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PARTICIPATION OF THE VIRTUAL POWER PLANTS TO THE FREQUENCY CONTROL IN POWER SYSTEMS

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This paper presents a dynamic model and simulation of a Virtual Power Plant (VPP) for participation to the frequency control in power systems. The simulations are performed in the Simulink software. Renewable Energy Sources (RES), Battery Energy Storage Systems (BESS) and classical generation units are considered in the VPP. The purpose is to determine the effectiveness of the control strategies currently applied, and to compare them with the improved solutions based on the extensive use of storage systems.

Keywords: Virtual Power Plant, Battery Energy Storage System, Frequency Control, Automatic Generation Control

1. Introduction

The massive penetration of intermittent renewable energy sources into the power systems, which began several years ago, is challenging the TSOs around the world to adapt their control strategies in order to solve the issues emerging from this new paradigm. Besides the multiple advantages that the PVs and wind power plants provide, the uncontrollable power output represents one of the main disadvantages as the TSOs require balancing resources for frequency control. Furthermore, as the PVs and WPP capacity expands, the difficulty in maintaining the demand-supply balance also increases, the need for new strategies in frequency control.

The Virtual Power Plant (VPP) concept consists in aggregating a significant number of small devices, such as generation units, controllable loads, and storage systems, to form a single entity which can be seen by the other actors as one power plant. For example, a VPP allows the TSO to integrate a huge number of small devices into its control structures under one single entity, while the complexity of controlling them is mitigated to the VPP control system.

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The VPP topic is regarded with high interests around the globe, as [1] demonstrates that, nine typical VPP projects were developed, mainly in Europe, USA, and Australia. The results indicate that VPPs can provide ancillary services for the TSO, participate to electricity wholesale markets, optimize the overall system reliability, and cost and facilitate renewable integration to the grid. The authors of [2] demonstrated that the VPPs with integrated storage systems can be used as a Frequency Restoration Reserve. Also, [3] presents a model predictive controller for a VPP combined with a BESS that provides primary and secondary frequency control. In [4] it is shown that a VPP is able to participate in frequency control and improve the grid response to power disturbances. A distributed scalable scheduling framework for large scale VPPs to provide secondary control reserve is presented in [5] and [6] introduces a control approach for large scale VPPs to improve the power system frequency characteristic without increasing the need for additional energy storage systems. Furthermore, [7] proposes a method to aggregate multiples EVs as a VPP in order to provide primary reserve in Smart Grids.

2. General aspects of the automatic frequency control

The ENTSO-E interconnected network of the Continental Europe is operated by 24 TSO as a single large synchronous network. The frequency in one system is strongly related to the frequency in all the other power systems. Maintained steady-state average frequency deviation is caused by power unbalances in the whole power system, although when analyzing closer within very short time frames the frequency is firstly influenced by local dynamic behavior of the power system components [8].

The primary frequency control, also called frequency containment control (FCC) is an independent and automatic control action, currently provided by all synchronous generation units connected to the grid. Therefore, the input signal to the regulator is the rotor angular speed of the synchronous generator, which is then compared to the reference value. The droop control technique is then usually employed to determine the equivalent power required to the provided in response to frequency variation. Such approach does not require special or complex power system architectures, but reliable and effective control resources [8].

A minimum frequency containment reserve must be maintained in each power system determined according to the total maximum load that can be recorded in the interconnected power system. Currently, the power system operator relies mostly on the large power plants and on the advantage provided by the wide synchronous interconnection which helps maintaining the frequency within tight limits almost all the time [9].

However, as the large and reliable synchronous power plants are replaced with small and intermittent nonsynchronous renewable energy sources, ensuring a deterministic frequency containment reserve is a challenge for the system operator. The reserves should be planned for both upwards and downwards power control.

