EXPERIMENTAL VALIDATION OF ADAPTIVE FCC AND BRC FUNCTIONALITIES FOR THE PROPOSED ELECTRA WEB-OF-CELLS

Mattia CABIATI
RSE S.p.A. – Italy
mattia.cabiati@rse-web.it

Evangelos RIKOS
CRES – Greece
vrikos@cres.gr

Antonio GUAGLIARDI
RSE S.p.A. – Italy
antonio.guagliardi@rse-web.it

Riccardo LAZZARI
RSE S.p.A. – Italy
riccardo.lazzari@rse-web.it

ABSTRACT

Distributed renewable energy sources are responsible for the rising of new challenges for the power system operation and control. To deal with the foreseen issues, the European funded project ELECTRA IRP has developed the Web-of-Cells control framework for the future power system. This paper will present laboratory proof-of-concept tests about the adaptive frequency containment control and the balance restoration control functionalities.

INTRODUCTION

It is expected that the future power system will be characterized by a huge number of Distributed Generators (DG) connected to any voltage level and dispersed all over the electrical grid. Most of them will be Renewable Energy Sources (RES) and this will cause additional challenges for the power system operation. Indeed, the non-continuous power production of RES increases the issue of having only partly dispatchable power generation. In addition, the distributed characteristic of these new resources implicates that the system operators have to interact with a huge number of non-centralised resources in order to control the power system.

THE WEB-OF-CELLS CONCEPT

In order to deal with the above mentioned challenges, the European funded project ELECTRA IRP has developed the Web-of-Cells (WoC) control framework for the future power systems [1], [2]. A cell is a portion of a power system managed by an own controller that is able to respect the scheduled import/export power profile. Inside a cell can exist any type of generation and load, but a cell must have enough flexibility to compensate deviations from the power profile during normal operation; these situations can happen as a consequence of forecast errors associated to renewable sources and loads or small disturbances.

A-FCC and BRC

The Balance Restoration Control (BRC) has the objective to minimize the *imbalance value* calculated by an "*Imbalance Observer*" function. The imbalance value is the sum of two terms: (1) the error between the active power exchange at the cell boundaries and the scheduled value and (2) the frequency error term $k\Delta f$. It presents similarities with the traditional secondary control and the main difference is that the cell controller activates a big number of resources in a fast way.

The other functionality of the cell controller is the Adaptive Frequency Containment Control (A-FCC). The idea behind this new approach is to make the frequency containment reserve activation as close as possible to the power disturbances. In order to reach this objective the cell controller requests from the generators to modify their droop slope according to the real-time cell power import/export and frequency deviations.

The amount of cell primary reserve, called Cell Power Frequency Characteristic (CPFC), is increased (that is, the generators increase their power contribution in response to a frequency deviation) if the frequency is below the nominal value and the cell is exporting less power than scheduled. In this situation, indeed, a cause of the under-frequency could be found within the cell. In the opposite situation the cell primary reserve is decreased. In Table 1 all the possible situations that could occur in a cell are presented, where f is the system frequency, P_{exp} is the cell power export and $P_{set\text{-}point}$ is the cell power export set-point.

Table 1 – A-FCC action on the cell primary reserve

	$f > f_n$	$f < f_n$
$P_{exp} > P_{set\text{-}point}$	CPFC increased	CPFC decreased
$P_{exp} < P_{set\text{-}point}$	CPFC decreased	CPFC increased

A schematic of these two cell controller functionalities is depicted in Figure 1.

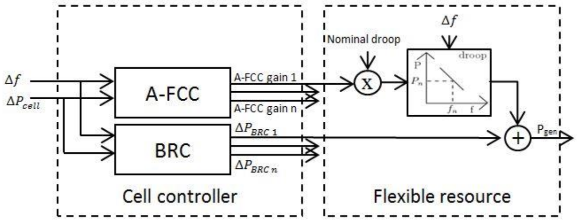

Figure 1 – Combined A-FCC and BRC deployment

Regarding the A-FCC functionality, two approaches were investigated: one, named "*Const. A-FCC*" (CA), computes the droop scaling factor used to modify the generators droop and so the CPFC as described above, by simple operations based on the frequency and cell power export deviations and the other one uses a *fuzzy logic* approach to achieve the same result.

