} - \sum Pact_{ik} \text{ [MW]} \quad (6)$$

Where:

i - Interconnection area;

k – tie-line;

Afterwards, this function compares the signals of the errors in the interconnected areas and in case all signals are negative, it means that the problem was in this cell; otherwise, the problem was in another cell.

## V. Scenarios and Results

This section presents the test system used to simulate the control functions previously presented, the scenarios created for the simulations and the main results that were obtained.

### *A. Test System*

The software chosen to create and test the developed FCC functions was Matlab v2015a, from Mathworks. The test system used is presented in Fig. 4.

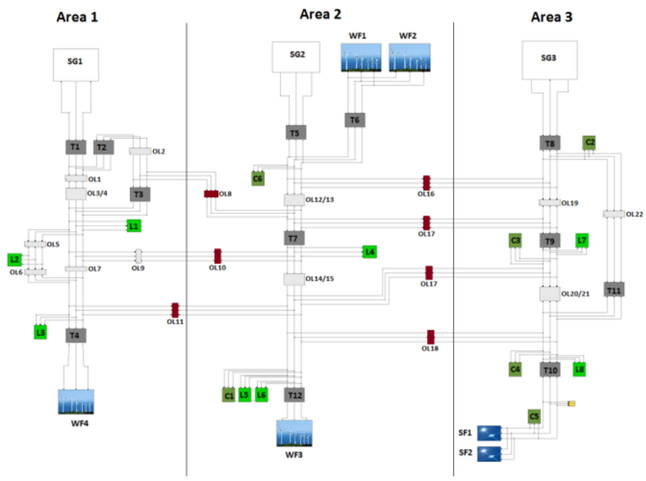


Fig. 4 - Test System used

It is a High Voltage (HV) grid with 3 control areas. There are 3 Synchronous Generators (SG), one in each control area, 4 Wind Farms (WF) and 2 Solar Farms (SF). There are 8 Loads (L), with a total power consumption of 3200 MW and 1950 MVar, and 6 Capacitors Banks (C). There are also 7 tie-lines between the different areas.

TABLE I - Data of the Network

| Cells | 1 | | 2 | | 3 | |
|---|---|---|---|---|---|---|
| | *nº* | *Total (MW)* | *nº* | *Total (MW)* | *nº* | *Total (MW)* |
| **Synchronous Generator** | 1 | 1000 | 1 | 900 | 1 | 1100 |
| **Wind Farm** | 1 | 110 | 3 | 1000 | 0 | 0 |
| **Solar Farm** | 0 | 0 | 0 | 0 | 1 | 550 |
| **Load** | 3 | 500 | 3 | 1200 | 2 | 1500 |

The NPFC was calculated using the following equation, as described in [11]:

$$\beta = \frac{1}{R} + D \text{ [MW/Hz]} \quad (7)$$

Where

– $\beta$ is the stiffness of the system, equivalent of the NPFC;

– R is the droop of the system (in the range of 5 %);

– D is the load-damping constant (in this case, it is assumed negligible in comparison to 1/R).

The system droop is calculated as shown next:

$$\frac{1}{R} = \frac{Load + \text{Reserve}}{droop \times f_n} = 1884.5\, MW / Hz \quad (8)$$

Where:

– Load=3200 MW;

– Reserve=1511 MW;

– droop=5%;

– $f$ =50Hz.

*B. Scenarios*

Several scenarios were considered in order to evaluate the performance of the developed FCC functions:

1. 1. Scenario 0 – loss of a generator in each area:
   - Scenario 0.1 – loss of a generator in area 1;
   - Scenario 0.2 – loss of a generator in area 2;
   - Scenario 0.3 – loss of a generator in area 3;
2. Scenario 1 – loss of a generator in area 3 with reduced capacity of the synchronous generator in that area to provide reserves;
3. Scenario 2 – similar to scenario 1 but with some adaptions in the models of the FCC control functions, so that, when an area is not able to solve the problem locally, the neighbor cells start contributing again;
4. Scenario 3 – loss of a generator in area 3 with half of the load in the system:
   - Scenario 3.1 – the value of the NPFC is not updated and so it is equal to the previous scenarios;
   - Scenario 3.2 – the value of the NPFC is updated according to the new load of the system.