The FCC comes after the instant reaction of the synchronous machines that naturally provide kinetic energy to counteract transient phenomena. Until now, a faster intervention of the FCC was not necessary because of the large mechanical inertia and kinetic energy available in classic power plants. On the other hand, we have to note that the FCC of conventional power plants are not capable in intervening faster than a few seconds from the identification of the perturbation.

The secondary frequency control (SFC), called also automatic frequency restoration control (aFRC) or automatic generation control (AGC), is a coordinated action, and has both technical and economic purposes:

- From *technical point of view*, it is designed to restore the frequency to the reference value, and at the same time to replace the frequency containment reserve. In order to avoid overlapping with the primary control actions, the deployment time of the secondary frequency control reserve, called also automatic Frequency Restoration Reserve (aFRR), is greater than that specific to the frequency containment reserve.
- From *economic point of view*, the SFC aims at cancelling the power mismatches on the interconnection lines, thus reducing the contribution of the neighbor power system on longer term to the frequency control and power balancing inside a certain power system.

The aFRC is activated in order to restore the Frequency Containment Reserve so that, at any instant, a larger fast acting power reserve is available to correct rapid frequency variations within the system. Additionally, aFRC is designed to cancel the frequency deviation and bring the system frequency back to the reference value. This will indirectly restore the net power interchange to the scheduled value [10].

Some power systems rely on hydro-generators and/or large turbo-generators. The power systems relying mostly on turbo-generators are subjected to significant changes in order to ensure the internal balance of the active power. These solutions depend on the technology development and the power market structure. Inter-TSO support can also be considered.

As the aFRC is a slow action, there is a wider freedom for qualifying other types of energy resources in case that the resources available in classical power plants are no longer available. In order to ensure a predictability of these resources, the aggregation of resources of various characteristics are operated in such a way to be seen by the power market operators as a single entity. Such aggregations are the Virtual Power Plant (VPP), and the microgrid (MG). An aggregation may not necessary be limited to generation entities, but also can include flexible loads and battery energy storage systems (BESSs) [11].

The VPP is seen as any other power plant by the AGC regulator, which means that a control signal is sent to the VPP controller either in upward or in downward direction. The VPP consists of any type of intermittent sources, BESS units, hydro units, as well as controllable loads. Usually, intermittent sources are not involved in providing secondary frequency control because of their stochastic behaviour. Only hydro units and BESSs participate in the aFCR. A VPP is created to cancel out the fluctuations in the power generation caused by the intermittent sources. The main idea is to use deterministic type sources to balance the intermittent sources [12].

3. Description of the block diagrams

3.1. The control scheme of the BESS

In the simulations discussed in this Section, the ESS considered is a Battery Energy Storage System (BESS). The control scheme of the BESS consists of two loops (Fig. 1) [13][14]:

(i) **The droop control loop**, modelling the primary frequency control. This loop is based on the change in the frequency by comparing the system frequency, f_{sys}, with the reference frequency, f_{ref}. A deadband is used to avoid unnecessary contributions from the battery when the frequency deviation is too small. The frequency deviation value Δf is filtered out by using a low-pass filter (LPF), then amplified by a droop value, $K_{\Delta f}$. This control signal can be optional and can be enabled/disabled by means of the coefficient α_f.

(ii) **The VPP loop**. The battery is one of the main units that may be suitable for balancing the power generation of a VPP around the predefined value, which is an economic engagement of the VPP owner on the electricity market. Depending on technical and economic characteristics of all the VPP components, the battery system can produce or absorb more or less active power whenever there is an order from the VPP controller, especially to counteract strong intermittencies. Long term and large unbalances can be cancelled out within the VPP by considering other options, such as the hydro units. In Fig. 1, the power order received by the battery energy storage system from the VPP controller is $P_{VPP\text{-}bat}$, whereas this option can be enabled or disabled by the coefficient α_{VPP}

