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Frequency Containment and Restoration Process of the Photovoltaic Power Plant in the Smart Region during Overfrequencies

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***Abstract*— This paper presents the smart region consisting of the photovoltaic (PV) power plant, the conventional source represented by the small synchronous generator with the speed controller and the load. The paper deals with the application of the new Grid Code established by the ENTSO-E to the created smart region. It also studies the application of the frequency containment reserve and the frequency restoration process to the PV power plant and its impact on the smart region operation.**

Keywords—photovoltaic power plant; control requirements; smart region;

I. INTRODUCTION

The electric power system was designed to produce electricity at the large power plants in remote locations, send it over the high-voltage transmission lines, and deliver it at the lower-voltage utility distribution systems to passive customers. Increasingly, the electricity is produced by smaller, cleaner distributed generation units at or close to the customer sites and connected to the utility distribution system [1]. The utilization of such distributed generation (DG) is also one of the definitions of the smart grid concept. Application of this concept could contribute to unloading power transmission system and also to meet goals defined by the directive 2009/28/EC with its utilization of the renewable energy sources (RES) [2].

Smart region could interconnect sources with different operation, dynamics or control possibilities. The largest part of the required RES capacity installed in the Slovak Republic is covered by the photovoltaic (PV) power plants (573 MW) therefore the simulation model for PV system as example of RESs is used in the paper. The example of the smart region is supplemented with the synchronous generator, its speed controller and the load.

The renewable energy sources are usually not considered as normal energy sources as in [3], [4], [5], which can control their generated output and can cooperate with other sources, conventional or renewable ones, on the covering local demand. However, control of the three-phase voltage inverters, which are used by many RES applications, is fundamentally the same as the control of synchronous generators. This allows controlling the voltage and frequency and injects the power corresponding to the actual load demand into the network. On the other side, some studies propose the control possibilities for this kind of sources, but they do not take into account the regulations in force as in [6], [7], [8], [9].

Therefore, the authors decide to study the applications of a new Grid Code established by the ETNSO-E [10] to the created smart region. The frequency containment process (FCP) and also the frequency restoration process (FRP) was applied to the PV power plant during overfrequencies as defined by the grid code. The paper describes the impact of such kind PV power plant control on the smart region operation. The authors focus on the case of overfrequencies in the region, because of the currently used operation at maximum power point of the PV power plant. There is no possibility to increase the power of the power plant in this case without the use of the storage devices.

II. SMART REGION

A study system consists of the unit electronically interfaced to the grid represented by the PV power plant, a synchronous generator and the local load as shown in Fig. 1. The voltage level of the system is 22 kV.

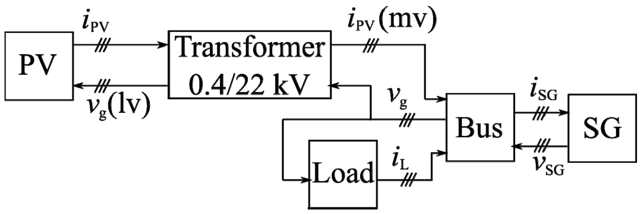

Fig. 1. The block diagram of the smart region example.

A. Model of Synchronous Generator

The synchronous power generating module is represented by the diesel generator with the nominal output 2.5 MW. Its simulation model is represented by a swing equation [11]:

$$\frac{d\omega_m}{dt} = \frac{1}{J \cdot \omega_m}\left(P_m - P_e\right), \qquad (1)$$

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where ω_m is the mechanical speed of the rotor (in case of 2 pole's machine $\omega_m = \omega_e$), J is the inertia of the synchronous generator (SG), P_m and P_e are the mechanical and electrical power of the SG, respectively.

The SG has the constant output voltage but is equipped with a speed control system consisting of a PI regulator. The control of speed is implemented within the range of 70 – 100 % of the SG rated power (1.75 – 2.5 MW).

