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Provision of Virtual Inertia Support Using Battery Energy Storage System

SUMMARY

The paper presents the importance of the grid inertia constant for the frequency stability of the future high-res low-inertia power systems. Since more and more renewable energy sources (RES) are being connected to the power system via inverters, the grid inertia constant is reduced. This issue can be mitigated by applying appropriate control mechanisms through which RES can provide virtual inertia and provide rotating reserves for primary frequency control. The concept of a virtual inertia provision using battery energy storage system (BESS) is elaborated in the paper. By applying a virtual inertia concept, RES can provide support for frequency control during disturbances almost like conventional synchronous generators. The influence of virtual inertia on the stability of the part of Croatian power system was analyzed using BESSwith a control mechanism that enables its participation in frequency control.

KEYWORDS

frequency control, power system inertia, renewable energy sources, battery energy storage systems

1. INTRODUCTION

To reduce the impact of energy industry, especially electricity production, on climate change and the level of CO2 in the atmosphere, European Parliament in the framework for achieving climate neutrality brings key goals for upcoming years. These goals include reducing greenhouse gas emissions by at least 55% compared to 1990 levels, increasing energy efficiency by at least 32.5% and at least 32% of total energy obtained from renewable sources. The long-term goals of the European Union for 2050 have an optimistic goal of achieving a climate-neutral society, that is, reducing greenhouse gas emissions to net zero. All goals and directives adopted both in the European Union and in the world encourage the use of energy from renewable sources [1,2]. The consequence of such policies is a significant increase in the installed capacity of renewable energy sources in the world, Figure 1.

It is evident from the figure below (Figure 1) that the largest increase in installed power is recorded by wind power plants and photovoltaic power plants, which are technologically very different from classic power plants that produce energy using synchronous generators.

Synchronous generators, with a governor and excitation control systems, contribute to the stability of power system after disturbances, due to their inherent inertia of the rotor, damping torque and the possibility of reactive power production. However, renewable energy sources connected to the grid via inverters are characterized by low output impedance, fast response to changes in active and reactive power, and little or no inertia and damping torque.

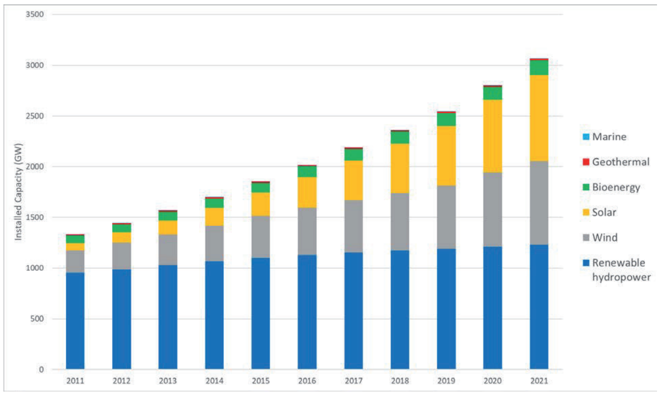

Figure 1. Yearly cumulative increase in RES installed capacities [3]

Due to the significantly lower operating costs of renewable energy sources, compared to traditional power plants, especially those running on fossil fuels, the share of renewables in the production mix is growing constantly. The number of renewable generating units in the daily operation on the grid is increasing, which consequently negatively affects the inertia and thus the stability of power system, which becomes more vulnerable to frequency disturbances.

To improve the dynamic performance and stability, it is necessary to provide additional inertia to the power system. To achieve this, the concept of a virtual synchronous generator was proposed, that is, adding virtual inertia to a renewable energy source using a short-term energy storage together with a frequency converter and a suitable control mechanism. In this way, the renewable generating units will provide inertia and damping torque like conventional synchronous generators [4].

In [5] a literature review of the current state-of-the-art of virtual inertia implementation techniques is given, and potential research directions and challenges are explored, while the major virtual inertia topologies are compared and classified.

In [6] a comprehensive review of virtual inertia (VI)-based inverters is presented and discussed, together with a provision of dynamic models for RMS studies in PowerFactory software tool.

Evaluation, comparison, and technical analysis of each VI-based inverter techniques, including virtual synchronous machine (VSM), virtual synchronous generator (VSG), and synchronverter are given. The assessment of VI emulation techniques, including the critical analysis, current challenges, and future research on virtual emulation, are presented.

The studies of future low-inertia power systems, [7,8], review the various control techniques and technologies that offset a decrease in inertia and discuss inertia emulation control techniques available for inverters, wind turbines, photovoltaic systems, and microgrids.

A comprehensive review of VSG and control system topologies for virtual inertia simulation are given in [9] and [10]. Classification of VSG based on model's order is presented, and future research directions are given.