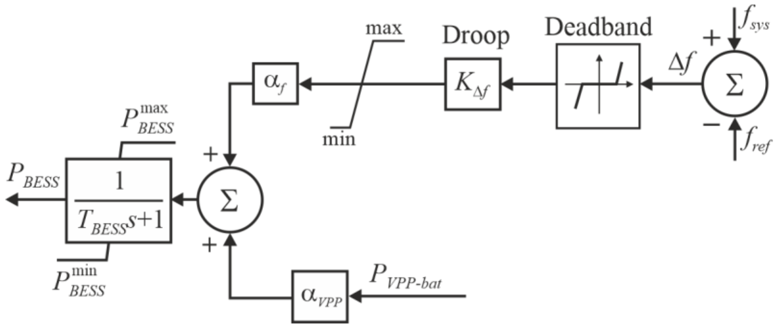

Fig. 1. The power and frequency control scheme of an battery energy storage system.

The output power of the ESS, P_{BESS}, is limited to its power capability in either direction, that is P_{BESS}^{min} and P_{BESS}^{max}.

3.2. The Virtual Power Plant (VPP) controller

The VPP controller aims at maintaining the total produced power around a reference value (Fig. 2). The VPP generation units can be located in different nodes of the electrical network. For this reason, individual measurements should be performed. Power measurements from wind units, e.g. P_{w1}, P_{w2}, …, P_{wn}, are inputs to the VPP controller, which are filtered out to avoid reacting to very fast wind power spikes. The VPP power order $P_{VPP\mathrm{ord}}$ is added to the total power input, then the resulted power, P_{VPP}, is compared with the VPP reference power, P_{VPPref}, decided by the VPP owner.

The resulted power error, ΔP_{VPP}, is passed through a PI regulator that provide the VPP power order, $P_{VPP\mathrm{ord}}$, to which the control signal received from the national AGC controller, P_{VPP_AGC}, is added. The resulted power order is introduced into a power repartition unit to determine the control setting of the hydro, P_{VPP_hyd}, and battery, P_{VPP_bat}, units associated to the VPP.

The PI regulator of the VPP should be faster than the PI regulator of the AGC to avoid unaccepted delays in frequency recovery within the secondary frequency control level.

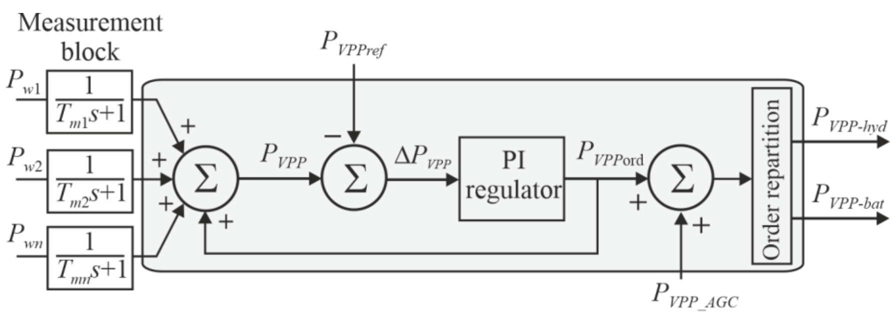

Fig. 2. The VPP control scheme.

3.3. The central AGC controller

Fig. 3 illustrates the control scheme of the central AGC controller. The central AGC operation is based on two types of measurements, i.e.:

- the active power flows (P_1, … P_n) on the tie-lines;
- the system frequency, f_{sys}, which is multiplied by a K-factor.

