VARIABLE SPEED HYDROPOWER PLANT WITH VIRTUAL INERTIA CONTROL FOR PROVISION OF FAST FREQUENCY RESERVES

Abstract

Variable Speed Hydropower (VSHP) is well suited for Virtual Inertia (VI) control since it can utilise the kinetic energy of the turbine and generator to provide a fast power response to a frequency deviation. Moreover, governor control of the turbine can effectively regain the optimal turbine rotational speed. Despite this advantage, no investigation into different VI control structures for VSHP has previously been performed. In this paper, the results of dynamic simulations and eigenvalue analysis show that all five tested control structures deliver fast power reserves to maintain grid stability. The VI controllers based on the Virtual Synchronous Machine (VSM) algorithm provide the best response in terms of inertia; however, a proportional controller must be added to also provide Frequency Containment Reserves (FCR). The Virtual Synchronous Generator (VSG) is concluded to be the overall best alternative. It is better at reducing frequency deviations, it provides Fast Frequency Reserves (FFR) and contributes more effectively to power oscillation damping in the two-area power system. The behaviour of the hydraulic system is similar for all VI control structures. However, a more advanced control system is needed to optimise the internal control of the VSHP plant while considering the constraints of the hydraulic system.

Keywords

Virtual Inertia, Synthetic Inertia, Virtual Synchronous Generator, Virtual Synchronous Machine, Variable Speed Hydropower

1. Introduction

The increasing share of variable and less controllable renewable energy demands the introduction of new flexible producers and consumers to ensure the balance of the power grids. In the Nordic power system, large hydro and thermal power plants have until recently supplied inertia and power-frequency control. The introduction of wind, solar and HVDC connections to Europe creates new production scenarios where the inertia in the grid is very low. This compromises the frequency stability as the inverter-based generation does not provide any response to frequency deviations unless it is implemented in the controls, e.g. as Virtual Inertia (VI) control. The goal of VI is to control the converters to increase the effective inertia in the grid.

In this paper, we investigate the use of Variable Speed Hydropower (VSHP) to provide Fast Frequency Reserves (FFR) and VI to the grid. These are ancillary services that are or will be demanded to improve balancing control and frequency stability. One of the challenges is that these services require very fast controlled responses to frequency deviations - with the typical activation time of within $1s$. Since the system inertia reduces as the share of converter-interfaced generation increases, the utilisation of VI may be essential for the green shift.

The ancillary services related to power balancing control and reserves are often divided into four levels as in [1], each of them necessary for maintaining the balance between power generation and power consumption and thereby ensuring that the frequency is kept within the limits given by the grid codes. The fastest power reserves are the instantaneous power reserves, also called inertia. These are generated by the physical stabilising effect of all the grid-connected synchronous machines due to the energy in the rotating masses in turbines and generators. The Frequency Containment Reserves (FCR) or primary control should be fully activated within $30s$ in the Nordic grid. The FCR is locally activated and implemented as part of the governor control of turbines with a frequency droop characteristic. There are two levels of FCR in the Nordic grid; FCR-N is activated at frequency deviations $\pm 0.1Hz$ while FCR-D is activated at $49.9Hz$ and fully activated at $49.5Hz$. The two slowest levels of power reserves, secondary and tertiary reserves, are not considered in this paper.

A report from the Nordic Transmission System Operators (TSOs) [2] states that Fast Frequency Reserves (FFR) is the best technical and economical solution to improve frequency stability [3].

This assumes the FFR is activated at $49.60Hz$, reaches the full value within $2s$, and holds this value for at least $30s$. A market for offering FFR has been tested in a pilot project in Norway; however, offers from hydropower plants with Pelton and Francis turbines were found to be too slow to deliver the power step within $2s$.

The use of VSHP plants is attractive because of their higher efficiency at lower production levels than conventional hydropower plants and their ability to control power in pumping modes while keeping the efficiency at an acceptable level [4]. Moreover, the converter technology of the VSHP can improve the speed of the voltage control and potentially increase the reactive power capability. The drawbacks are the power losses of the converters, increased costs and the reduced reliability if bypassing the converters is impossible. The limited short circuit current of the converters may also cause challenges for the generator and grid protection.