A comparative analysis of a power system stability with virtual inertia is given in [11]. The paper presents power system modal analysis with Voltage Source Converters (VSCs) controlled as synchronverters, vector control, or Rate of Change of Frequency-based Virtual Synchronous Generator, thus comparing different approaches to VSC control. The results demonstrate the benefits of synchronverters over other control strategies.

Extensive work has been done to obtain simplified wind generator models for frequency response studies. In [12] it is proved that the coefficient K_G of wind turbines is not constant. When wind direction and speed vary, the output power changes, and this means that the actual power of the wind generator transmitted to the primary frequency control changes. As a result, the value of K_G should be determined at different wind speeds. Therefore, modifications to the wind turbine control systems are proposed to take advantage of the inertial behavior of wind farms.

The increasing penetration of wind power with static converters has led to a reduction in the equivalent inertia of power systems, which worsens the dynamic response of the system frequency (lower frequency support and frequency instability). The criteria for the allowable reduction of system inertia can be the rate of change of frequency (ROCOF) or the maximum frequency deviations [13,14].

Application of BESS for enhancement of grid inertia is studied in [15]. The paper quantitatively assesses the impact of large-scale BESSs on frequency containment for low inertia power grid and compares the performance of grid-forming and grid-following control modes. It is concluded that BESSs can provide significant value to both frequency containment and restoration services.

In [16] a virtual adaptive inertia control (VAIC) strategy for distributed battery energy storage system in microgrids is proposed, while in [17] a hybrid energy storage system (HESS) consisting of supercapacitor and battery is employed for enhancement of frequency response in a microgrid, controlled by a virtual synchronous generator strategy.

The aim of this paper is to give an overview of the inertia shortage problem in future power systems, and to simulate a simple but effective solution for improving grid inertia constant with BESS for a part of Croatian power system.

The rest of the paper is organized as follows: Section 2. presents the fundamentals of inertial response from synchronous generator, and gives discusses the inertial response in future power sytem with high RES share. General virtual inertia concept is presented in Section 3. Results of the simulation of BESS influence on Croatian power system stability are given in Section 4.

2. GRID STABILITY OF FUTURE HIGH-RES LOW-INERTIA POWER SYSTEMS

2.1. Inertial response of a synchronous generator

Inertia is one of the main parameters of power system's secure operation. Inertia of the synchronous generator and turbine coupled rotating masses, and to a smaller extent electrical drives, determines the frequency response of the power system to the imbalance between production and consumption, and thus affects frequency stability. Rotational speed of large and heavy rotating machines cannot be changed instantaneously. When frequency change occurs, the rotating masses inject kinetic energy into the power system or absorb it from the power system, in order to oppose frequency changes, and will slow down in the case of energy injection or speed up in the case of energy absorption, [18].

The ROCOF (*df/dt*) is defined by the swing equation:

$$\frac{df}{dt} = \frac{1}{2\pi}\frac{d\omega}{dt} = \frac{1}{2\pi}\frac{P_m - P_e}{2H_G} \tag{1}$$

where: ω - grid frequency in pu; Pm and Pe - mechanical and electrical powers in pu, respectively; H_G - grid inertia constant in seconds.

With higher grid inertia constant, a lower rate of frequency change is achieved, and thus the power system is more stiff in the event of a disturbance. However, in the case of a smaller grid inertia constant, the frequency response is more dynamic and oscillatory when a disturbance occurs, which can lead to a violation of power system frequency stability and finally to the loss of power system integrity, and even to complete blackout. The inertial response begins at the instant of disturbance occurrence, before the primary frequency control reaction. Synchronous generators oppose frequency change by absorbing real power from the grid or injecting real power into the grid. The real power that is injected into the network comes from the kinetic energy of the machine rotating masses, what results in a decrease in the machine rotational speed. This applies to the case of an increase in consumption compared to production, that is, in the event of a production unit outage or connection of a large load.

In the case of production increase or consumption decrease, absorption of energy from the network occurs and consequently an increase in machine's rotational speed. Figure 2 shows the inertial response and the response of frequency containment reserves (FCR) and automatic frequency restoration reserve (aFRR), after connection of a significant load. The minimum frequency that appears after the disturbance depends on the value of the grid inertia constant.

Inertial response, as an inherent property of synchronous machines operation, cannot be controlled. In thermal power plants, turbogenerators contain from 30 to 60% of the inertia in the turbine, and in the case of hydro generators, 4 to 15% of the inertia is contained in the turbine, including the inertia of the water. Incidents that significantly disrupt power system frequency stability are mainly outages of large production units and loads from the network, disconnection of HVDC links that connect different power systems, and system separation.