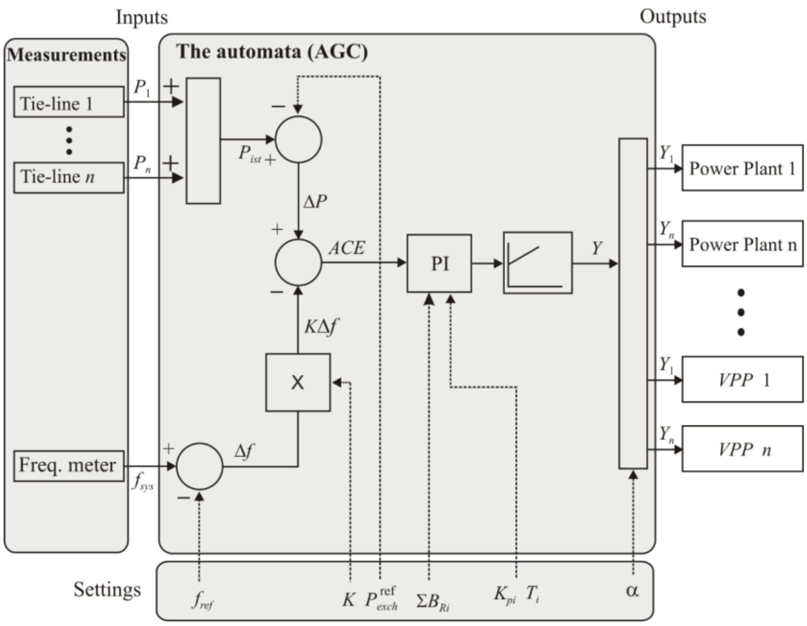

Fig. 3. The AGC control scheme.

The deviation resulted from the combination between the area power unbalance and frequency deviation results in an area control error (ACE), which is passed through a PI regulator. The output of the AGC regulator consists in control signals sent to the controllers of the power plants as well as to the VPP control.

4. Simulations and results

Fig. 4 illustrates the one-line diagram of the Dobrogea region from the Romanian power system. The Dobrogea region was chosen for simulations because it hosts ≈80% of the power installed in wind power plants. Additional, currently there are two large nuclear units located at Cernavoda (generators represented in yellow in Fig. 4), while one more unit is planned to be built here depending on the political decisions [13][14].

In order to simulate the power exchanged with the neighboring areas, an external system (Fig. 4) was considered, consisting of two hydro units (represented in blue in Fig. 4) and one load, together with the interconnection lines. Additionally, the interconnection with the Bulgarian power system was simulated by considering static loads at the ends of the two interconnection lines on the Southern part.

A VPP was created in the Dobrogea area, by considering two active wind power plants (represented in green in Fig. 4) at Stupina and Tariverde, modelled by a variable power generation curve. We assume that a VPP can work efficiently by including also one BESS (represented in orange in Fig. 4). In our model, we assume that the storage system connected to Stupina bus.

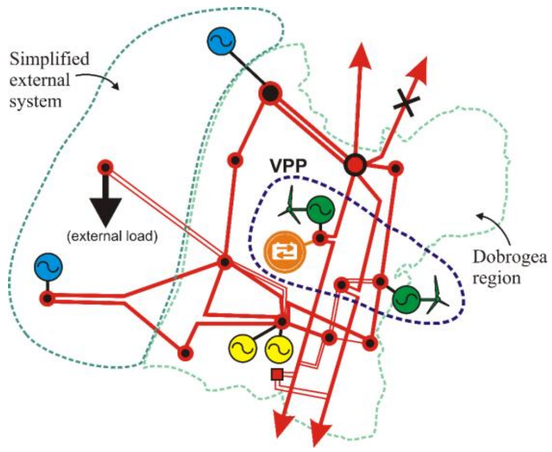

Fig. 4. The simplified system of Dobrogea.

Simulations have been performed in Simulink. The model implemented is illustrated in Fig. 5. In this scheme, the synchronous machines are colored in red, and the loads are colored in orange. The total simulated in this model is ≈1800 MW.

In all simulations, we assume the sudden connection of a 100 MW load, at 30 s after the simulation inception. This perturbation can, in terms of power unbalance, be somehow equivalent with the disconnection of a 100 MW generator. The main purposes of these simulations are to demonstrate:

1. The operation of a VPP;
2. The integration of a BESS into a VPP;
3. Integration of a VPP into the frequency restoration control (FRC) system;
4. The use of BESS for frequency containment control (FCC).