B. Model of Photovoltaic Power Plant

The unit electronically interfaced to the grid is represented by the model of photovoltaic power plant with a rated power of value 1 MW. The model consists of mathematical models of a PV array, a DC boost converter with a maximum power point tracking (MPPT) controller and a voltage source converter (VSC) with a phase locked loop (PLL) controller (Fig. 2). The PV array, the DC boost converter and the MPPT controller are more described in [12].

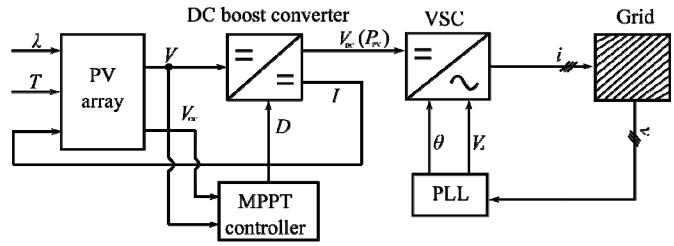

Fig. 2. The block diagram of the PV power plant model.

The inputs of the PV array model are a solar irradiance λ, a temperature T and a load current I from the DC boost converter. They are used to calculate the PV array voltage V that is used as an input for the model of DC boost converter and the PV array open circuit voltage V_{OC} that is used in the MPPT controller. The DC boost converter calculates the increased output voltage V_{DC} and the load current I.

The switching of the DC boost converter is controlled by the MPPT controller, which changes its duty cycle D according to the voltage from the PV array and the open circuit voltage of the PV array. The MPPT controller´s algorithm determines the duty cycle needed to operate the PV array at its maximum power point.

The increased voltage V_{DC} from the DC boost converter (to simplify inverter's modelling an array's power P_{PV} is used instead), together with the phase angle θ and the amplitude of the grid voltages V_d from the PLL, is consequently used in the voltage source converter for the three phase currents i determination. The phase angle and the amplitude of the grid voltages are identified from the grid voltage using the phase locked loop algorithm.

The VSC is represented by the Northon equivalent using dq0 transformation [13]. Assuming that the photovoltaic power plant should operate at a unity power factor and at maximum power point of the PV array, the current injected to the grid would be only for the active power and so the amplitude of the output current is:

$$I_G = I_d = \frac{2 \cdot P_{MPP}}{3 \cdot V_d}, \quad (2)$$

where V_d is the direct-axis projection of the grid voltage defining the amplitude of the voltage, I_d is the direct-axis projection of the source current defining its amplitude and P_{MPP} is the maximum power of the PV array.

An inverse Park transformation and phase angle from the phase-locked loop algorithm are then used to convert the current I_d to the three-phase current system.

The ability of limited frequency sensitive mode - overfrequency (LFSM-O) operation has been added to the PV power plant model, with the frequency threshold firstly set to 50.2 Hz and then to 50.01 Hz and droop value equal to 5 %, with respect to definitions required in [10] and shown in Fig. 3 [10].

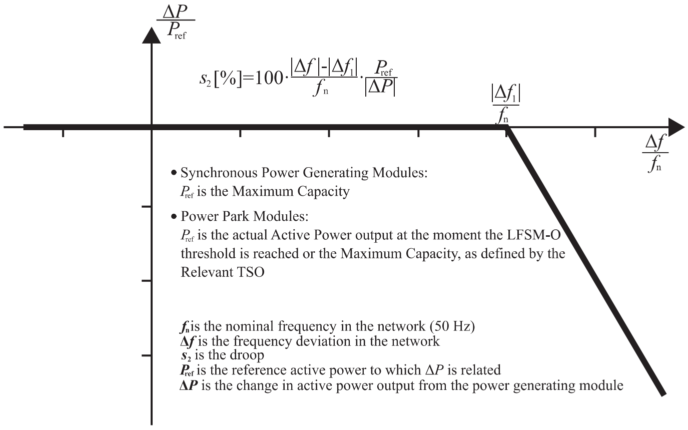

Fig. 3. Active power frequency response capability of power generating modules in overfrequency mode.