*C. Results*

This section presents the results obtained from the simulations performed, which allow evaluating the performance of the models created and the differences between the scenarios analyzed.

*1) Scenario 0*

In this scenario, the performance of the developed models is tested by simulating the aforementioned disturbances in each cell of the test system. The results obtained for the frequency for each scenario are shown in Fig. 5.

As it can be observed, the frequency is constant until the disturbance takes place (at 50s). After the incident, the frequency drops in all scenarios due to the loss of a synchronous generator. The drop of the frequency and the response of the system varies in each scenario due to the incident location, as it occurs in different control areas.

When the frequency reaches the steady-state, the frequency drops again as a result of the control concept that was envisioned: after detecting the cell when the imbalance occurs, all the other cells in the system stop contributing to the power-frequency control in the overall system by cancelling their power-droop characteristic. After this last drop, the frequency ends up stabilizing again, meaning that the area had enough reserve capacity to respond to the problem.

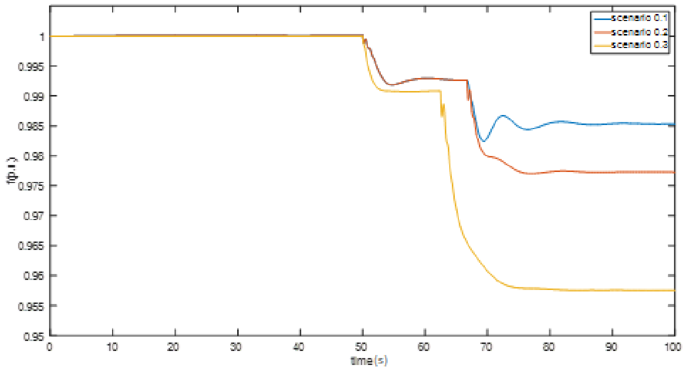


Fig. 5 Frequency (Scenario 0)

Fig. 6 shows the results obtained for the active power generated by the synchronous generators.

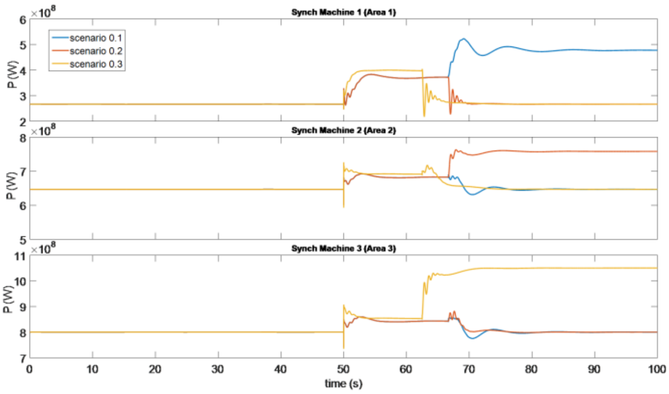


Fig. 6 - Synchronous Machine Power (Scenario 0)

In the first chart, it is possible to observe the active power of the synchronous generator of cell 1 for the different scenarios. The active power is constant until the problem occurs and then the generator increases its power output in order to mitigate the frequency drop. After that increase, two behaviors are observed: in scenario 0.2 and 0.3 the generators' power output returns to its initial value; in scenario 0.1 the generator increases its power output. This is due to the fault location, which occurred in the area where this generator is located, and so it will be this generator that will try to mitigate the problem alone.

In the other two charts, the same behavior can be observed. Observing the active power output of generator 2, it can be seen that in scenario 0.2 it has a first increase of power and then it increases again, while in scenario 0.1 and 0.3 it returns to its initial operating condition. The same situation happens for the power output of generator 3.

As expected, when a disturbance occurs in the system, all cells contribute to frequency control in the moments subsequent to its occurrence; when the frequency reaches the steady-state, the cell where the problem occurred assumes the frequency control alone.

