MITIGATING POWER SYSTEM INERTIA REDUCTION WITHIN A WEB-OF-CELLS CONTROL FRAMEWORK: A PRELIMINARY ANALYSIS

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ABSTRACT

This work is focused on short-term frequency behaviour after significant load/generation imbalances and it is part of the ELECTRA IRP European Project studies on novel observability and control concepts for future power systems characterized by high levels of generation from Renewable Energy Sources (RES) and of distributed generation.

Within ELECTRA, the so-called Web-of-Cells (WoC) control framework is proposed, based on dividing the power system into subsystems, called cells. These are controlled by cell operators, with roles similar to the ones of the current system operators (TSOs and DSOs). Each cell has to contribute to power balance/frequency and voltage control and is responsible for its behaviour at its boundaries. With reference to a test WoC, this work analyses system inertial response in several scenarios with increasing RES penetration levels, and introduces synthetic inertia in different cells in order to reduce the amplitude of the Rate Of Change Of Frequency (ROCOF) just after large power imbalances.

INTRODUCTION

Frequency behaviour in AC power systems depends on the instantaneous balance between power generation and consumption. Traditionally, frequency has been controlled and kept close to the nominal one by large synchronous generators connected to the transmission grid. They keep it within suitably narrow ranges even in case of sudden and large balance perturbations [1].

When an imbalance occurs, the Inertial Response (IR) of the synchronous generators is the first phenomenon that takes place in the power system, and contributes to reducing the initial (absolute) value of the frequency gradient, i.e. of the Rate Of Change Of Frequency (ROCOF), after the event. Then the Frequency Containment (FC) regulation acts in order to stop the frequency deviation and finally secondary and tertiary regulations act on longer time scales in order to restore the initial frequency conditions and the available power reserves [1]-[2]. Additional contributions to the frequency transient mitigation are provided by the self-regulating behaviour of load units.

However, the power system in the future decades is foreseen to be characterized by a significant increase of generation from Renewable Energy Sources (RES), mainly non-programmable and connected to the grid through power electronic converters. This evolution implies a decrease in system inertia, and therefore in power system stability margins [3]-[9], [10]-[13]. Besides [4], inertia of large interconnected power systems is already becoming more and more heterogeneous and with a non-uniform geographical distribution (e.g., wind generation in Europe is mainly in the Northern countries and up to now PV generation has developed in few countries, Italy and Germany mainly). Additionally, production from RES is time varying and not always dispatchable, so inertia is also becoming time varying. Furthermore one can remark that the displacement of conventional generators causes a reduction of the availability of operating reserves and that power production is gradually moving towards small generators connected to distribution grids.

All the issues mentioned above pose new challenges to future power system operation. Therefore, new control actions to regulate frequency, and consequently new ancillary services, have to be conceived. For instance, an artificial IR and contribution to FC control can be obtained from resources other than conventional generators, e.g. from renewable generators and from other flexible resources such as battery energy storage systems. Indeed, renewable power plants in Ireland and UK are already required to do FC in both directions [14], and in the UK battery storage systems have recently started to provide an enhanced frequency response (namely a fast FC action) [15]. There is a need both to implement these control actions at the single device level and to coordinate groups of devices at a higher level, in particular at the system level.

To cope with these challenges, in the ELECTRA EU project [16]-[17], a so-called Web-of-Cells (WoC) control architecture is proposed, based on dividing the power system into subsystems, or cells, which have to contribute to both balance/frequency and voltage control. Cells are individual control entities, operated by cell operators (similar to present transmission system operators and distribution system operators), but they are coordinated together system-wide, in order to ensure secure and reliable overall system operation, on the Pan-European scale. A cell, in fact, needs to aggregate sufficient flexible resources to handle the variability of internal generation and loads, but in case of need it can reach its balanced condition by interacting with neighbouring cells.

This paper is focused on frequency behaviour as part of ELECTRA studies on novel observability [18] and control concepts, in particular in view of developing cell control actions and inter-cell coordination mechanisms to exploit physical and synthetic inertia. A preliminary analysis of the impact of decreasing inertia on system frequency is carried out here, by means of simulation on a multi-cell test grid model. Starting from a set of grid scenarios with the current FC control architecture and with increasing levels of RES interfaced to the grid with static converters, short-term frequency dynamics just after relevant power imbalances are analysed. Then, Synthetic Inertia (SI) control actions are introduced, in order to make up for the deterioration of the post-event ROCOF due to the increase of the renewable penetration.

