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Improving Dynamic Response of Hydro Power Plants Using Electrical Energy Storage in Low-inertia Power Grids

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***Abstract*—The share of renewable energies in the electricity generation side is increasing to replace fossil fuels and address environmental concerns. Consequently, the total rotational mass of conventional generations and the inertia of the power system will decrease. Here, first the potential of hydro power plant assisting the power system operator managing frequency deviations, in a low inertia power system is studied. Then, the capability of electrical energy storage (EES) to assist hydro power plant in primary frequency response services, is surveyed. The droop control method is considered for the operation of EES facility, with values of 1 and 5. Different case studies are defined, to study the impact of the hydro power plant and the EES facility on primary frequency response of the system. Based on the results, the hydro power plant will improve the settling time, and final recovered value of frequency of the system after a disturbance. However, it has a rather slow dynamic response facing deviations in the power system frequency. The EES facility has the best improvement in the Nadir point, while the settling point is better than when the system is without hydro power plant. Moreover, the final value of the frequency after a disturbance is also higher than the case without hydro power plant and EES facility. Finally, the droop control with value of 5 has better performance than droop with value of 1.**

Keywords—Dynamic response, Electrical energy storage, Hydro power plant, Low inertia power system, Primary frequency response.

I. INTRODUCTION

The environmental concerns over fossil fuels drive the trend to increase the share of renewable energies like wind, and solar on the electricity generation side [1]. This will lead to a decrease in the total rotational mass of conventional generations and consequently, lower inertia of the power system [2]. The lower inertia of the system will decrease the capability of the power system to manage deviations of the frequency [3]. In traditional power systems, load variations and generation unit trippings are considered the main disturbances for controlling the frequency. However, the integration of renewable energies considering their intermittent nature will further increase the deviations in the frequency [4]. The output of these resources is highly fluctuating and the lower accuracy of their production will further increase the mismatch between the power supply and demand [5]. The frequency of the power system, as an indicator of the balance between electricity generation and consumption, needs to be always kept in a small range around its nominal value [6]. Therefore, solutions to manage the frequency deviations caused by increasing amounts of renewable energies in the system are required, including hydro power plants and flexible resources like storage.

One of the solutions to manage the frequency deviations is to implement resources like hydro power plants [7]. Hydro power plants have been one of the main participants in the frequency regulation services of power system for a long time [8]. The hydro power plants can increase the capability of the power system to manage frequency deviations by participating in the primary frequency response services. In [9], the hydro power plant is implemented to decrease the frequency deviations caused by renewable power generation in the power systems. The authors concluded that with hydro generators in charge of frequency regulation, the fluctuations caused by wind power had less impact on other conventional generators. However, the hydro power plants have a limited dynamic response in frequency regulation services. This is due to the behaviour of the water columns that are inside penstocks and controlled by water flow control valves. Here, the potential of electrical energy storage to improve the dynamic response of hydro power plant will be studied.

Electrical energy storage also has the capability to participate in the primary frequency response services. Authors in [10] implemented a grid-connected battery to assist the power system via participation in the primary frequency regulation. The battery energy storage is implemented in [11] for primary frequency regulation based on power system frequency samples. The battery will get charge in down-regulation (when frequency is higher than the nominal value) and get discharge in up-regulation (when frequency is lower than nominal value). Here, the potential of electrical energy storage (EES) to further increase the capabilities of hydro power plants to participate in the frequency services will be investigated. A new control method based on droop will manage the operations of the EES facility in frequency regulation services [12]. The EES facility paired with hydro power plant will try to manage the frequency deviations in a low inertia power system.

The main contributions of this paper are as follows:

- The impact of the hydro power plant on the frequency response of low inertia power systems is studied. The transient features of primary frequency response consisting of settling time and Nadir point are studied. Moreover, the final value of the frequency after the disturbance will be surveyed.
- A new model for the operation of the EES facility is proposed. The role of the EES facility in improving the performance of hydro power plants while participating in the primary frequency response is investigated. The droop control is implemented for the operation of the EES facility. The transient features of frequency including settling time and Nadir point are studied. The final value of the frequency of the power system after the disturbance is also surveyed. A sensitivity analysis on the size of the droop to control the EES facility will be performed.

The rest of the paper is organized as follows. The Problem description is presented in Section II. The data and case studies to evaluate the proposed model are defined in Section III. The simulation results are discussed in Section IV. The conclusion of the results of the paper is presented in Section V.