VSHP plants are particularly well suited for VI control since the rotational energy of the turbine and generator can be utilised by allowing the rotational speed to vary. Following an activation of VI, the guide vane opening, water flow and, consequently, the mechanical power, can be effectively controlled to regain the rotational speed to the optimal setpoint. Although VSHP has better qualifications than other sources of VI, the research on VSHP with VI is limited. Alternative solutions, such as from Photovoltaic systems (PV) and wind power plants have their limitations. PV systems lacks energy storage if not integrated with batteries. The kinetic energy of wind turbine rotors can be utilized but the rotational speed [5,6] must be regained by reducing the power output, which may cause a second drop in the frequency. Wind turbines are therefore best suited for power-frequency response-based control with temporary grid support [7]. Other possibilities investigated in the literature are to provide VI from battery energy storages [8] and through HVDC-links [9].

Different VI controllers are reviewed in [10] and divided into three categories. The simplest type is the frequency-response based models where the power is controlled proportionally to the frequency deviation and/or the rate of change of frequency [11]. Other models emulate a synchronous machine by use of a machine model and are therefore referred to as synchronous generator-based models. They might contain models of inertia, damping and voltage [12]. The swing-equation models are similar to the synchronous generator-based models; however, they are based on a simpler power-frequency swing equation [13].

This paper investigates the instantaneous and primary power reserves of a VSHP and aims to find the best-suited control scheme for VSHP considering the defined control objectives. The implementation of known VI control structures on VSHP is investigated, and these are further developed in order to improve their contribution of FFR. Eigenvalue analysis shows the impact of the VI control on the power oscillation modes while the dynamic analysis shows the reduction for the maximum frequency deviation and the effect on the hydraulic system of the VSHP.

The paper is outlined as follows: The VI models and the VSHP and grid models are presented in, respectively, Sections 2 and 3. The dynamic analysis results and discussion are given in Section 4. Section 5 presents the results and discussion from the eigenvalue analysis. Finally, some conclusions are offered in Section 6.

2. Virtual Inertia Models

2.1. Control Objectives

The control objectives for a VSHP are divided into objectives for internal control and grid support:

- Objectives for internal control of the plant:
  - To optimise the rotational speed of the turbine with respect to the efficiency;
  - to minimise water hammering and mass oscillations;
  - to minimise guide vane servo operation;
  - and to minimise the hydraulic and electric losses.
- Objectives for grid support control:
  - Contribute to FCR by faster and more precise frequency droop control;
  - contribute to increasing the effective system inertia by VI control;
  - improve the voltage control response time;
  - and increase the damping in the system.

The main focus of this paper is to maximise the grid support from the VSHP by utilising the turbine and generator rotational energy. The VI controllers should deliver VI by changing the power instantaneously to reduce the Rate of Change of Frequency (ROCOF). Moreover, the

Table 1: Parameters

Parameter	Value	Parameter	Value
CPC		**VSM-PD**	
Proportional gain k_{Pp}	0.045 p.u.	Proportional gain $k_{vsm-pd,p}$	100 p.u.
Integral gain k_{Pi}	0.023 p.u.	Derivative gain $k_{vsm-pd,d}$	500 p.u.
VSG		Derivative filter constant ω_{vsm-pd}	1 s
Proportional gain $k_{vsg,p}$	100 p.u.	Frequency controller gain k_{vsm-pd}	200 p.u.
Derivative gain $k_{vsg,d}$	33.6 p.u.	**VSG-PID**	
Derivative filter constant ω_{vsg}	0.01 p.u.	Proportional gain $k_{vsg-pid,p}$	100 p.u.
VSM-PID		Integral gain $k_{vsg-pid,i}$	286 p.u.
Proportional gain $k_{vsm-pid,p}$	3000 p.u.	Derivative gain $k_{vsg-pid,d}$	33.6 p.u.
Integral gain $k_{vsm-pid,i}$	476 p.u.	Derivative filter cons. ω_{vsg-pd}	0.01 s
Derivative gain $k_{vsm-pid,d}$	12600 p.u.	**Common parameters**	
Derivative filter const. $\omega_{vsm-pid}$	1 s	Droop R_d	0.01 p.u.
Frequency contr. gain $k_{vsm-pid}$	2000 p.u.	PLL frequency filter constant	0.001 s

VI controller will contribute with primary reserves/FCR to regain the grid frequency as fast as possible after a disturbance.

This section presents five different VI control structures. The power-frequency PD controller known as Virtual Synchronous Generator (VSG) [14] and the Virtual Synchronous Machine (VSM) [15, 16] are known from the literature. The other three structures are extended versions of the ones presented in this paper; Power-frequency PID controller with permanent droop (VSG-PID), VSM with power-frequency PD controller (VSM-PD), and VSM with power-frequency PID controller and permanent droop (VSM-PID). The parameters are given in Table 1.