A sensitivity analysis with respect to the artificial IR control parameters is carried out. Simulations results are discussed with reference to the Centre-Of-Inertia Frequency (COIF), defined for the whole WoC [18]. The COIF concept could be used to improve system inertia estimation [19], both as an offline task to identify the system minimum inertia requirements and as an online task to check if such requirements are met or if it is necessary to deploy SI control actions to meet them. Online estimation can be carried out also thanks to the development of Phase Measurement Units and of wide-area measurement systems. Difficulties in estimating the overall system COIF, such as those highlighted in [19], could be overcome in a WoC framework by referring the overall WoC COIF to the individual cell COIFs. In addition, one can observe that tracking the overall COIF [20] can be an effective way, for instance, to fast mitigate frequency oscillatory phenomena with reduced control effort.

DYNAMIC MODELS

In this section, we give an overview of the dynamic models adopted in the simulations here. We consider a set of conventional generators, namely Synchronous Generators (SGs) each of which equipped with its governor [21]-[22], Automatic Voltage Regulator (AVR) and Power System Stabilizer (PSS). An ideal AVR is assumed. A block scheme of the model adopted for each synchronous machine is depicted in **Figure 1**, where f_n is the system nominal frequency, P_m the machine mechanical power, P_e its electric power, V_{SG} its terminal voltage, ω the rotor speed, δ the rotor angle, H the machine inertia constant (referred to the machine nominal apparent power), R the FC droop, and where the dot indicates per unit values. **Table 1** reports the values adopted for the main parameters.

A set of renewable generators, in particular Wind Parks (WPs), is also considered. Each of them is here represented by a power source with active and reactive power reserve, in order to support FC and voltage control. The FC dynamic model is the same as the one for the conventional generators, order to have comparable results. The related block scheme is reported in **Figure 2**, where a SI part is also represented. This will be described below.

The load units are modelled as constant power loads.

Synthetic inertia support

The IR is an inherent behaviour of the rotating masses of electric machines. The electrical frequency and mechanical rotational frequency of such machines are strongly linked by the electromagnetic field inside them and a change of rotating speed results in electrical frequency variation and vice-versa. Therefore, when a power balance disturbance takes place, the mechanical inertia of rotating masses act as a first and intrinsic countermeasure against frequency deviations. The phenomenon is well described by the swing equation [23]. With reference to the synchronous machine modelled in **Figure 1**, this equation reads as

$$2H\frac{d\dot{\omega}}{dt} = \dot{P}_m - \dot{P}_e$$

If in the above expression we insert the overall inertia constant of the power system and the power imbalance refers to the whole system, then ω will represent the system COIF. As already mentioned, in the future more and more generation, typically from RES, will be characterized by low or null inertia. Therefore, in order to support frequency stability, an idea is to emulate mechanical inertia by means of a synthetic one, to get from the RES a response similar to the one of the SGs. This can be obtained by modifying the RES power output proportionally to the derivative of the measured frequency. We have introduced such control in the WP model, as shown in **Figure 2**. In particular, the H_w constant has the same role as the inertia constant in the synchronous machine model. H_w can be chosen of any value, it is only limited by the power capability of the wind turbine power converters. Here we have chosen a value for H_w equal to the inertia constant of the synchronous machines, in order to have comparable dynamic behaviour.