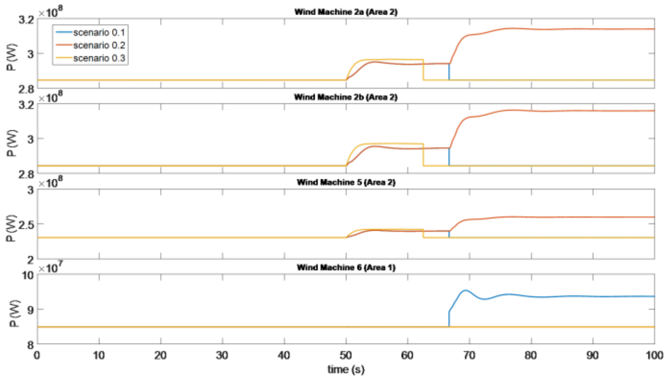


Fig. 7 Wind Machine Power (Scenario 0)

Observing the behavior of the wind generators, it can be noticed that it is the same as the synchronous machines, as they are assumed to have a frequency sensitive mode that is able to make them suitable to provide primary frequency control reserves. For wind farms 2a, 2b and 5 (all in area 2), in scenario 0.2, the power output increases when the problem occurs and then increases again when the frequency reaches the steady-state, while in scenarios 0.1 and 0.3 the power output returns to its initial value.

For wind farm 6 (area 1), it can be observed that it only increases its power in scenario 0.1. This happens because initially, when the problem occurs, this generator was not participating in frequency control, as there was already enough reserve being provided. However, when the frequency reaches the steady-state, this generator has to increase its power output. This is because the disturbance in this scenario occurred in the area of this generator (area 1) and only generators of this area should contribute to mitigate the problem, as the objective of the FCC is to solve local problems locally.

*2) Scenario 1*

In this scenario, the power capacity of the synchronous generator of area 3 was reduced to analyse how the system would react if a disturbance occurs in that area and not enough reserves are available to overcome the problem.

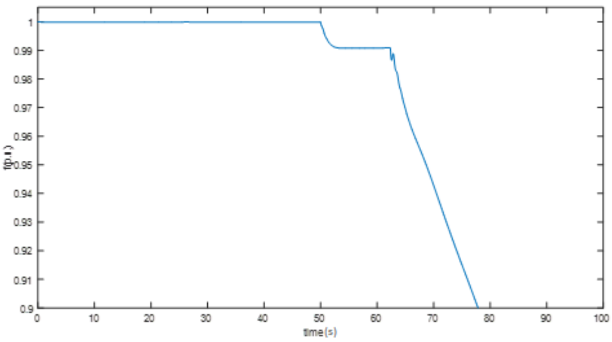


Fig. 8 Frequency (Scenario 1)

In Fig. 8, it is shown that the frequency has a first drop when the problem occurs and then it stabilizes due to the fast action of the generators. When it reaches the steady-state, it has another drop because only the generators in the affected area will contribute to solve the problem. However, the frequency keeps dropping since the generators do not have enough capacity to mitigate the problem. Although the results from these simulations are obvious, they have the purpose to alert for the necessity of defining adequate global reserves levels in the WOC concept.

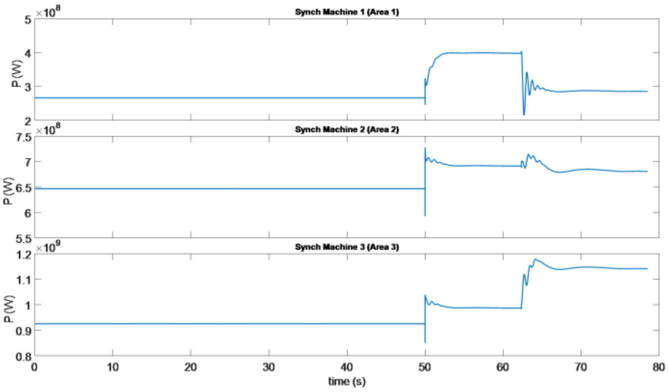


Fig. 9 Synchronous Machine Power (Scenario 1)

As shown in Fig. 9, the generators of area 1 and 2 decrease their values when the steady state is reached. They should return to their initial values (since it was the set-point that they received), but their own controls force the generators to act due to the frequency drop.

*3) Scenario 2*

As a solution for the problem encountered in the scenario 1, some modifications were made to the models so that when an area cannot support the frequency on its own, the other areas contribute again, though now not as much as before. Therefore, when the frequency passes a minimum value (assumed to be 49 Hz), the FCC control mechanisms in other areas are re-activated.