2.2. Virtual Synchronous Generator

The VSG is a power-frequency response based VI system. It tries to emulate the inertial response characteristics of a synchronous generator simply, without incorporating all the detailed equations involved in a synchronous generator. A PD controller calculates the current reference in the d-axis, $i^*_{g,d}$ from the deviation in grid frequency $\Delta\omega_g$ as shown in (1). The power reference p^*_g is added to achieve the desired VSG output power P_{vsg} at zero frequency deviation and the controller compensates for deviations in voltage ($v_{c,d}$, $v_{c,q}$ and for reactive power q delivery [10].

$$\begin{aligned} p_{vsg} &= k_{vsg,p}\Delta\omega_g + \frac{k_{vsg,d}\omega_{vsg}s}{s+\omega_{vsg}}\Delta\omega_g + p^*_g \\ \Delta\omega_g &= \omega^*_g - \omega_g \\ i^*_{g,d} &= \frac{v_{c,d}p_{vsg} - v_{c,q}q_g}{v^2_{c,d} + v^2_{c,q}} \end{aligned} \tag{1}$$

The VSG is current-controlled and unable to operate in an islanded system. Over-current protection is easily implemented; however, multiple units as current sources and the use of Phase-Locked Loop (PLL) may result in instability.

2.3. Power-Frequency PID Controller with Permanent Droop

An alternative control layout for the VSG with PID controller and permanent droop R (VSG-PID) is shown in (2) to calculate the VSG-PID output power $P_{vsg-pid}$. The benefit of the PID controller is that it can be tuned to be somewhat faster than the PD controller. Due to the integration part, the permanent droop is needed to ensure power-sharing between generators as seen with conventional power plants.

$$\begin{aligned} p_{vsg-pid} &= k_{vsg-pid,p}\epsilon + \frac{k_{vsg-pid,d}\omega_{vsg-pid}s}{s+\omega_{vsg-pid}}\epsilon + \frac{k_{vsg-pid,i}}{s}\epsilon + p^*_g \\ \epsilon &= \omega^*_g - \omega_g - Rp_f \\ i^*_{g,d} &= \frac{v_{c,d}p_{vsg-pid} - v_{c,q}q_g}{v^2_{c,d} + v^2_{c,q}} \end{aligned} \tag{2}$$

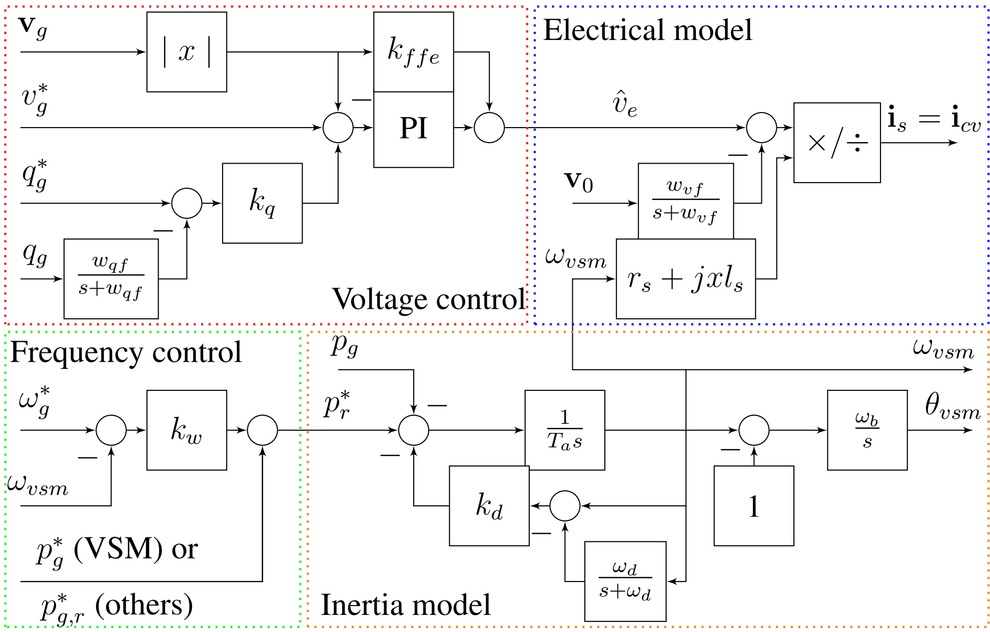

Figure 1: Virtual synchronous machine (VSM)

2.4. Virtual Synchronous Machines

The VSM is a synchronous generator-based VI model. In this paper, the model presented in [16], with equal variables and parameters, is utilised. It includes models for voltage control, frequency control and a model for inertia and the electrical system, as shown in Fig. 1. The main benefit of the VSM is that it can work in islanded systems without changing parameters and control structure [17, 18].