The value of the inertia constant affects:

- the initial slope of the frequency change curve after disturbance,
- the time when the highest frequency deviation occurs,
- maximum frequency deviation from the nominal value (frequency nadir).

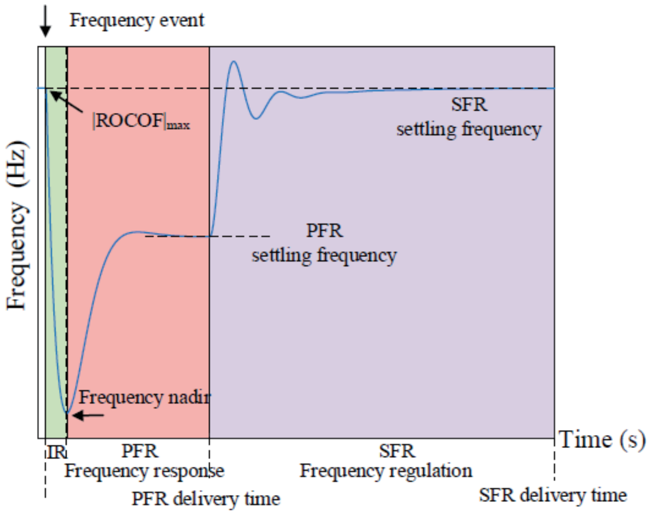

Figure 2. Inertial response and FCR and aFRR response, after connection of a large load [19]

With larger values of grid inertia constant, the frequency drop in the system occurs more slowly, but the duration of the transient is longer. When the ROCOF is slower, the turbine controllers have a longer time for reaction, and therefore the maximum frequency deviation will be smaller. The inertia constant does not affect the value of frequency at which the frequency stabilizes after the disturbance.

In contrast, lower values of the grid inertia constant will allow very fast frequency changes and large frequency deviations, whereby the response of the turbine controller will be faster, which will result in larger and faster frequency oscillations, which is undesirable. The initial slope of the frequency change curve after the disturbance will be very large for systems with a small value of the grid inertia constant.

2.2. Inertia in high RES power systems

In future power systems, with a high RES share, conventional power plants will be often replaced in favor of RES units with lower marginal costs, thus reducing grid inertia. RES operate very differently from conventional power generating units. RES are connected to the grid via power electronics devices, i.e. converters, what results in partial or complete electrical separation of the power generating units from the grid. As a result, the relation between the rotational speed of the generator and the frequency of the system is not relevant anymore. Therefore, the generating units connected to the grid via inverters do not contribute to the overall grid inertia. Then, the kinetic energy reserve present in conventional energy sources is often missing in RES. For example, photovoltaic power plants have no rotating parts, and a very small amount of energy can be stored in capacitors.

The lack of grid inertia results in higher rates of frequency changes and maximum frequency deviations from the nominal frequency during sudden changes in production and consumption, which can lead to system instability, as well as relay protection triggering and thus disconnection of generating units from the network, or even underfrequency load shedding. Reduced grid inertia also affects other elements of power system operation, such as voltage stability, system protection, control reserves, etc.

The inverters that electrically separate RES generating units from the grid are not set to act on system frequency changes. However, by measuring the frequency deviations, the inverter can be adjusted to exchange energy with the grid in a controlled manner. This kind of energy exchange is called the virtual inertial response.

If the inertia constant of a classical machine with a synchronous generator is expressed as:

$$H = \frac{E_k}{S_n} = \frac{J\omega_0^2}{2S_n} \tag{2}$$

where: H - inertia constant [$MJ/MVA= s$], E_k - total kinetic energy of the rotating mass [MJ], S_n – machine nominal power [MVA, J - machine total moment of inertia [kgm^2], ω_0 - synchronous speed of the rotor [rad/s].

then the contribution to the grid inertia constant of conventional generating units and generating units connected to the grid via inverters can be expressed as, [20]:

$$H_G = \frac{\sum\frac{J\omega_0^2}{2}+\sum\frac{J_V\omega_0^2}{2}}{S_G} = \frac{\sum E_k+\sum E_v}{S_G} \tag{3}$$

where: H_G – total grid inertia constant [$MJ/MVA= s$], J_V - total virtual moment of inertia [kgm^2], EV - total virtual kinetic energy [MJ], S_G – total system nominal power [MVA].

Figure 3 shows an illustration of the effect of the added virtual inertia on the inertial response when disturbance occurs in the system compared to the inertial response without the added virtual inertia. Primary control cannot act fast enough to stop the frequency change instantaneously. It can be concluded from the figure that systems with low inertia have higher maximum frequency deviations and a higher ROCOF.