The CA version uses the frequency deviation Δf and the cell power export deviation ΔP_{export} to increase or decrease the cell contribution to the primary reserve maintaining the overall power system frequency characteristic close to a desired constant value. The schematic of this approach is depicted in Figure 2. In order to better understand how this concept works, let's consider a system composed by three cells and with a flexible resource connected to each cell as the one that will be used for the tests presented in the following sections, where grid supporting Voltage Source

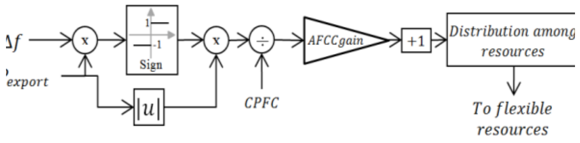

Figure 2 - Frequency behaviour with different control functionalities activated in case of a load disturbance.

Inverters controlled as voltage sources [5] are used. These converters have a power/frequency droop as reported in equation (1) where ΔP is the power output deviation of the inverter.

$$\Delta f = k\Delta P \quad (1)$$

Consider the modification of the droop parameter k of the inverters dividing it by a gain g.

$$\Delta f = \frac{k}{g}\Delta P \quad (2)$$

Take into account a grid with three inverters. It is possible to write:

$$\Delta f\left(\frac{g_1}{k_1}+\frac{g_2}{k_2}+\frac{g_3}{k_3}\right) = \Delta P_1 + \Delta P_2 + \Delta P_3 \quad (3)$$

Equation (3) can be rewritten considering that $g = 1 + g'$ (as shown in Figure 2):

$$\Delta f\left(\frac{1}{k_1}+\frac{1}{k_2}+\frac{1}{k_3}+\frac{g'_1}{k_1}+\frac{g'_2}{k_2}+\frac{g'_3}{k_3}\right) = \Delta P_1 + \Delta P_2 + \Delta P_3 \quad (4)$$

Finally, in order to have a constant system droop coefficient it is possible to write:

$$\frac{g'_1}{k_1}+\frac{g'_2}{k_2}+\frac{g'_3}{k_3} = 0 \quad (5)$$

Considering again the schematic in Figure 2, it is possible to recognise that the gain g is proportional to the cell power export and to the CPFC, in our example case is $CPFC = 1/k$. The sign of g depends also on the frequency deviation, but since the frequency deviation is common to all the cells it does not matter for this analysis. Taking this into account we can write:

$$\frac{g'_1}{k_1}+\frac{g'_2}{k_2}+\frac{g'_3}{k_3} = \frac{\Delta P_{c1}k_1}{k_1}+\frac{\Delta P_{c2}k_2}{k_2}+\frac{\Delta P_{c3}k_3}{k_3} = \Delta P_{e1}+\Delta P_{e2}+\Delta P_{e3} \quad (6)$$

Where ΔPc is the cell power export deviation. The sum of the three ΔPc is always zero (neglecting losses over the tie-lines and measurement errors). In this way, equation (5) is verified and the overall droop is always constant.

Instead the *Fuzzy Controller* (FC) version of A-FCC [3] takes into account only the part of the WoC power frequency characteristic which is related to the specific cell. The controller monitors the frequency and tie-line power errors and it adjusts the CPFC value multiplying it by a coefficient that varies between 0.5 and 1.5. In this way, the cell undergoing an imbalance increases its droop, whereas its neighbours decrease it in order to obtain an increased FCC reserves activation in the proximity of the imbalance. In Table 2 we can see the selected rules that determine the output signal of the fuzzy controller. For the output defuzzification, the Centre-of-Gravity method was used.

Table 2 – Implemented rule table

Δf_i / $\Delta P_{tie,i}$	NH	NL	ZE	PL	PH
NH	50%	75%	100%	125%	150%
NL	75%	75%	100%	125%	125%
ZE	100%	100%	100%	100%	100%
PL	125%	125%	100%	75%	75%
PH	150%	125%	100%	75%	50%

TEST SET UP

The above described functionalities have been tested resorting to the RSE DER Test Facility (DER-TF) [4]. A schematic representation of the system during the tests is depicted in Figure 3. The setup includes three cells with power generation, a controllable load and energy storage systems. With this configuration, tests were performed in island mode. The A-FCC and BRC functionalities were tested starting from normal conditions (nominal frequency and power at tie-lines regulated as requested) and considering various scenarios: BRC and A-FCC were enabled or disabled and the $k\Delta f$ term of the BRC input error signal was also disabled or enabled.