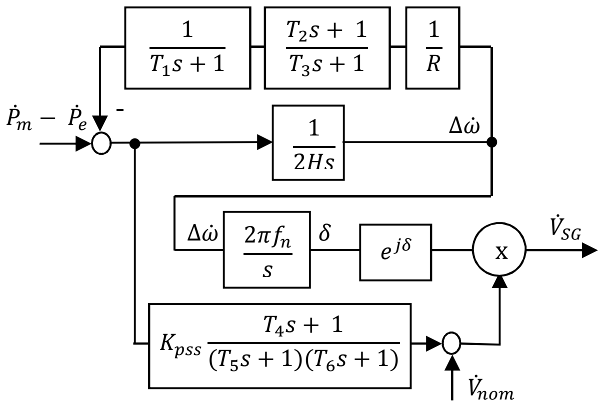

Figure 1 - Synchronous machine model

Table 1-Synchronous machines parameters

Parameter	Value	Parameter	Value
H	5 s	T_2	3 s
f_n	50 Hz	T_3	10 s
R	0.05 p.u.	T_4	0.03 s
K_{pss}	2.2 p.u.	T_5	0.005 s
T_1	0.5 s	T_6	0.5 s

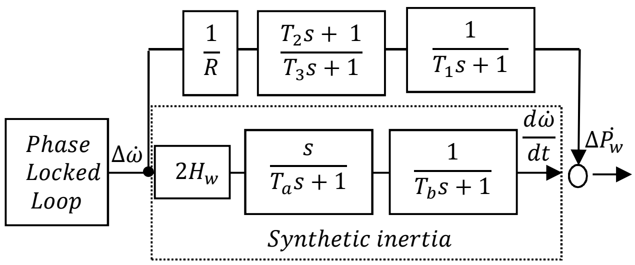

Figure 2 - Wind park model

REFERENCE GRID AND SCENARIOS

For simulation purposes, the grid adopted in this work (see **Figure 3**) is a modification of the one described in [18] and [24]. It has been derived from the European HV Benchmark network proposed by CIGRÉ [25] and it is composed of four AC cells. The models adopted for the main components are those discussed in the previous Section. Six different scenarios with a variable level of wind energy penetration are simulated here; they are fully described in [18] and [24], and their main features are summarized in **Table 2**. The generation from RES ranges from 0 to 75% with respect to the total load, which is 2600 MW + 776 MVar.

The system is heavily loaded: this makes it more interesting to study, since generally the stability of highly loaded systems is low. Scenario I is the base case without RES generation, i.e. with generation exclusively from SGs. In such a scenario, no SI is present. For each of the other scenarios, the system response is evaluated both without and with the SI provided by the WPs.

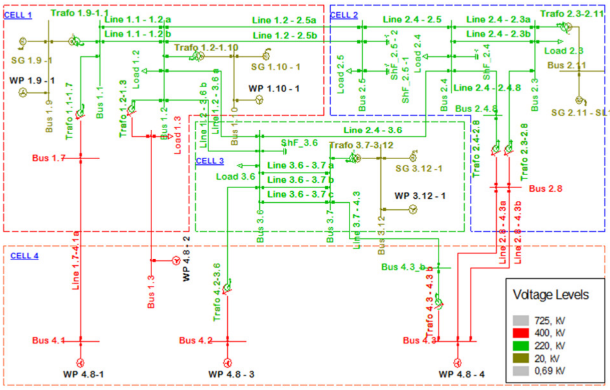

Figure 3 Reference grid single-line diagram

Table 2 Summary of the defined simulation scenarios

	I	II	III	IV	V	VI
P_{res} [% of the total load]	0	25	25	50	50	75
P_{res} [MW]	0	650	650	1300	1300	1950
Number of SGs in service	8	8	6	6	4	3
SGs set-points [MW]	325	244	325	217	325	217
SGs loading [% P_{nom}]	76	57	76	51	76	51
Total system inertia 2H [s]	10	10	7.5	7.5	5	3.75
Inertia in Cell 1(2H_1) [s]	10	10	5	5	2.5	2.5
Inertia in Cell 2 (2H_2) [s]	10	10	10	10	10	10
Inertia in Cell 3 (2H_3) [s]	10	10	10	10	5	0

SIMULATION RESULTS

In order to investigate the benefits introduced by SI, the power system described in the previous section has been implemented in a RMS simulator in the Matlab/ Simulink® environment.

Frequency/ROCOF dynamics and control effectiveness are analysed here by simulating the disconnection of a large load unit or a portion of it, in order to create a sudden imbalance between instantaneous generation and absorption. In **Figure 4** the WoC COIF transients resulting from disconnecting 100, 200, 300, 400 MW (cosφ = 0.95) load in scenario I are reported. The effects of the primary frequency control and of the intrinsic inertia of conventional power units can be easily noticed. The magnitude of the frequency deviation, both during the transient and at steady state, is proportional to the entity of the imbalance. Also the ROCOF is proportional to the imbalance as expected. The response of the system COIF and ROCOF depends only marginally, instead, on the location of the simulated load disconnection, which has been repeated for all the three cells.