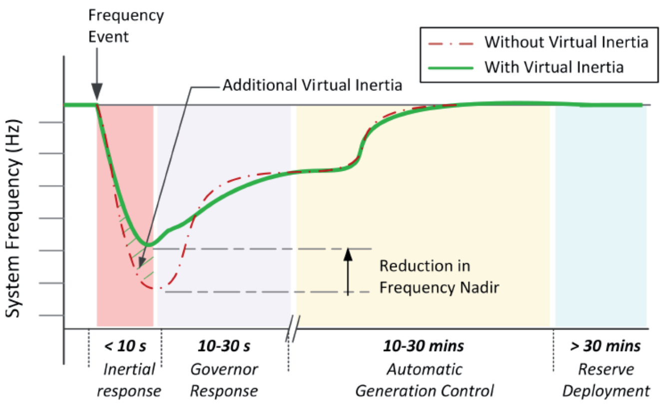

Figure 3. Time response of frequency control to load increase including virtual inertia [21]

Since inverters electrically separate the RES generating unit from the grid, any kind of energy source or storage can be used to contribute to the moment of inertia of the system, for example flywheels, batteries, supercapacitors, etc. In wind farms, there is a large amount of stored kinetic energy in the turbine blades and generator, whose inertia constant is equal to conventional power plants and ranges from 2 to 5 s. However, since the wind power plant is separated from the grid with the inverter, it does not contribute to the grid inertia, therefore this kinetic energy could be used to provide the virtual moment of inertia.

In the case of photovoltaic power plants, additional energy storage can be implemented in the form of batteries. It is also possible to curtail production units in order to have available power reserve. However, the problem with such solutions are some restrictions that occur: limitations of the inverter operation, minimum rotor speeds, maximum acceleration and deceleration of wind turbine blades, and dependence on the operating point. The inertia provided by the load to the system, mainly motors and fans, will decrease in the future due to the increasing use of frequency converters to control these devices [19].

Under almost all scenarios, kinetic energy from conventional energy sources will be lower in the future than today. Therefore, it is necessary to take particular measures that would compensate for the lack of conventional inertia from synchronous generators:

- Virtual inertia of generating and consumption units connected via inverters,
- Use of hydroelectric power plants operating at minimum power or in compensator mode,
- Changing the parameters of the control systems of power plants that provide frequency control services.

The challenges of electric power system operation and control will be solved by a combination of the above-mentioned measures in order to ensure the necessary stability. Providing the inertial response of wind farms is a

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method that is already beginning to be applied in practice and will become widely applicable for all systems with a high portion of electricity produced from wind farms. Other methods of providing virtual inertia are currently still in research stages. However, with the increasing RES integration, there should be a greater implementation of virtual inertia and thus the gradual increase of its importance in maintaining the dynamic stability of power system.

3. VIRTUAL INERTIA CONCEPT

The idea behind virtual inertia is based on implementing dynamic properties of synchronous generators to generating units that are connected to the grid via inverters, simulating this way dependency of the rotor speed and grid frequency, controllable active and reactive power output, influence of rotating masses and damping windings, and stable parallel operation, improving stability of the power system. This principle can be applied to one or a group of generating units. The latter is, of course, more economical, and better from the grid operator's point of view, but the first method is more suitable for owners of generating units.

Generation system with implemented virtual inertia, used in the simulations, consists of an BESS, inverter, and the control system, Figure 4. Virtual inertia concept is implemented between the energy source and the grid, and presents the energy source as a synchronous generator to the grid in terms of inertial and damping properties. Virtual inertia is emulated by controlling the active power through the inverter inversely proportional to the rotor speed. From the grid point of view there is no difference between an electromechanical synchronous generator and an electrical virtual synchronous generator, except for the increased frequency noises due to the switching operations of the inverter's semiconductor valves.

Since the described generation system should be able to inject or absorb electrical energy, while operating in normal state of operation, the state of charge of the BESS should be at 50% of the nominal storage capacity. Depending on charging conditions, the operating conditions can be described depending on the specified upper and lower limits which are determined depending on the energy storage technology, for example 20 and 80% of the maximum charging state. When the charging state is between these limits, the generation system works in active mode, and when there is an excess of energy in the system, it works in virtual load mode.

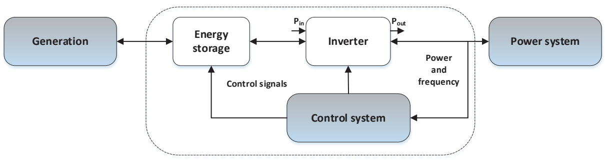

Figure 4. Structure and concept of a generation system with implemented virtual inertia

The main purpose of the virtual inertia concept is to increase the grid inertia constant H. The output power of the generation system with implemented virtual inertia can be expressed as:

$$P_G = P_0 + K_H \frac{d\Delta\omega}{dt} + K_D \Delta\omega \tag{4}$$

where: P_G - generation system output power, P_0 - initial power transmitted to the inverter, K_H - virtual inertia characteristic coefficient, K_D - virtual damping characteristic coefficient.