II. PROBLEM DESCRIPTION

The objective of this study is to investigate the impact of hydro power plant and the EES facility on the primary frequency response of the power system. To do this, first the dynamic response of a conventional unit participating in the primary frequency response, is modelled via Figure. 1. This figure represents the transfer function of a conventional power plant with reheat thermal units. In order to represent a low inertia power system, lower value for the inertia parameter (H) is considered. Here, the focus is on the primary frequency response of the power system. Therefore, the secondary frequency response is not considered and is displayed as a zero input to the system. In Figure. 1 the parameters T_G, T_{CH}, T_{RH} are the time constants of governor, main inlet volumes, and reheater. F_{HP} is the fraction of total turbine power generated by high pressure section and R is the droop of governor.

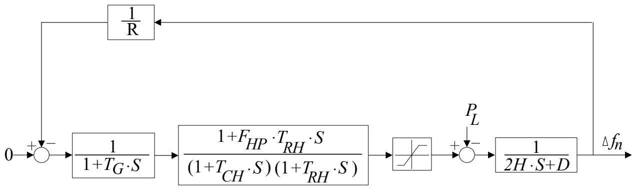

Fig. 1. Block diagram of the conventional unit participating in the primary frequency response.

The hydro power plant is implemented to assist the power system overcome the deviations in the frequency. The transfer function of this unit is presented in Figure. 2. In this figure, T_P, T_G, and T_W are the time constants of pilot valve and servomotor, gate servomotor, and water starting time. R_P is the permanent droop, while K_P and K_I are the PI controller parameters. The output of this unit will apply to the output of the conventional unit to decrease the deviations in the frequency caused by fluctuations in the power balance of the power system.

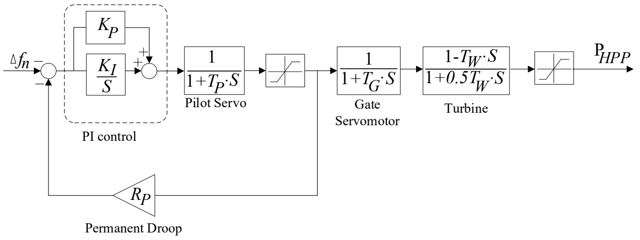

Fig. 2. Block diagram of the hydro power plant.

Moreover, here the potential of EES facility to improve the dynamic responses of hydro power plant, will be studied. The hydro power plant paired with the EES facility will participate in the primary frequency response service. The operation of the EES facility is designed based on the changes in the frequency of the system. The block diagram of the proposed model is presented in Figure. 3. When the frequency is greater than 50.1 Hz, there is a sudden decrease in load or increase in the generation. Here, the down-regulation is required and the storage function is to get charged, if its state of charge (SOC) is between 20% and 95%. This function is modeled via the upper part of Figure. 3. Blocks in this branch consist of a low pass filter (LPF) to decrease the sensitivity of the EES facility to noises. Moreover, to improve the primary frequency response of EES to deviations in the frequency, the droop control, is added to the model, [12]. The impact of this control method with two different droop values (α), will be studied in the simulations. The PI controller is used here to control the droop block. Furthermore, a first order transfer function is implemented to model the delay in the converter response. Finally, a limiter will put a boundary on the amount of charging power of EES.

In conditions where the frequency of the test power system falls below 49.9 Hz, the system faces a sudden shortage of generation or an increase in demand. In this condition, up-regulation is required, and the storage function is to discharge power to the system. This function is modeled via the lower part of Figure. 3. The blocks of this part are similar to the upper part of this figure. These blocks consist of a low pass filter to lower the sensitivity of the EES facility to noises, droop control to improve the primary frequency response of the EES facility, the PI controller to regulate the droop control, and a first order transfer function block to model the delay in the converter response.