So the decreasing of the PV power plant output is defined as [10]:

$$\Delta P = 20 \cdot P_m \frac{f_{threshold} - f_{network}}{50.0}, \quad (3)$$

where ΔP is the power reduction, P_m is the actual maximum power, $f_{network}$ is the actual grid frequency and $f_{threshold}$ is the threshold value of the frequency.

C. Model of the Load

The model of the local demand in the Smart Region is represented by the impedance to the bus voltage. The power demand varies from 2.45 MW to 2.25 MW during the simulation in order to simulate the overfrequency in the modelled Smart Grid region.

III. Simulation Case

The output of PV power plant changes according to the changes of the solar irradiance value. To balance the generation and the demand, the synchronous generator changes also its output within the pre-set range. The power demand remains constant during the first five seconds, so the changes of PV power plant output are compensated by the control of the synchronous generator. The solar irradiance curve is shown in

Fig. 4 and the comparison of the demand (Pload), the PV power plant output (Ppv) and the synchronous generator output (Psg) in Fig. 5.

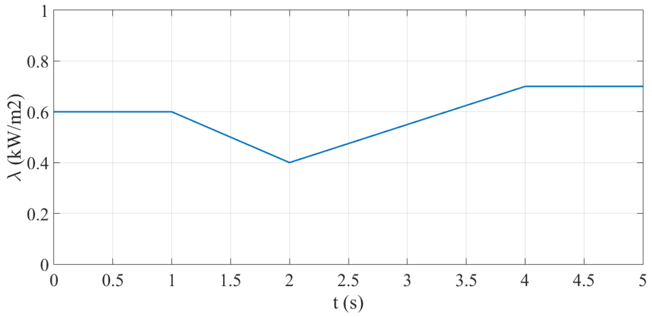

Fig. 4. The solar irradiance curve.

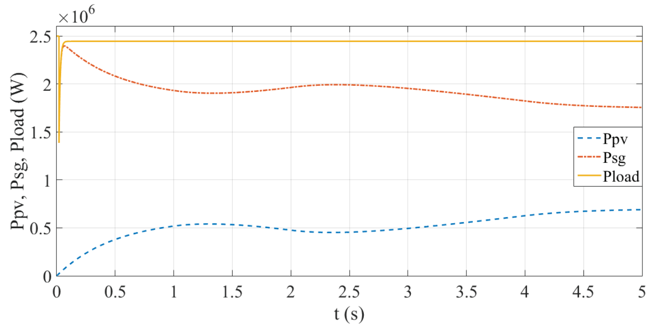

Fig. 5. The power comparison during solar irradiance changes.

However, the demand decreases from 2.45 to 2.25 MW in the 6th second and the synchronous generator meets its control limit and the frequency starts to increase.

A. The Application of the Slovak Legislation Requirements to the Smart Region

According to the Slovak legislation and the grid code of transmission system operator (TSO), the PV power plants in Slovak republic operate at their maximum power and at unity power factor. In cases of the grid faults or the exceeding of the frequency limit values, this kind of power plants are disconnected from the network. For example, the Slovak TSO defines in its grid code that a PV power plant has to be disconnected from the network, if the frequency exceeds 50.2 Hz.

Because the output of PV power plant stays constant (since the value of solar irradiance did not change and the frequency is lower than 50.2 Hz) and the diesel generator is operating on its minimum regulation limit in our simulation case, the frequency of the Smart Grid region starts to rise (Fig. 7). When it reaches the value 50.2 Hz, the PV power plant is automatically disconnected (Fig. 6), what results in the change of power balance within the Smart Grid region represented by the frequency drop (Fig. 7). When the frequency falls down under 50.0 Hz, the diesel generator increases its output, as shown in Fig. 6 (according to its droop characteristic), in order to return the frequency to the nominal value (Fig. 7).

