**Discussion**

Conventional synchronous machines were found not to be able to ensure transient frequency stability in such conditions. The slow governor operation in the order of seconds is by far too slow to constitute the unique solution for frequency support during the transient period. Inverter based fast power reserve would be needed to be activated in an extreme short time.

To avoid load shedding in penetration scenarios above 80% of non-synchronous generation, inverter based fast power reserve must be deployed over a time in the order of 50-500 ms for load imbalances up to 40%. Nevertheless, today’s full power activation time of renewable sources without storage is in the range of 200 to 600 ms. Hence with today’s frequency measuring time and power deployment from renewable sources; load shedding and possible total black outs would not be avoided. In scenarios with plenty of renewables and high expected imbalances, storage would be a key factor in order to avoid de-loading and curtailment of renewables, the fast activation times (<50 ms) and promising price reduction make storage a good strategy to provide power balancing in both over and under frequency cases.

Synthetic inertia could tackle with under-frequency phenomenon. With penetrations of 80% or higher of IBG, and contribution of at least 20% of the IBG from Wind turbines with synthetic inertia controls, UFLS is avoided up to imbalances of 10% with a fast synchronous response (1-3 s in the IEEE modeled cases). For primary reserve deployment of 30 s (European model), synthetic inertia was not enough for avoiding UFLS.

An effective frequency measurement in shorter time would contribute to reduce the amount of inverter based power reserve and therefore, to diminish the de-loading factor or the storage capacity needed to provide it, up to a 10%. In order to avoid UFLS, ramping capabilities up to 3 times the base power load per second (3 pu/s) would be required from the inverter based sources; for combinations of inverter based generation above 80% and load imbalance in the order of 30% in both, micro grid and European scale islands. To achieve such response from distributed source, a continuous knowledge of the connected inertia to the system is required by the inverters since the IBFPR is based on the imbalance on the system and the critical time, which depends on system inertia. Additionally, system inertia is the linking bridge between RoCoF and power imbalance determination.

If the reference scenario for primary reserve is increased (imbalance higher than 2%) in the European context, synchronous response is not fast enough for imbalances higher than 2%. Full activation time in the range of 0.14 and 2.75 seconds would need required for the fast power reserve for penetrations of non-synchronous generation above 80 % (~2.5 s) and imbalances between 3 and 10%. Additionally, fast power reserve would be almost equivalent to the imbalance. Faster synchronous response reduces needed fast power reserve.

Although UFLS is avoided in the extended model in scenarios with penetrations of non-synchronous generation above 85% with injection of inverter based fast power reserve; total system stability is not ensured after a few seconds (~5 s), due to the presence of undamped oscillations provoked by the poor damping torque present in the system as consequence of synchronous share reduction.

Even though the approach considered throughout this work was the fast power reserve deployment to avoid under-frequency load shedding. If the same frequency deviation from nominal is considered as the critical for the over-frequency case (51 Hz); the same values would be obtained for critical time and power response. The difference lies in the power direction, in this case power should be removed from the grid or the excess converter to another form of energy, like electrochemical storage. In the case of batteries, the critical time would represent the needed time to allow charging the surplus of power available from renewables.

In general, similar behavior is exhibit from the different models and approaches, even though they differ considerably in size and complexity. Hence, simplified block representation of the power system seems to be a fair way to sketch overall system trends and responses. The difference in critical time estimation between a full grid simulation and a simplified model was calculated to differ between 20-35%, such difference could be crucial in fast power reserve studies and therefore should be considered when precise applications are implemented. A comprehensive method for estimation of the inverter based fast power reserve and critical time were developed and proved through the implementation in the two cases.

# Outlook

It was demonstrated the need of a fast power reserve for the reliable operation of future’s grid. To do so, an accurate and fast estimation of the power grid state is fundamental in terms of frequency and connected inertia; to enable inverter based generation to play a dominant role in frequency support. Further investigation in this area is fundamental to allow flexible inverter based generation. The integration of energy storage systems are promising alternative to provide ancillary services to the grid, the diminishing trend cost and fast activation times could be optimized together with de-loading of renewable sources to provide frequency support.

Investigation of grid forming inverters connected along with synchronous machines and grid-following should be further investigated. So far, investigation and implementation of such type of inverters has been done mostly for stand-alone systems.