Fig. 6 shows the importance of a rapid contribution of a storage system to limit the frequency nadir. In such our model, the frequency drops to dangerous value when synchronous machines only are considered to operate in droop mode.

However, for this area we have to note that the Dobrogea area is inherited with strong mechanical inertia from the nuclear power plants.

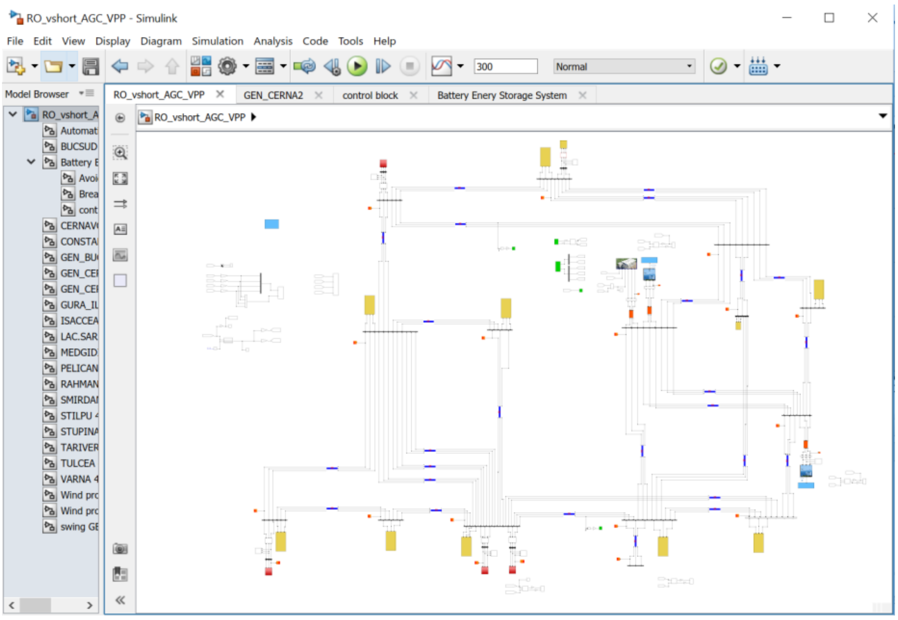

Fig. 5. The simulated network implemented in Simulink.

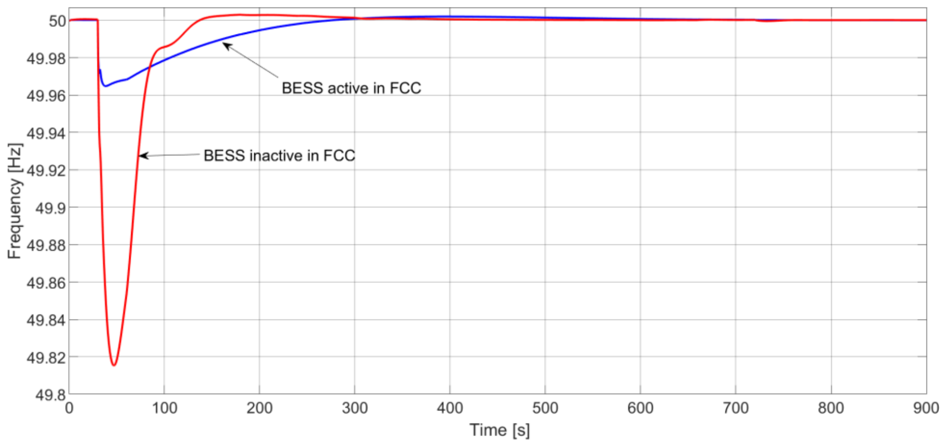

Fig. 6. Frequency dynamics in the case with and without BESS active in the FCC loop.