Within the test set up, the generators are:

- a lead-acid storage with 20 kVA of nominal power
- a lithium storage with 30 kVA of nominal power
- a DC grid interfaced through a bidirectional inverter with 30 kVA nominal power

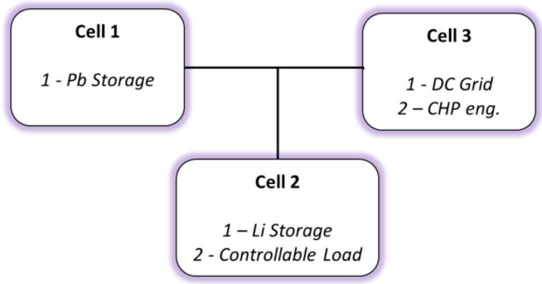

Figure 3 – Schematic view of the test set up

The selected units use grid supporting Voltage Sources Inverters (VSI) controlled as voltage sources [5], with an active power-frequency droop. In Figure 4 a simplified diagram of their external behaviour is shown.

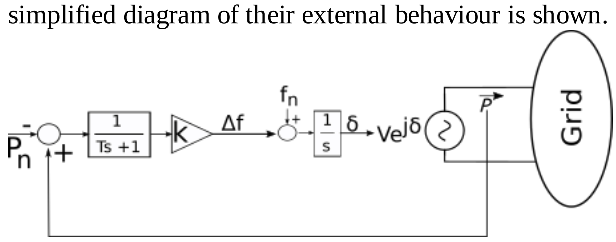

Figure 4 – Simplified schematic of a grid supporting VSI controlled as voltage source

TEST RESULTS

Balance Restoration Control

The first set of tests has the aim of investigate the BRC control. To understand the behaviour of the two terms of the BRC control on the frequency, a test with a load perturbation of 15 kW in the cell two is repeated 3 times (no BRC, BRC without the term kΔf and BRC). The load during the test is firstly increased and subsequently decreased. In Figure 5, it can be seen that without the BRC (between the time 0 and the time 300s) the variation of the frequency that is only due to the droop control in the converters. However, with the BRC without the *kΔf* contribution (between 300 and 700 seconds) the frequency is not constant and decreases slowly like a ramp. Finally, with the *full* BRC contribution (between 700 and 1000 seconds), the frequency is fast recovered to the nominal value.

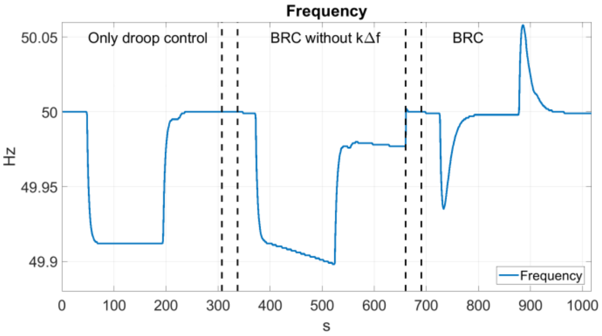

Figure 5 - Frequency behaviour with different control functionalities activated in case of a load disturbance.

In order to better understand the drop of frequency in the case of BRC without the term *kΔf*, it is possible to compute the closed loop transfer function between *Δf* and the measured cell power export for the simplified system reported in Figure 6. The system represents two simple cells made up of a single generator (a VSI controlled as a voltage source). In the figure P_{set} and P_{cell} represent the cell power export set-point and actual power export respectively. *k* is the generator droop parameter and the *BRC PI* block represents the BRC controller where the input error signal is composed only by the cell power export deviation. The power exchanged between the two cells is proportional to the difference between the voltage angles of the two inverters through the parameter *1/x*. *x* is the impedance of the line between the two inverters. We assume that the amplitude of the voltage produced by the inverters is kept constant. Then, since there are only two inverters the output power of one inverter is received by the other one as input power. In this situation the closed loop transfer function $\Delta f / P_{cell}$ is the following:

$$\frac{K_{dr}(xs^3 + (2\mathrm{K_{dr}} + 2\mathrm{K_{dr}}\mathrm{K_p} + \mathrm{K_i})s^2 + (4\mathrm{K_{dr}}\mathrm{K_i} + 2\mathrm{K_{dr}}\mathrm{K_i}\mathrm{K_p})s + 2\mathrm{K_{dr}}K_i{}^2}{(xs^2 + (4\mathrm{K_p}\mathrm{K}_{dr} + 4\mathrm{K_{dr}})s + 4K_i\mathrm{K}_{dr})s}$$