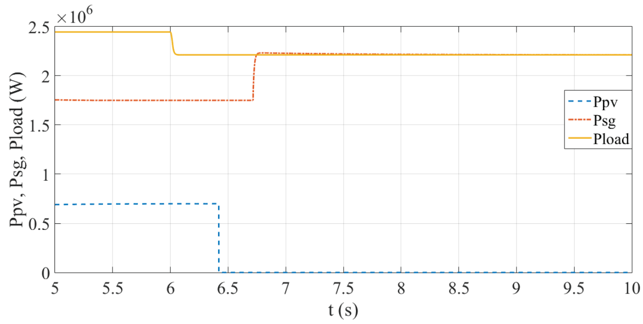

Fig. 6. Results of demand change according to the Slovak legislation.

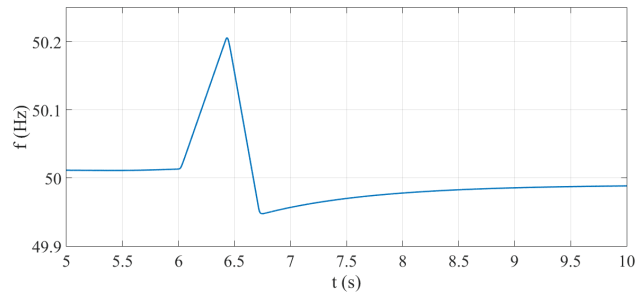

Fig. 7. Frequency's changes due to PV power plant disconnection

Such operation looks to be good for the region. Unfortunately, when the nominal frequency is reached, there is no reason for the PV power plant to stay disconnected. So, when it is reconnected again, e.g. after some time delay or at dispatcher's command, and the region's demand does not change, the situation presented by Fig. 6 and Fig. 7 will repeat, thus will result in cycles of PV power plant disconnections and reconnections called frequency vibrations [14], [15].

B. The Application of the ENTSO-E Grid Code Requirements to the Smart Region

According to the new grid code [10], the generating unit with the maximum installed capacity under 50 MW should be capable of remaining connected to the network and to operate within the frequency ranges 49.0-51.0 Hz unlimited and it should be even capable of activating the provision of active power frequency response at the threshold between 50.2 - 50.5 Hz according to the Fig. 3, which in the case of increasing frequency (Fig. 8) will result in PV power plant output decreasing as shown in Fig. 9 .

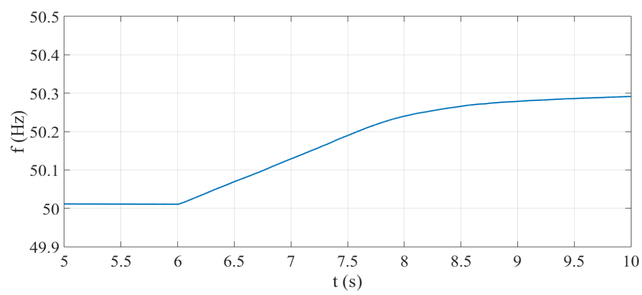

Fig. 8. The increasing frequency of the Smart Region.

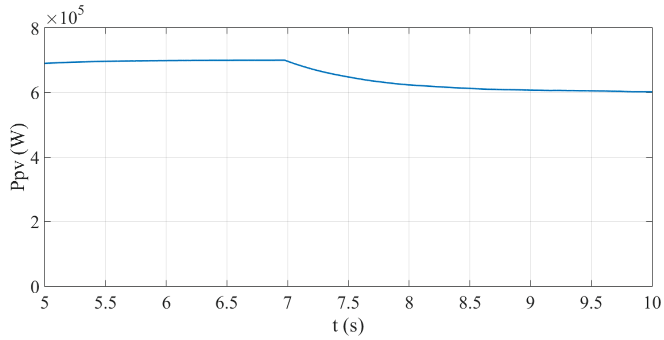

Fig. 9. The decreasing output of the PV power plant.

This requirement contributes to the stabilisation of the region frequency, however above 50.2 Hz as shown in Fig. 8 [15]. So it is necessary for the system operator to make another control intervention to keep the frequency within the ± 200 mHz range to maintain the normal operation of the region.