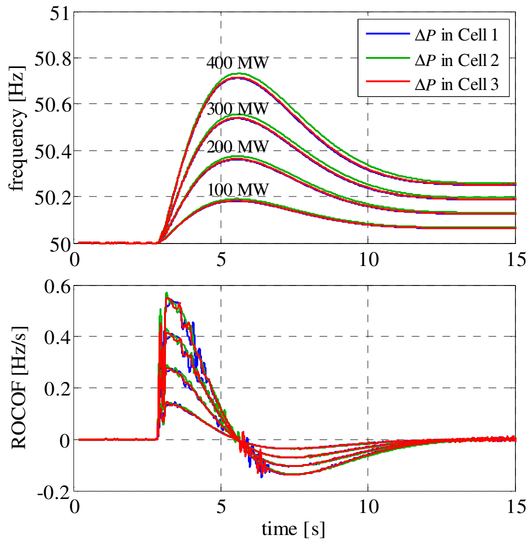

Figure 4 COIF (top) and related ROCOF (bottom) transients in scenario I, for different values and locations of load disconnection

For the other scenarios reported in **Table 2**, the frequency transient is expected to significantly change insofar the amount of power contribution from wind power plants is increased without SI. This is shown in **Figure 5**, where the same power imbalance is simulated: 400 MW load step (cosφ = 0.95), in cell 1. Particularly visible is the effect of the scenario on the ROCOF transient. Scenarios I and II, as well as III and IV, show the same response to the introduced disturbances. This because the level of rotating inertia is unvaried, since the same amount of conventional units are in operation. Scenarios V and VI, on the contrary, feature lower mechanical inertia, so the ROCOF is higher. The frequency derivative values resulting in these scenarios of high wind power penetration are normally considered critical [13][1] and the implementation of a SI controller on the wind generators can be very beneficial for the system dynamics.

As anticipated above, since power sources based on static converters are not intrinsically capable of providing an inertial response, dedicated controllers have been implemented acting on the power exchange set-point on

[1] For the Continental European System, 20% system imbalance ratio - the maximum one that can be overcome by the current power plant capabilities and system protection devices - causes 0.5-1 Hz/s absolute ROCOF. In the future, machines will be probably asked to be able to face 2 Hz/s absolute ROCOF for 40% imbalance ratio.

the basis of the measured system ROCOF. The estimation of this last quantity is normally subject to delays and, depending on the latency in providing inertia contribution, the power system behaviour may vary significantly. **Figure 6** reports the COIF transients due to a sudden load disconnection in scenario VI. Several curves corresponding to different time constants T_a and T_b of the inertia controller (see **Figure 2**) are plotted: in particular, the range from 0.1 s to 1 s is assumed for them and the assumption $T_a = T_b$ is made. One can observe that, when all the static generators promptly react to power system perturbations, the frequency transient is similar to the one featured in scenario I (green curve); when the inverter response is too slow, instead, the frequency transient tends to the one featured in scenario VI when no SI control is implemented (red curve).

Thanks to adequate SI, the system features practically the same dynamics for each penetration of non-conventional generation. **Figure 7** reports the frequency transient due to a load disconnection in all the considered scenarios with wind generators equipped with SI, with $T_a = T_b = 0.1$ s. It can be noticed that the trends are very similar and only two minor variations are observed: in fact, depending on the scenario, the frequency dynamics feature different overshoot magnitudes and initial ROCOF values. These phenomena can be justified by the latency of static power converters in providing the inertia contribution. Particularly for the ROCOF, the first instants of the transients are mainly regulated by the remaining conventional machines, although SI (according to its time constants) gradually succeeds to it, thus restoring the conventional dynamics of the power system.