The transfer function has a pole in the origin. This means that a small error in the power measurement over the tie lines is integrated and results in a frequency drift. In practise a small mismatch between the two measurements and losses over the tie-lines contributes to have two different measures for the two cells. In Figure 7 the cells power export are shown. In the case of only droop control, the tie-line power flow after the disturbance remains, as expected, far from the set-point. Instead, in the presence of BRC, even without the *kΔf*, the power follows the set-point but in this case the frequency is not restored as pointed out previously. The same behaviour happens in the presence of the BRC control, as expected.

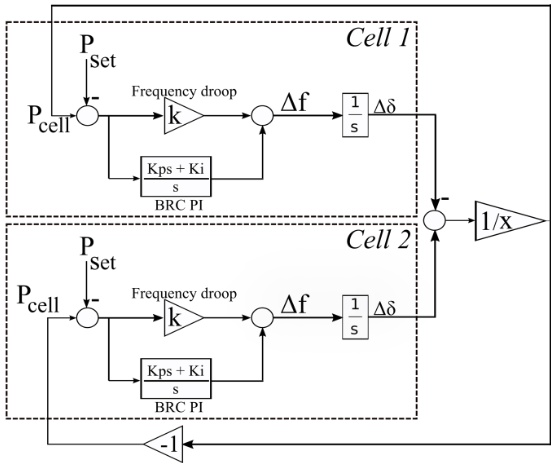

Figure 6- Simplified block diagram of a two cell

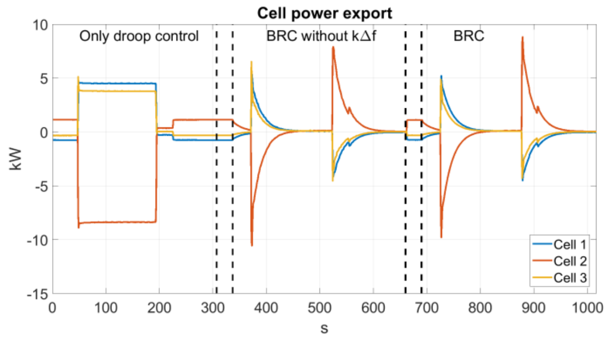

Figure 7 - Cell power export with different control functionalities activated in case of a load disturbance.

Adaptive Frequency Containment Control

The second set of tests has the aim to investigate the two described version for the A-FCC. To understand the behaviour of the A-FCC control, a test with a load perturbation of 15 kW in the cell two is repeated twice (A-FCC disabled, A-FCC enabled). In Figure 8 the trend of the frequency with the two versions of the A-FCC both enabled and disabled are shown. It's possible to see that the response is quite similar between the two A-FCC versions. This is due to the fact that both the gains for the A-FCC versions are selected to maintain the overall system droop quite constant.

In fact, the overall system power frequency characteristic does not vary significantly, as shown in Figure 9. The small deviations from the reference value are due to the measurement errors in the export powers. In fact, the CA is able to maintain the overall WoC droop constant only in the case that the sum of the cell exported power is zero. In practice this is not achievable because of losses over the tie-lines, measurement errors and delays.

In any case, the tests show that the cell where the disturbance took place decreases its CPFC and so the primary reserve contribution of this cell is increased.

This happens both with the CA (Figure 10) and the FC (Figure 11) version of the A-FCC. Finally we can say that the use of the A-FCC function permits the reduction of the cell export power error compared to the basic situation, as shown in Figure 12 for the case of CA A-FCC.