In expression (4), P_0 represents the power that was transferred through the inverter to the grid before the disturbance occurred. Then, the second term of the equation represents the injected or absorbed power from the network depending on positive or negative frequency deviation from the nominal frequency. Furthermore, $_{H}$ can be expressed as:

$$K_H = \frac{2HS_n}{\omega_n} \tag{5}$$

where: ω_n is the nominal grid frequency.

K_H acts as a gain constant, and it must be chosen in such a way that the virtual synchronous generator gives the maximum active power when the maximum ROCOF occurs, for example 1 Hz/s. The drop in frequency, i.e., rotational speed, can be reduced by increasing the virtual mass, but in this way oscillations of synchronous units can occur. By increasing inertia, i.e., the parameter K_H, the maximum frequency and rotor speed deviations will decrease, but the natural frequency and damping will also decrease.

Given that $d\omega/dt$ is by its nature an error signal, because the balance point is at zero, the power will alternate only in transient states, which does not necessarily mean that the system frequency will return to nominal value. To avoid this problem, a static part should be added, that is, the third part of the expression (4). In this way, at every moment the nominal frequency is subtracted from the measured one, thus providing an error signal whenever a frequency deviation occurs within the power system. The purpose of K_D is to imitate the influence of synchronous generator damping windings and represents a linear damping. It is chosen in such a way that the third part of equation is equal to the rated power of a generation system with implemented virtual inertiaat the maximum allowed frequency deviation.

Unlike conventional synchronous generators, which are opposing to changes in the rotor speed, or frequency, using the kinetic energy of rotating masses, generation system with implemented virtual inertia usually use energy from the BESS. Also, for the case of energy consumed during disturbance damping, the energy is dissipated on the resistances of the damper windings. However, in the presented concept, this energy needs to be absorbed by the BESS to balance the power system generation and load. The most important parameters for choosing the appropriate BESS technology for generation system with implemented virtual inertia are: maximum power system load, rated power of production units providing frequency control services, mean value of charging state in normal operation, detection time, control delay, maximum of the total response delay.

From the last two terms of expression (4), it can be concluded that power can flow in both ways, from the electric power system to the energy storage and vice versa. The result is that generation system with implemented virtual inertia can act as conventional synchronous generator, but also as a load, depending on the sign of the frequency deviation.

Essentially, virtual inertia opposes network frequency deviations, while virtual damping suppresses grid oscillations, thus obtaining equally effective features of synchronous generators. The gain constants K_H and K_D must be negative in order to provide power which will counteract the change in frequency. Increasing the value of characteristic constants means that there will be more power injected or absorbed for the same frequency change, i.e. ROCOF change. However, there is a limit to how much the constant K_H can increase. This limit depends on the rated power of the inverter and the phase synchronization mechanism precision. Namely, the inverter has no possibility of overloading like a synchronous machine, therefore a high derivative term leads to higher power overloading during transients. Then, the precision of frequency determination depends on phase synchronization mechanisms. Because of the afore mentioned, the optimum value of the derivative term K_H is determined by a compromise among the size of virtual inertia, inverter's overload capacity, and characteristics of the phase synchronization mechanism [8].

4. SIMULATION OF VIRTUAL INERTIA INFLUENCE ON CROATIAN POWER SYSTEM STABILITY

For the simulation of the virtual inertia influence on Croatian power system stability the DIgSILENT Power Factory 2020 power system analysis software was used. The aim of the simulation was to show the impact of BESS contribution to grid frequency control and grid inertia constant. BESS with nominal power of 10 MW was added to the 110 kV substation Vrataruša. The BESS was connected to the 110 kV busbars via a two-winding transformer. As previously explained, the BESS injects or absorbs active power when an imbalance between production and consumption occurs, that is, when the frequency deviates from the nominal value. The BSEE model used in simulations is shown in Figure 5.