In the range of frequency between 49.9 Hz and 50.1 Hz, the operation of the EES facility is as follows. Here, the EES will restore its state of charge to the reference value of 50%. This operation is modeled via the middle part of the Figure. 3. Therefore, in case the state of charge of the EES facility is

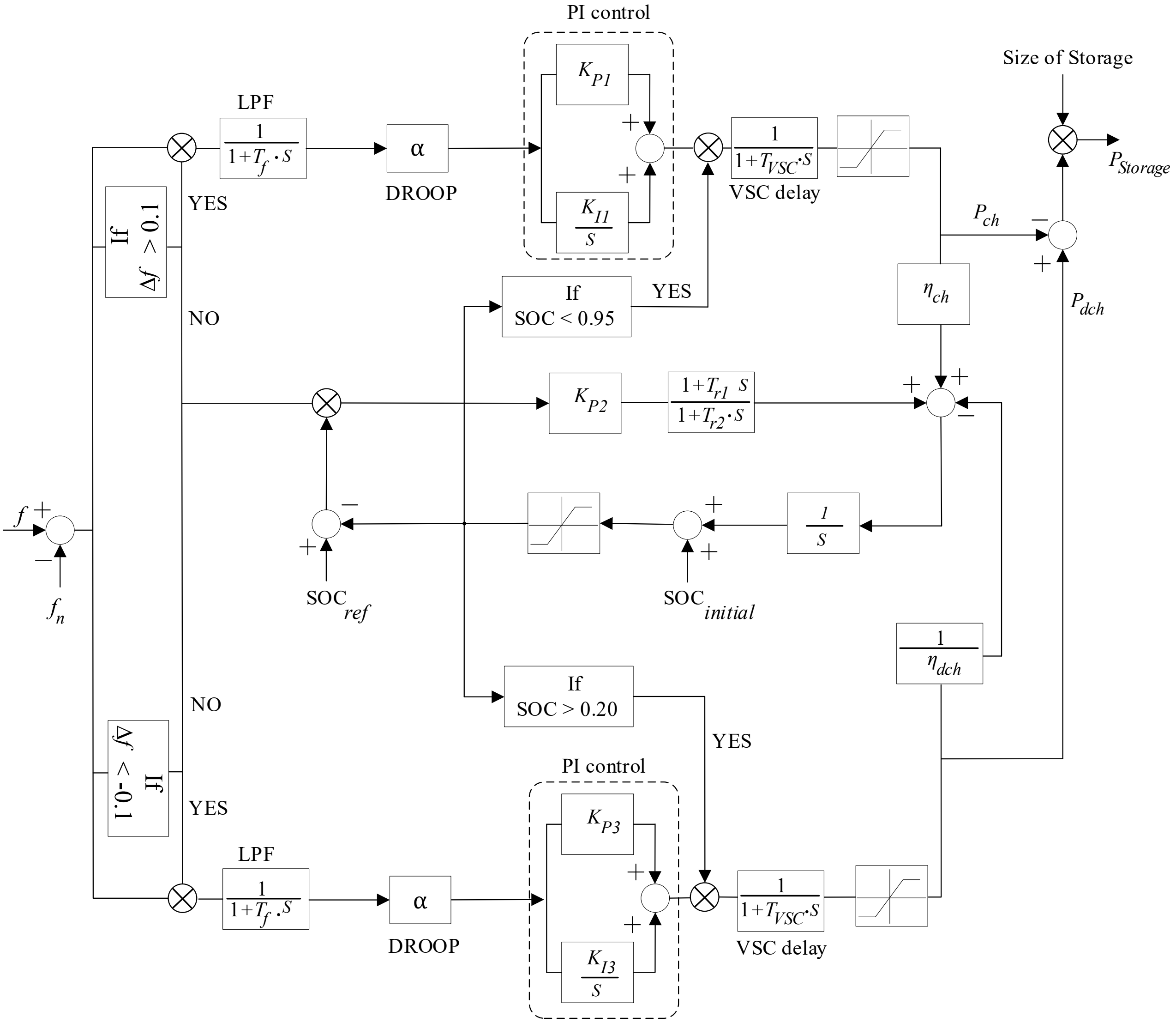

Fig. 3. Block diagram of the proposed model for the EES facility.

higher/lower than the reference value it will discharge/charge to reach this value.

The objective of this design for the operation of the EES facility is to assist the hydro power plant in providing primary frequency response services.

III. DATA AND CASE STUDIES

A. Data

Here, the data required for the simulations are provided. This data includes the parameters of the power system, conventional unit, and hydro power plant, which is presented in Table I. In this work, a conventional unit is considered for participation in primary frequency response and providing maximum of 1 GW. In order to present a weaker grid, lower inertia, H=2.5 and D=5 for the power system is considered. Moreover, a 127.4 MW hydro power plant (HPP) participates in the primary frequency response service. The HPP can pair with the EES facility with power capacity of 100 MW to improve its dynamic response capabilities. The parameters of the EES facility are presented in Table II.