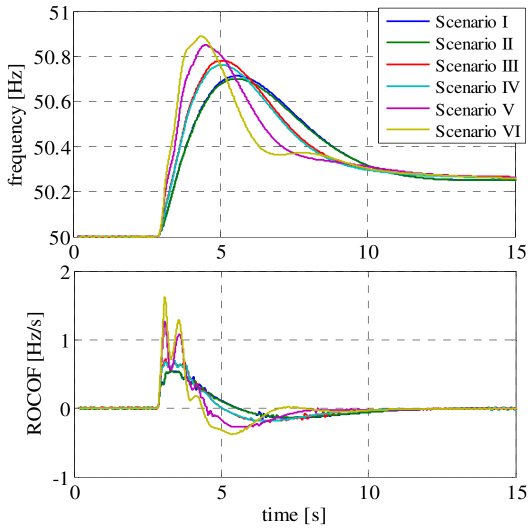

Figure 5 COIF (top) and related ROCOF (bottom) transients in all the scenarios without SI

CONCLUSION

Frequency stability is significantly related to the amount of inertia that dynamic devices in the power system can guarantee. In future scenarios, inertia is expected to be provided not only by traditional generation but also via advanced control of power-electronic-based units. The latter, however, is characterized by an intrinsic delay which has to be kept as small as possible (see **Figure 6**) in order to provide an effective contribution to frequency transient mitigation.

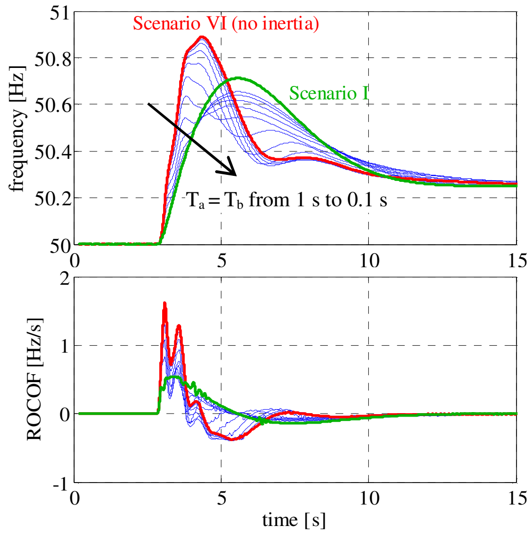

Figure 6 COIF (top) and related ROCOF (bottom) transients: scenario VI with different SI

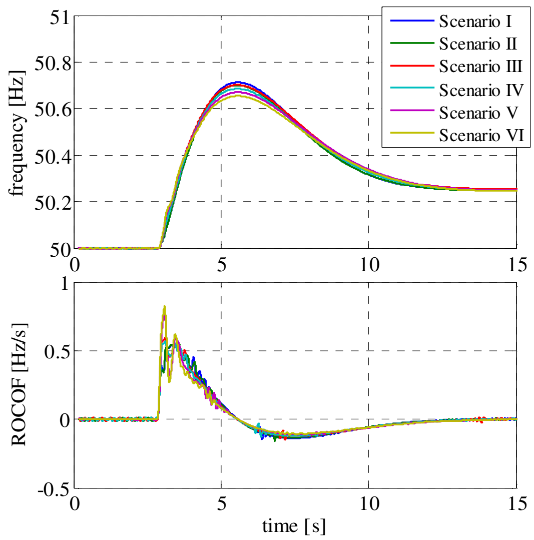

Figure 7 COIF (top) and related ROCOF (bottom) transients with $T_a = T_b = 0.1$ s

In large power systems, mechanical inertia is expected to become less uniform than today and to be deeply affected by the intermittency of renewable power sources. Therefore, SI optimal dispatch, together with adaptive tuning of the related controller parameters, can become a challenge. Such a challenge can be faced, in a WoC context, by suitable coordination among cell operators; in particular, the needed SI resources could be identified for each cell (as it happens, e.g., today for primary frequency minimal reserves at control area level).

In the present work, a preliminary analysis highlighting the possible benefits of SI has been carried out, with reference to a very small WoC. Although frequency transients are not exactly the same throughout the cells, they can be confused with the system COIF transient, probably due to the small size of the considered network. However, in larger networks they can be expected to become less similar to each other, so a cell management approach could be effective. Therefore, future work will involve the analysis of a more complex WoC, with the investigation of the effects of uniform or non-uniform SI.

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