The BESS was sized to 50 MW and 60 MWh. The state of charge (SoC) of the BESS is initialized to 50%, assuming that the power variations can be either positive or negative. In our simulations, because of the loss of a large load, the BESS is ordered to produce power.

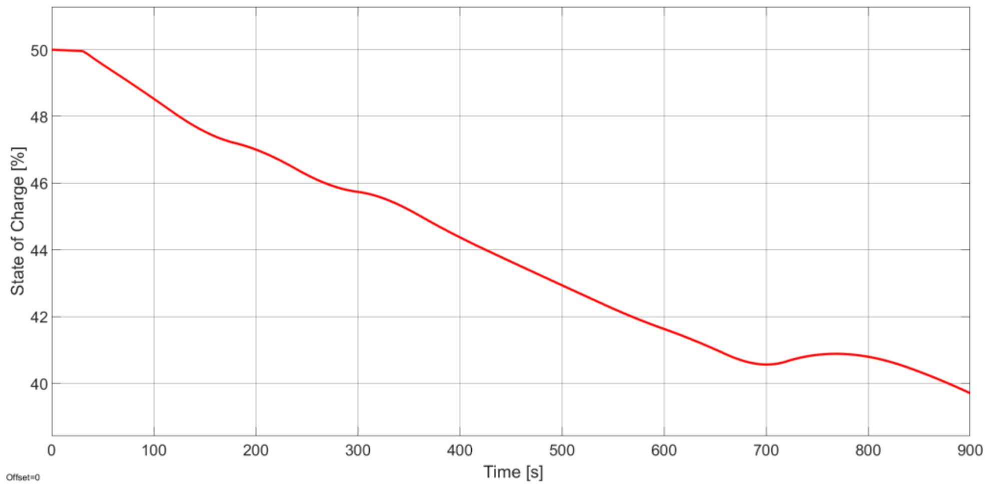

Fig. 7. State of charge of the BESS in the case with FCC active.

The BESS controller includes tree control signals, one as frequency response in FCC, one as power order from the AGC, and one as balancing response within the VPP. Fig. 8 illustrates the BESS power variations in in the three control loops, as well as total power response. BESS provides power very quickly after the perturbation inception then decreases toward zero, while the AGC power is initiated at instant 60 s and, together with a synchronous machine acts to replace the frequency containment reserve and to bring the frequency close to the reference value.

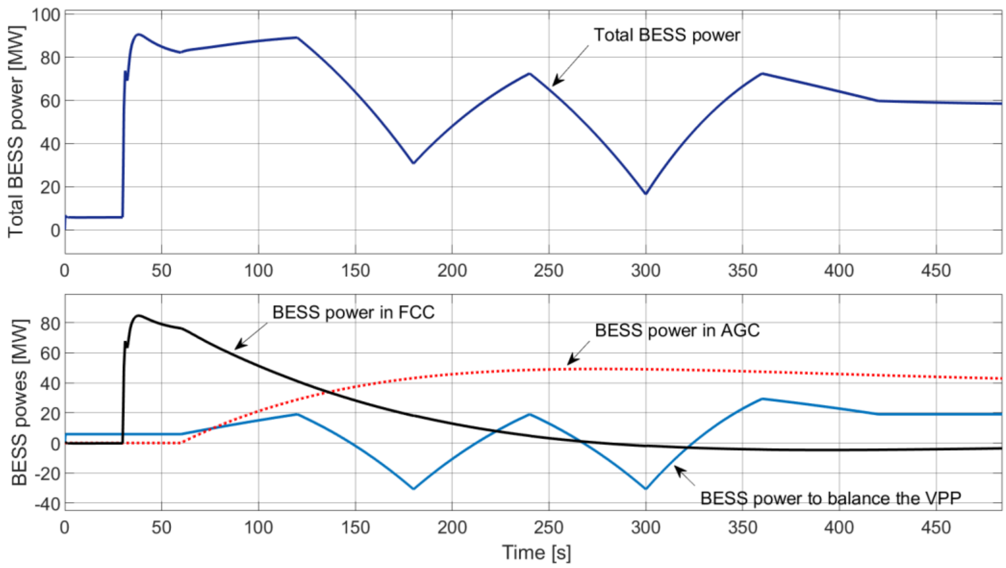

Fig. 8. BESS control powers.