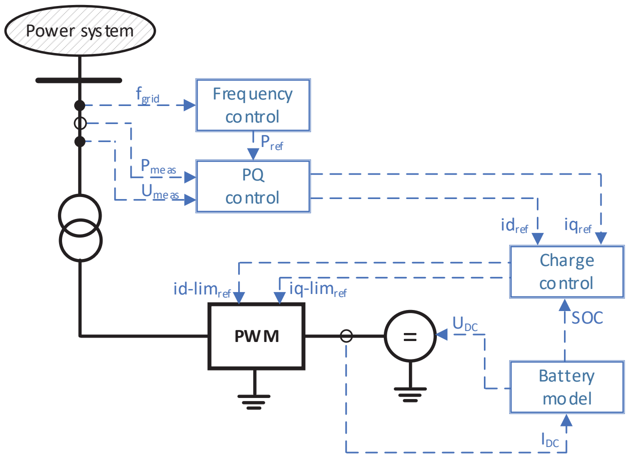

Figure 5. BSEE model used in simulations

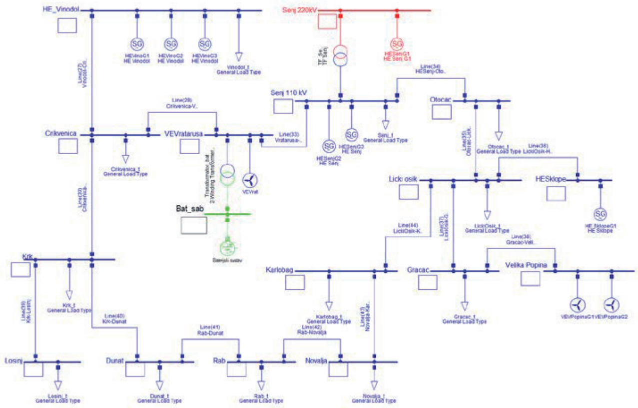

Figure 7. Power factory model of the analyzed system

The simulation is done on the part of the Croatian 110 kV transmission subsystem, shown in Figure 6. The corresponding Power factory model of the subsystem shown in Figure 6 is presented in Figure 7. Total load of the analyzed system is 231 MW.

To clearly show the influence of a relatively small BESS on the frequency transient, island mode of operation was assumed for the modeled subsystem. Generally, in the island mode of operation, the power system is more susceptible to disturbances, because the total amount of generating capacity, and thus the grid inertia constant, are smaller.

Generator G2 of the Senj hydropower plant (HPP) was set as the reference machine. Every HPP is modeled as participating in FCR. The modeled wind farms Vrataruša and Velika Popina produce only active power (unity power factor), and do not participate in frequency control, nor provide inertia to the system. Simulation of inertial response and frequency control considers four scenarios: step increase of system load by 10% and step decrease of system load by 10%, with and without BESS connection.

In the first scenario, the load increase occurs in the third second, followed by frequency drop and generation increase of generation units participating in FCR. Maximum frequency nadir (deviation) occurs in the scenario without BESS operation, when the frequency drops to 0.971 p.u. that is, at 48.55 Hz. In the scenario with BESS operation, the frequency drops to 0.983 p.u., i.e. at 49.15 Hz. Frequency response at 110 kV bus Vrataruša with and without BESS is shown in Figure 8.

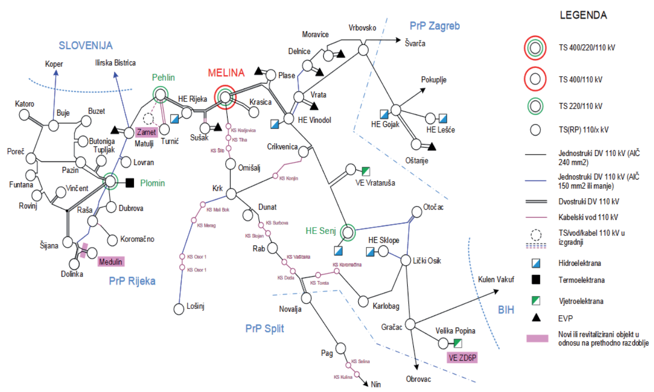

Figure 6. Part of Croatian 110 kV transmission system (Rijeka area)

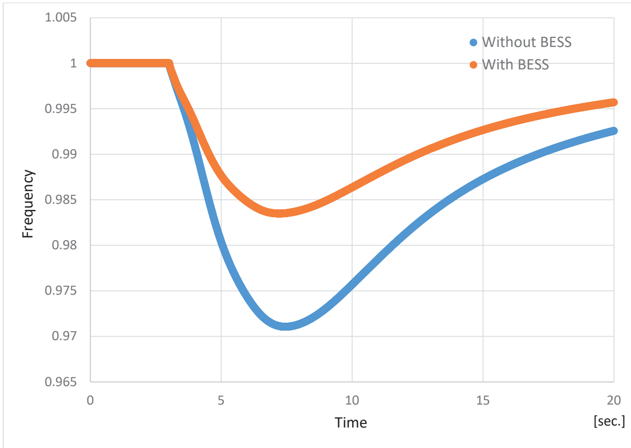

Figure 8. Frequency response at 110 kV bus Vrataruša with and without BESS when the load increases by 10%

The BESS from the simulated example provides virtual inertia to the power system, thereby reducing the maximum frequency deviation and the ROCOF. However, it also participates in FCR for a certain period of time, which depends on its total capacity and current state of charge. Therefore, for realistic application of such a technology, it is necessary to take into account these parameters. The BESS power injection is shown in Figure 9.