C. *Application of the Frequency Containment Process to the PV Power Plant in the Smart Region*

One of proposed solutions presented in this paper is to set-up the threshold for the activation of the active power frequency response to the lower value of 50.01 Hz, as shown in Fig. 10. This value takes into account also the deadband ± 10 mHz [10].

The PV power plant output and the region frequency with application of capability presented in Fig. 10 are shown in Fig. 11 and Fig. 12, respectively. As demonstrated, if the frequency exceeds the deadband value, the PV power plant starts to decrease its power according to the requirement in Fig. 10. This results in the stabilisation of the frequency within ± 200 mHz range and so the PV power plant contributes to the frequency containment process in the region.

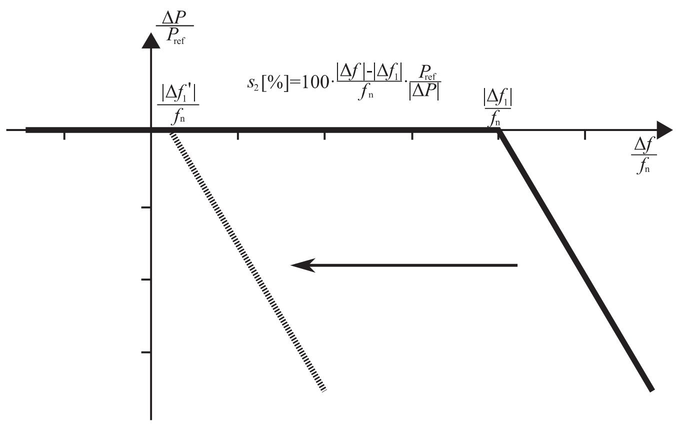

Fig. 10. Active power frequency response capability of power generating modules in overfrequency mode with the lower threshold limit.

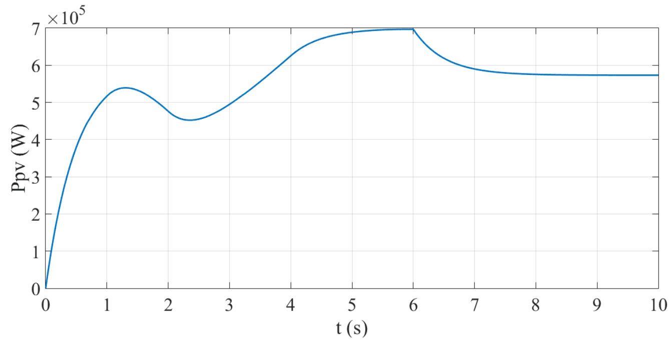

Fig. 11. The PV power plant output curve during FCP.

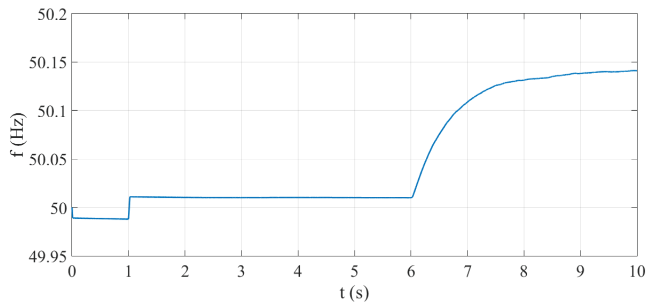

Fig. 12. The region frequency curve during FCP of the PV power plant.

D. *Application of the Frequency Restoration Process to the PV Power Plant in the Smart Region*

Other possibility is to utilize the PV power plant also in the frequency restoration process. It means that the PV power plant would change its output according to an area control error (ACE). The area control error is defined according to the [16] as follows:

$$\Delta G = \Delta P + K \cdot \Delta f \ , \qquad (4)$$

where ΔG is the area control error, ΔP is the power deviation of the area, K is the K-factor and Δf is the frequency deviation [16].