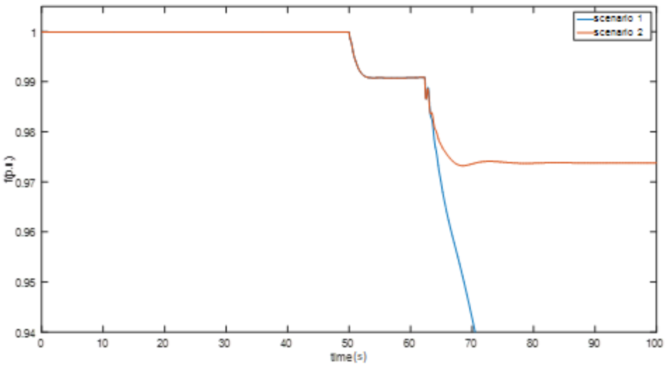


Fig. 10 - Frequency (Scenario 1 and 2)

As shown, with the new adaptations (scenario 2) the frequency stopped decreasing and ended up stabilizing again.

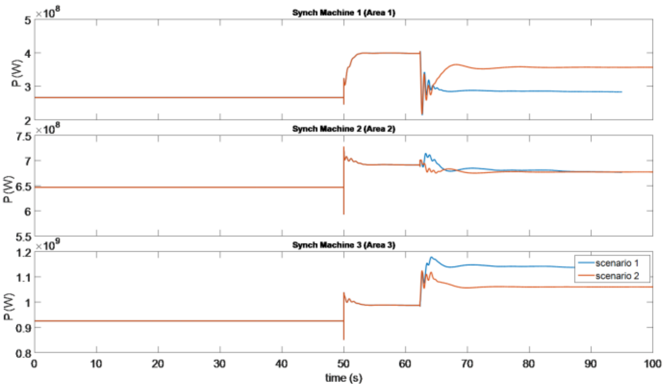


Fig. 11 Synchronous Machine Power (Scenario 1 and 2)

In Fig. 11, it is possible to observe that the power output of generator 1 and 2 was decreasing to the initial value since the problem was in other area. However, when the frequency exceeded the lower limit, the generators in area 3 of mitigating the problem alone and so the other generators were forced to increase their power output again to stabilize frequency.

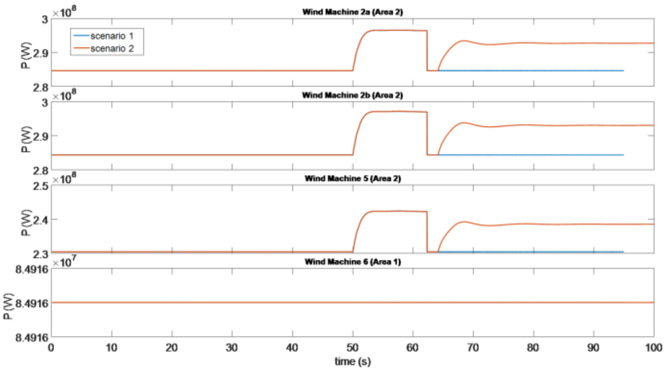


Fig. 12 Wind Machine Power (Scenario 1 and 2)

The same situation is visible with the wind generators. Due to the fact that generators of area 3 do not have enough capacity to control the frequency when the steady state is reached, some of the wind generators of other areas had to increase their power again as shown in Fig. 12.

*4) Scenario 3*

This scenario was simulated in order to study the response of the system to different values of the NPFC and thus, the load of the system was reduced to half. In scenario 3.1 the NPFC is equal to the previous scenarios (1884.5 MW/Hz) while in scenario 3.2 it was calculated a new value according to the new load of the system:

$$\frac{1}{R} = \frac{Load + \text{Reserve}}{droop \times f_n} = \frac{1600 + 2320}{0.05 \times 50} = 1568\,MW\,/\,Hz \qquad (9)$$

Fig. 13 shows that the frequency ended up stabilizing in both scenarios in a very similar manner. Observing Fig. 14, it is possible to see that the power deployed by the synchronous generators is also very similar.