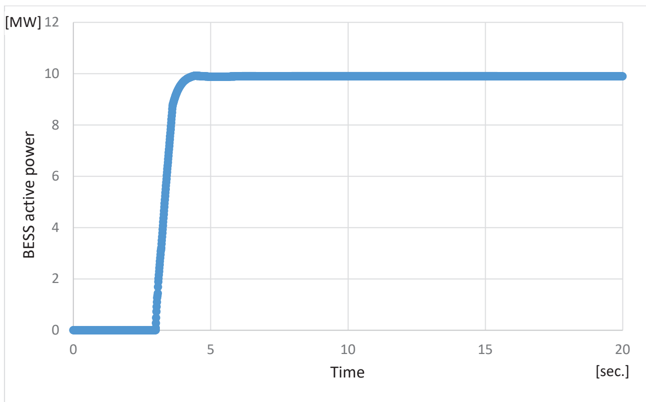

Figure 9. BESS active power injection

Furthermore, when the load changes in the third second, the generating units inject power into the grid to balance production and load. The power increase of HPP units without and with BESS is given in Figure 10. If BESS is applied, lower power of the HPP units in the stationary state can be observed.

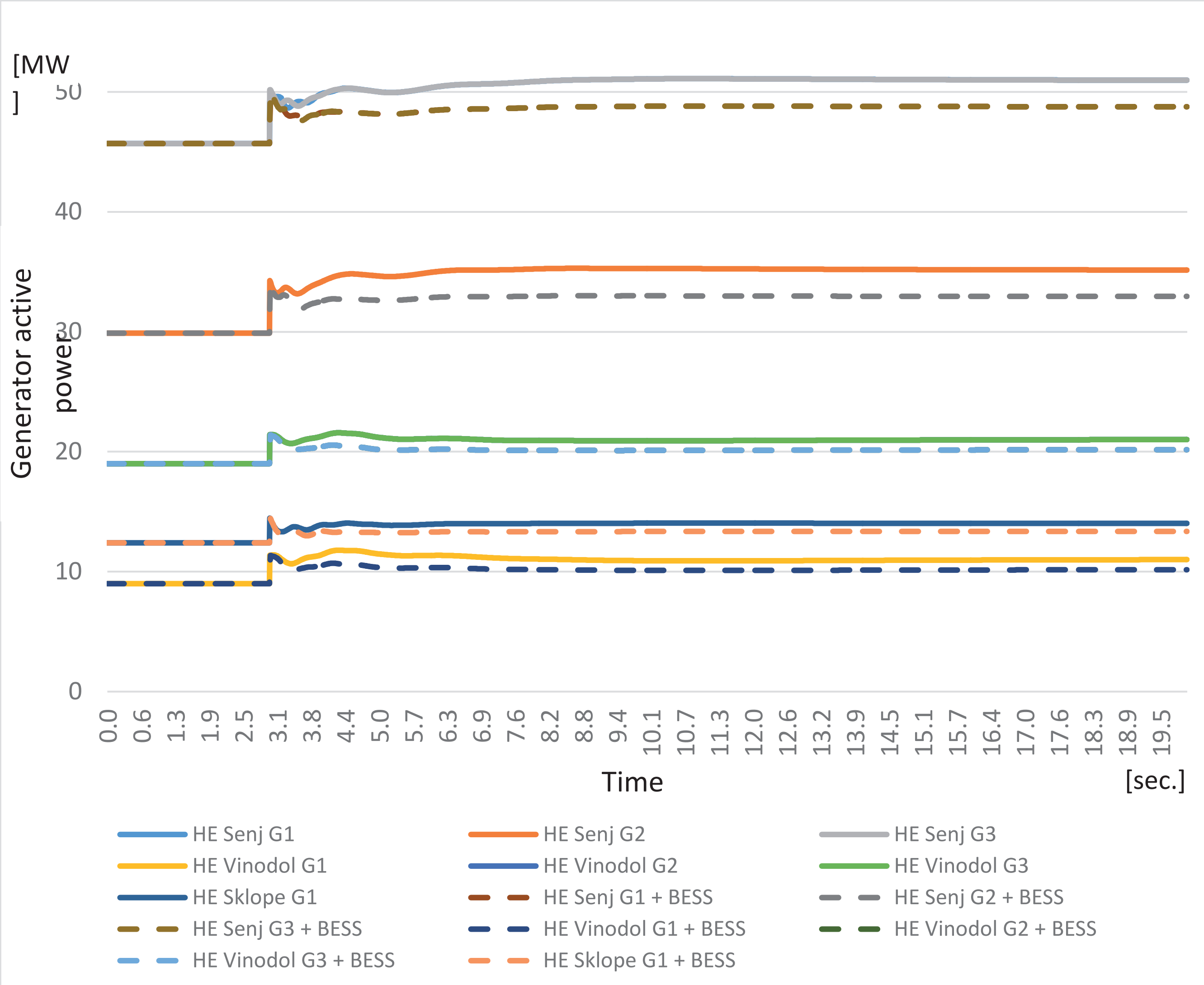

Figure 10. HPP units active power production with and without BESS

In the second scenario, when the load is reduced by 10%, the frequency increases and then generating units active power production decreases. In this case, the difference is that the BESS does not inject active power into the system, but absorbs it from the system, i.e., it acts as load. A BESS can absorb active power from the power system until it reaches the maximum allowed state of charge.

During maximum frequency deviation that occurs in the scenario without BESS, the frequency will increase to 1,028 p.u. that is, at 51.4 Hz, while in the scenario with BESS, the frequency increases to the value of 1.023 p.u., that is to 51.15 Hz, Figure 11.

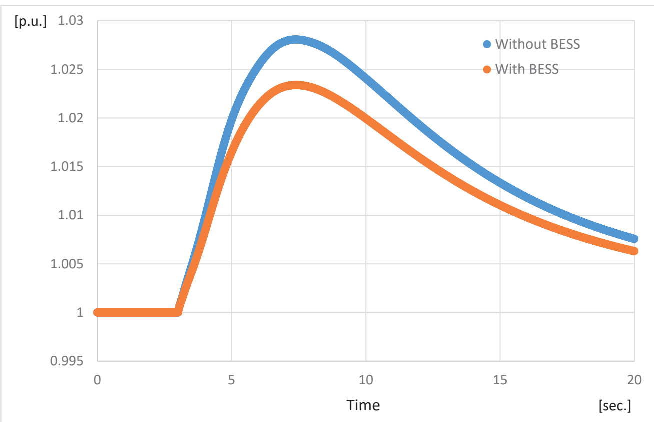

Figure 11. Frequency response at 110 kV bus Vrataruša with and without BESS with load decrease by 10%

5. CONCLUSION

The influence of virtual inertia on Croatian power system stability was analyzed in the paper. The virtual inertia is obtained using a BESS with a control mechanism that enables its participation in frequency control. The result of the simulation confirmed the effect of the virtual inertia to reduce the maximum deviation of the frequency from the nominal one, and to reduce the ROCOF.

In fact, the beneficial influence of the BESS upon frequency deviations in the simulated scenarios, prevents over/under frequency elements from tripping loads and generators. In contrast, without BESS the frequency drops below 49 Hz for a sudden step wise load increase, thus triggering the first stage of under-frequency load shedding scheme. For the scenario of a sudden load decrease the frequency increases to 51,4 Hz, just below the over-frequency limit of 51,5 Hz when disconnection of generating units occurs.