TABLE I. SIMULATION DATA

Conventional unit		**Hydro Power Plant**	
Symbol	***Value***	***Symbol***	***Value***
R	0.05	K_P	5
T_G	0.2	K_I	0.7
F_{HP}	0.5	T_P	0.05
T_{RH}	10	T_G	0.5
T_{CH}	0.3	T_W	2
		R_P	0.04

TABLE II. SIMULATION DATA

Electrical Energy Storage			
Symbol	***Value***	***Symbol***	***Value***
T_f	0.01	K_{P3}	20
T_{VSC}	0.1	K_{I3}	0.01
α	1 or 5	K_{P2}	0.4
K_{P1}	20	T_{r1}	2
K_{I1}	0.01	T_{r2}	1

B. *Case Studies*

a) Base Case: The power system only with conventional unit without the hydro power plant and electrical energy storage responds to deviations in the frequency

Here, the hydro power plant and the electrical energy storage are not present. Therefore, the power system only with the conventional unit will face deviations in the frequency. The primary frequency response of the power system to changes in the frequency will be simulated and used as a benchmark for other case studies.

b) Case I: The hydro power plant assist the power system facing deviations in the frequency

In this case, the hydro power plant and the conventional unit can assist the power system by participating in the primary frequency response service and trying to decrease the deviations in the frequency. The results of this case study will be compared with the Base Case and Case II. The electrical energy storage is not present in this case study.

c) Case II: the hydro power plant paired with electrical energy storage assist the power system in managing the frequency deviations

In the last case study, the hydro power plant is paired with electrical energy storage and participates in primary frequency response. Moreover, the conventional unit is also present in the dynamic response. The impact on the primary frequency response of the power system will be studied. The results of this case will be compared to the previous cases. Moreover, the performance of different droop values to control the operation of the EES facility will be surveyed.

IV. SIMULATION RESULTS AND DISCUSSION

The simulation of the case studies is performed in SIMULINK of MATLAB. The Base Case study considers the power system with only conventional unit and without the hydro power plant and EES facility. The primary frequency response of the power system is simulated for 60 seconds. The disturbance of 0.1 PU (on the base of 10 GW, which is the total load in the power system prior to the disturbance) increases in the load of the system starting at time 3 seconds is applied to the power system. The dynamic response of the power system to this disturbance is displayed in Fig. 4. The settling time and Nadir point of this case study are presented in Table III. These two features of the frequency response (settling time and Nadir point) are explained in [13].

In Case I, the hydro power plant also participates in the primary frequency response service. Therefore, when power system is facing deviations in frequency, the hydro power plant tries to decrease this deviation. Here, in up-regulation conditions, it opens the gates and generates electricity. In the down-regulation condition, it closes the gates and decreases its generation. The dynamic response of the power system considering the contribution of hydro power plant is presented in Fig. 4. The settling time and Nadir point of Case I are displayed in Table III. It can be observed from this table, that the participation of hydro power plant in the primary frequency response, improves the settling time of the power system. The Nadir point in this case study is the same as the Base Case. Moreover, the final value of the frequency after disturbance in Case I is higher than the Base Case study.

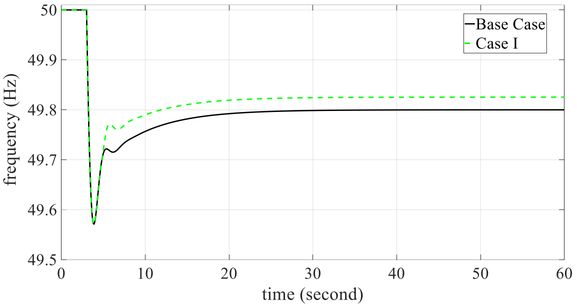

Fig. 4. Dynamic responses in Base Case and Case I to disturbance.