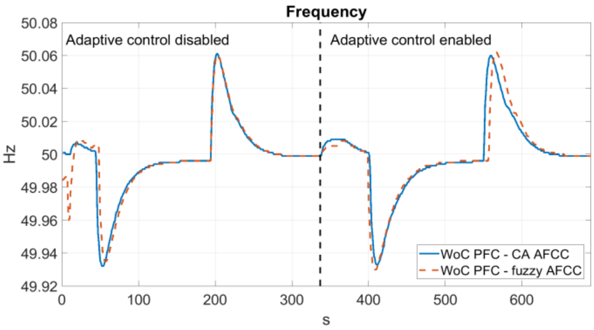

Figure 8 – Frequency with CA and FC enabled and disabled

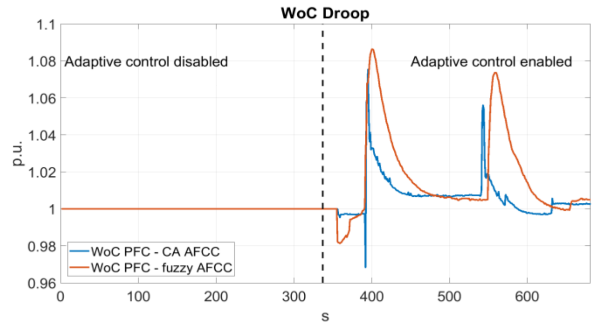

Figure 9 – Overall system droop with CA and FC enabled and disabled

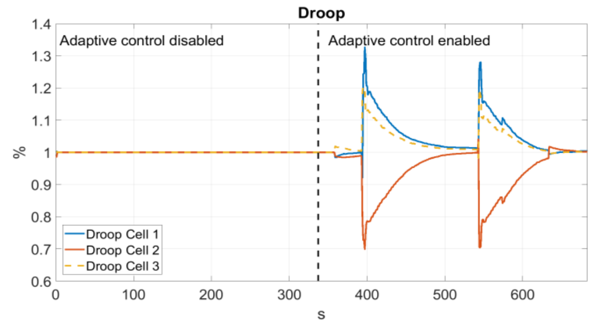

Figure 10 – Cell droop with CA enabled and disabled

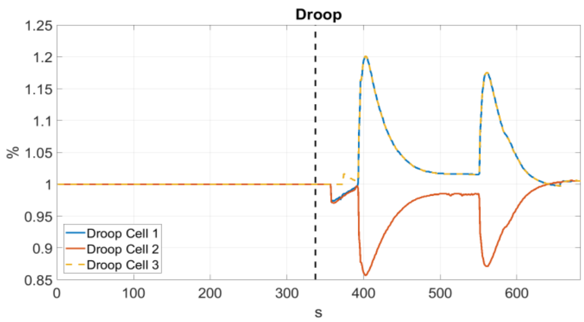

Figure 11 – Cell droop with FC enabled and disabled

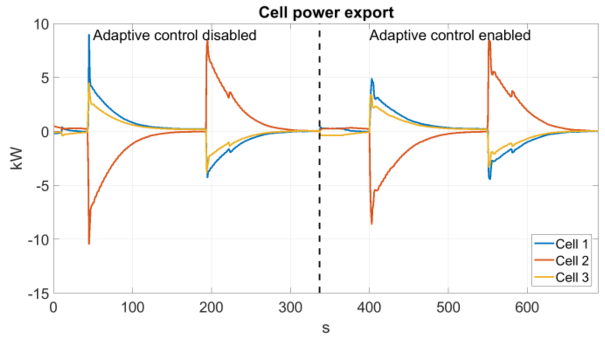

Figure 12 – Cell power export with CA A-FCC *version* disabled and with CA enabled

CONCLUSIONS

This paper focuses on the results of the Adaptive Frequency Containment Control implementation and Balance Restoration Control functionalities defined by the ELECTRA project to control a power system organized as a Web of Cells. The work has been done in the frame of the ELECTRA Researcher Exchange (REX) program. The tests show the effectiveness of the BRC in maintaining the cell power export close to the scheduled value. It was also tested a BRC version without the frequency contribution on the error signal and it was shown that is unstable, also by computing the transfer function that is governing the phenomenon. The tests also show a good behaviour of the A-FCC control functionality, that was implemented using both a fuzzy logic (FA) both following an *algebraic* approach (CA). The A-FCC can effectively detect the imbalance location and, as a result, modify the FCC reserve if the imbalance took place outside its cell.

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