The VPP is set to produce a constant power. Since the two wind generators are fluctuating, the BESS either produce or absorb power to balance the wind generation and maintain the VPP power at the predefined value. We should note that if the VPP requires negative power, and the AGC required positive power, the total generation is the aggregation of the two.

6. Conclusions

Based on the simulations performed the following remarks and recommendations are relevant for the frequency containment:

- In low-inertia power systems, the hydro units are not capable of stabilizing the frequency. Furthermore, because of their construction, some hydro units have an inverse effect in the first instants after the unbalance inception which amplifies the instability. For this reason, faster units are necessary, e.g. electrochemical energy storage systems, super-capacitors, flywheels;
- A new component should be introduced within the balancing market called fast frequency containment control (FFCC). FFCC can be based on fast-responding devices such as converter-interfaced energy storage systems and renewable energy sources. However, the need for this market component should be decided for the whole Continental system of ENTSO-E based on detailed simulations of the entire ENTSO-E system database. The reserves and the type of technology (characterized by response time) needed for such a control should also be based on detailed simulations of the most severe perturbations;
- A minimum level of power reserve should be available in fast-acting resources. This level depends on the share of mechanical inertia available in synchronous generators and their location within the system. In transient state, the power rating is more important than the energy capacity. In order to maintain the system stability, it is not necessary to design a power reserve capable of recovering the frequency very close to the nominal value. This is because this control level should be designed to ensure the frequency stability, while the slow FCC can take the next steps in recovering the frequency. Note that, these aspects can involve economic discussions;
- If conventional, decentralized FCC is applied, no communication is necessary with external entities. All hardware systems required for the FCC are available on-site, as components of the metering and automation systems of each generation resource. This control approach is robust because it does not depend on other systems but reacts to local signals;

- Standardized operation characteristics should be provided for those units that respond to both inertial and frequency containment control. This is important because the two actions are linked in time, and the power provided as frequency control service is set eventually by the same controller.

Based on the simulations performed the following remarks and recommendations are relevant for the automatic frequency restoration:

- The Virtual Power Plants and the Microgrids will play an active role in the secondary frequency control. Both concepts can be classified as aggregators. Both types of aggregators require standardization of the operation in relation to the network operator in the grid cods, such as: communication type, reserve monitoring and QoS monitoring;
- A central controller is required for both VPP and MG. There must be a communication channel between the AGC and the VPP controller. For logistic reasons, the VPP controller can be better located in a city. The VPP controller can be seen as a power plant controller that distributes the signal received from the central AGC to the individual generation units. However, in the case of a VPP, there must also be an internal balancing that eventually causes the central AGC to react;
- Using an ESS within the aFRC can be an effective technical solution. However, long term analysis for multiple scenarios should be studied. This is because once the state of charge is low, the ESS is no longer available to participate in case of under-frequencies and has to wait for a load valley or surplus of power from renewables to charge. Therefore, large rated ESSs should be considered in the aFRC to cover large power unbalances;
- When an ESS is used for aFRC, delays should be added to the reaction of the BESS in order to avoid the frequency to be restored in a longer time. The ESS can be effectively used in various control levels by appropriately choosing the delay times;
- In order to save the energy available for aFRC, some ESSs can be included in the tertiary frequency control level. Therefore, faster reaction from the tertiary control reserves can be designed in order to optimize the use energy resources in all control levels. However, this requires a more intense activity from the system operator;
- As the share of RES is increasing, larger storage systems are required. These can be split into smaller units and operated in an aggregated manner, or large individual units can be built.

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