Of course, the presented simulation results are only orientational and give an insight on the possibilities for virtual inertia provision by BESS. For more accurate results, the exact type and technical parameters of the BESS should be known.

Actually, the behavior of the battery energy storage largely depends on the settings, that is, on the modeling of the battery itself. In fact, a BESS consists of two main components - a storage component and a rectifier/inverter component that transforms DC to AC and vice versa. The rectifier/inverter component is normally based on a voltage sourced converter (VSC) with a pulse width modulation (PWM). This element is well known and it's settings are known and easily obtainable. However, the storage component is a rechargeable battery i.e., an element that depends on the actual application and battery technology (Lead-acid, Ni-Cd, NI-MH, Li-ion etc.). Each type has its own assets and drawbacks.

In addition, oscillations between generators or among groups of generators may appear unexpectedly from small disturbances. These oscillation modes are inherently stable, but may get unstable by introducing feedback loops. With higher damping and lower inertia of the system the oscillations are well resolved at the cost larger transient frequency deviations in case of large disturbances. Therefore, a trade-off between improved damping and sufficient inertia against large disturbances has to be determined.

Although development and implementation of virtual synchronous generators is a good way to accelerate RES integration, it brings new technical challenges to power system operation. Therefore, further research is needed, so that virtual synchronous generators can be effectively integrated into future power systems.

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