In Case II, the hydro power plant is paired with the EES facility. The droop control method with values of 1 and 5, is considered. The results of these control methods for EES are displayed in Fig. 5. The result of Base Case study is also presented for comparison purposes. The participation of the EES facility in the primary frequency response improved the performance of the power system when facing deviations in the frequency. Fig.6 displays the contribution of the hydro power plant in Case I without the EES facility, and in Case II with droop of 5, for comparison purposes. From this figure, the impact of EES can be noticed compared to Case I. The settling time and Nadir point of the system considering these control methods in Case II are presented in Table III. It can be concluded from this table, that adding the EES facility will improve the Nadir point and settling time of the dynamic response of the power system compared to the Base Case. Moreover, the Nadir point is improved in Case II with the EES facility compared to Case I without the EES. The final value of the frequency after the disturbance in Case II is higher than the Base Case study. Therefore, the EES facility can further assist the power system to recover the frequency of the power system after disturbances. Moreover, the control method with droop of 5 has a better impact than control with droop of 1. It should be noted here that these results are obtained considering the size of 100 MW for the power capacity of the EES facility. The state of charge of the EES facility in Case II with droop of 5 when it assists the hydro power plant in primary frequency response is displayed in Fig. 7. It can be observed, that before the disturbance occurs at time 3 the EES facility is in the state where the middle part of the EES model is active. Therefore, the EES facility starts with the initial SOC value of 60% and tries to reach the reference value of 50%. After the disturbance at time 3, the EES facility discharges to assist in the primary frequency response service in up-regulation until it reaches the lower band of 20%.

TABLE III. SIMULATION RESULTS

Case study	**Nadir point**	**Settling time**
Base Case	49.5712	11.47
Case I	49.5712	10.3
Case II with Droop=1	49.5824	10.3
Case II with Droop=5	49.5942	10.3

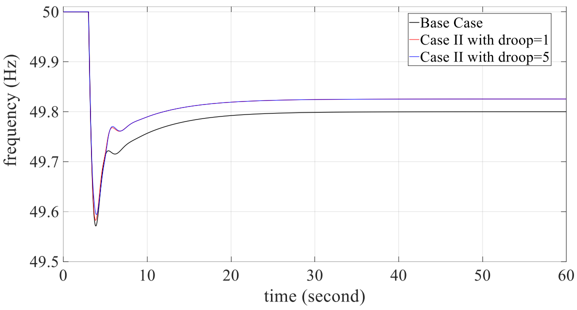

Fig. 5. Dynamic responses in Base Case and Case II to disturbances.

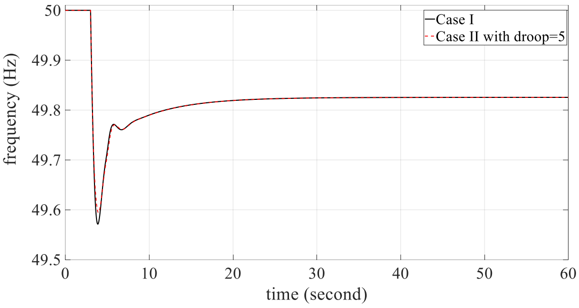

Fig. 6. Dynamic responses in Case I and Case II to disturbances.

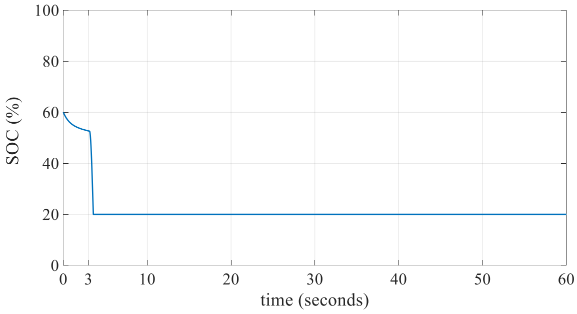

Fig. 7. The state of charge (SOC) of the EES facility in Case II with droop=5.

V. CONCLUSION

In this paper, the primary frequency response of a hydro power plant in a low inertia power system is investigated. First, the dynamic response of a low inertia power system to a disturbance with only the conventional unit present for assistance, is surveyed. Then, the hydro power plant participates in the primary frequency response service. The presence of hydro power plant improved the settling time of the power system. Moreover, the final value of the restored frequency is better than the case without hydro power plant. Then, to increase the capability of the hydro power plant in the primary frequency response, the potentials of electrical energy storage (EES) were studied. A droop control method for electrical energy storage is proposed. Sensitivity analysis is performed with different droop values of 1 and 5, for controlling the EES facility. Based on the results, when hydro power plant is paired with the EES facility and participates in the primary frequency response, the capability of the power system to manage frequency deviation improved. The presence of the EES facility, increased the Nadir point of the response while the settling time is better than the time when the power system is without the hydro power plant and EES facility. Moreover, the final value of the restored frequency after the disturbance, is higher than the case without hydro power plant and EES facility. Finally, the control method of the EES facility with a droop of 5 had a better performance than the control with a droop of 1.

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