The K-factor is determined by using the power frequency characteristic of the region. The desired change in the output of the PV power plant determined from the ACE is achieved by using the PI regulator. The PV power plant output curve is demonstrated in Fig. 13. Firstly, the PV power plant decreases its output according to the requirement from Fig. 10 and so stabilises the change of frequency in the region shown in Fig. 14. After 30 seconds, if there is no other possibility for frequency restoration, the PV power plant decreases again its output power according to a determined value of the ACE (Fig. 14).

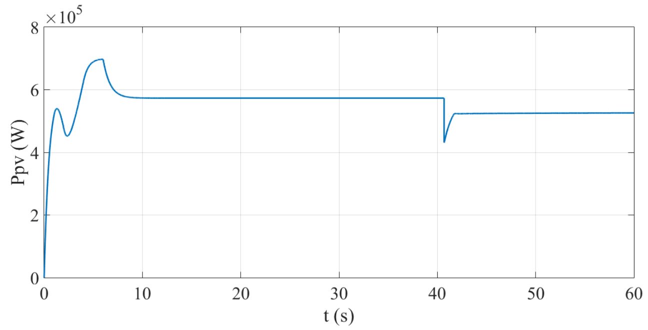

Fig. 13. The PV power plant output curve during FCP and FRP.

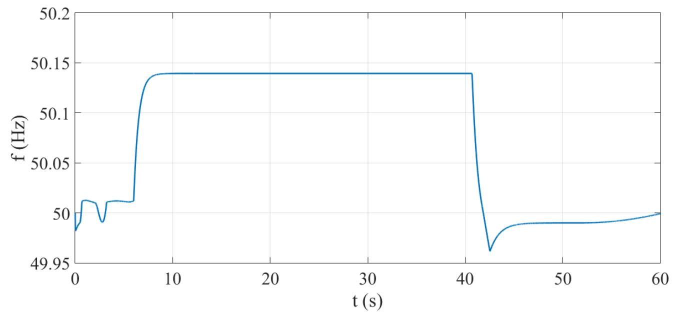

Fig. 14. The region frequency curve during PV power plant FCP and FRP.

The behaviour of the synchronous generator output, the PV power plant output and also the demand are shown in Fig. 15. The synchronous generator increases its output above its control limit due to the decreasing output of the PV power plant and so the frequency could be restored (Fig. 14). After the FRP the smart region returns to normal operation.

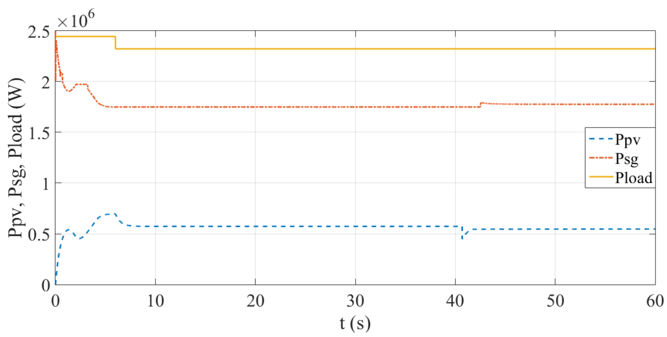

Fig. 15. The power comparison during the FCP and FRP.

IV. Conclusion

The high penetration of the RESs could result in some problems in current power systems. One of the problems is the controllability of these sources. In most countries, including Slovakia, these types of sources do not control their output and are operated at their maximum power point. They are also disconnected in case of a fault. The presented results have introduced the problems of such operation.

With an increased level of RESs penetration, it proves necessity to start using some mechanisms to control the generation of the renewable energy sources. These requirements have been already presented in the new Grid Code of the ENTSO-E. From the obtained results it is obvious that there is a possibility for applying the FCR and FRR to the PV power plant, as an example of RESs. This approach can also contribute to the smart region operation and it indicates that there is a possibility of controlling the smart region by complying with the requirements in force.

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