The greatest effect resulting from different values of the NPFC is depicted in Fig. 15. It is possible to observe that wind farm 5 is only activated in scenario 3.1 (when the value of the NPFC is the original one). When the new calculated value is used (scenario 3.2), this machine will not need to be activated, and so the cost of reserves' activation will be reduced. It can also be seen in Fig. 13, that the frequency ended up stabilizing even without activating wind farm 5.

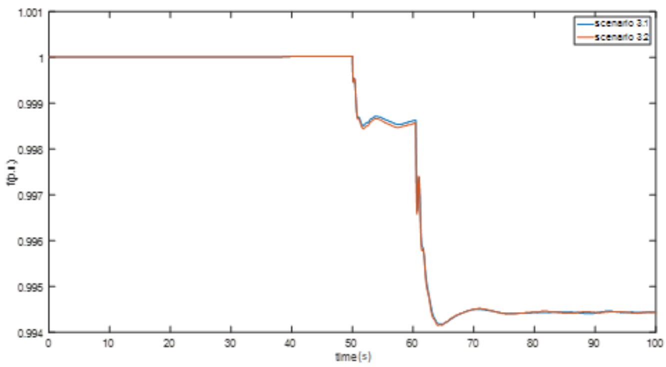


Fig. 13 Frequency (Scenario 3)

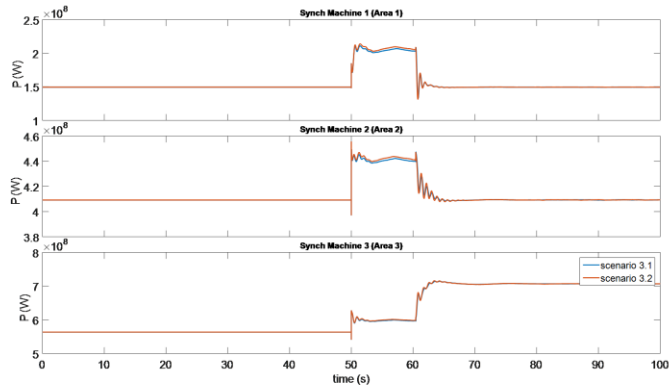


Fig. 14 Synchronous Machine Power (Scenario 3)

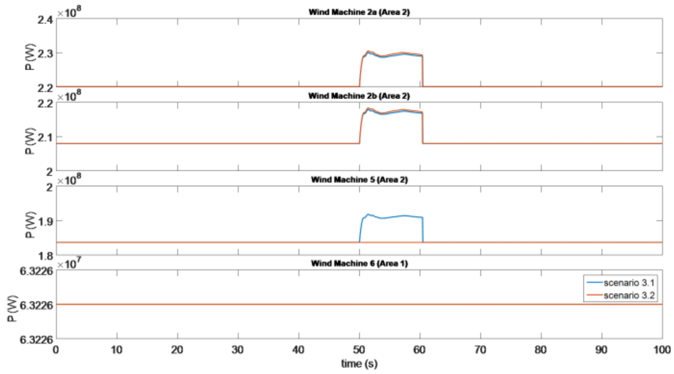


Fig. 15 Wind Machine Power (Scenario 3)

## VI. Conclusions

In this work, a new approach was developed to adapt the the conventional primary frequency control solution to the Web-of-Cells concept under development within the the European Union FP7 ELECTRA project. The core idea of the approach under development relies on solving local (cell) problems using locally available resources.

By simulating the loss of a generator in a certain area, the FCC functions developed allowed the system frequency to be controlled. The difference of the results obtained in comparison with the traditional primary frequency control is that after the frequency stabilizes, the only cell in the system that will contribute to the problem is the one where the problem occurred.

In case a cell does not have sufficient reserve capacity to solve the problem by itself, the other cells will contribute with the required amount of power to mitigate the problem. Although in this situation the other cells will also contribute to solve the problem, the reserve power they provide will not be as much as it would have been with the traditional primary control.

It was also verified that if the NPFC is calculated according to the actual system operating conditions, instead of using a reference incident, the total amount of reserves required to assure a safe system operation may be significantly reduced. Future work will focus on the quantification of the economic benefits that this new approach will yield in terms of balancing reserves' cost.

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