2.5. VSM with Power-Frequency PD Controller

The main drawback with the VSM is that its output power does return relatively quickly to the reference power, even if there are still deviations in the grid frequency. It does not, therefore, contribute to primary control/FRC. This problem can be solved by combining the VSM with other frequency-regulation schemes. The first option to be tested is to add the output power reference from a power-frequency PD controller to the VSM power reference $p_{g,r}^*$, as presented in (3). Both a deviation and a change in grid frequency will adjust the output to the VSM p_{vsm-pd}. A PLL is used to measure the grid frequency ω_g.

$$
\begin{aligned}
p_r^* &= p_g^* + k_\omega \left(\omega_{vsm}^* - \omega_{vsm}\right) + p_{vsm-pd} \\
p_{vsm-pd} &= k_{vsm-pd,p}\Delta\omega_g + \frac{k_{vsm-pd,d}\omega_{vsm-pd}s}{s+\omega_{vsm-pd}}\Delta\omega_g \\
\Delta\omega_g &= \omega_g^* - \omega_g
\end{aligned}
\tag{3}
$$

2.6. VSM with Power-Frequency PID Controller and Permanent Droop

Frequency control can alternatively be added to the VSM by including a PID controller with permanent droop, as presented in (4). The output of this controller p_{vsm-pd} is added to the VSM power reference $p_{g,r}^*$. The function of the PID controller will be similar to the function of the governor of a conventional hydropower plant. However, since the speed of the governor servo is not limiting, the frequency response of the VSM-PID will be significantly faster primary frequency control.

$$
\begin{aligned}
p_r^* &= p_g^* + k_\omega \left(\omega_{vsm}^* - \omega_{vsm}\right) + p_{vsm-pid} \\
p_{vsm-pid} &= k_{vsm-pid,p}\epsilon + \frac{k_{vsm-pid,d}\omega_{vsm-pid}s}{s+\omega_{vsm-pid}}\epsilon + \frac{k_{vsm-pid,i}}{s}\epsilon \\
\epsilon &= \omega_g^* - \omega_g - Rp_f
\end{aligned}
\tag{4}
$$

p_f is the low-pass filtered active output power p_g.

3. Variable Speed Hydropower and Grid Models

The VI controllers are tested on the VSHP model provided in [19, 20] connected to the Kundur two-area power system [21], as shown in Fig. 2. The VI is implemented as the outer control loop of the grid converter. For the VSG controllers, the VSG supplies the current reference in the d-axis $i_{g,d}^*$ to the current controller to control active power, while the reactive power is controlled by a conventional voltage controller. For the VSM controllers, both the active and reactive power is controlled by the VSM model.

4. Dynamic Analysis

The performance of the different control schemes is first analysed by dynamic simulations, both in cases with overproduction and underproduction in the grid. In Fig. 3, the responses to step load

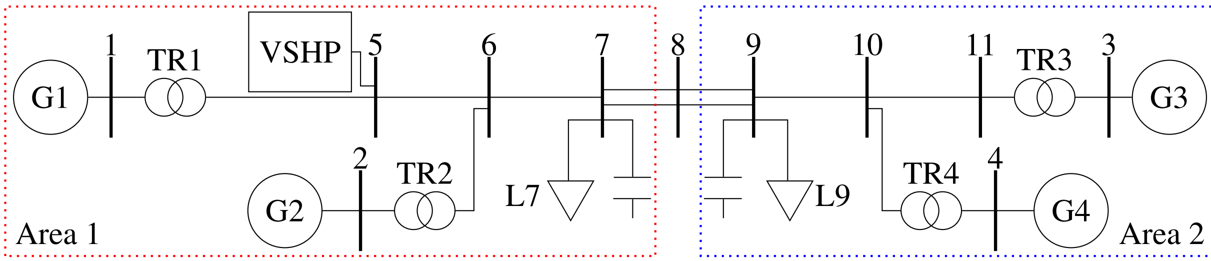

Figure 2: Kundur two-area system

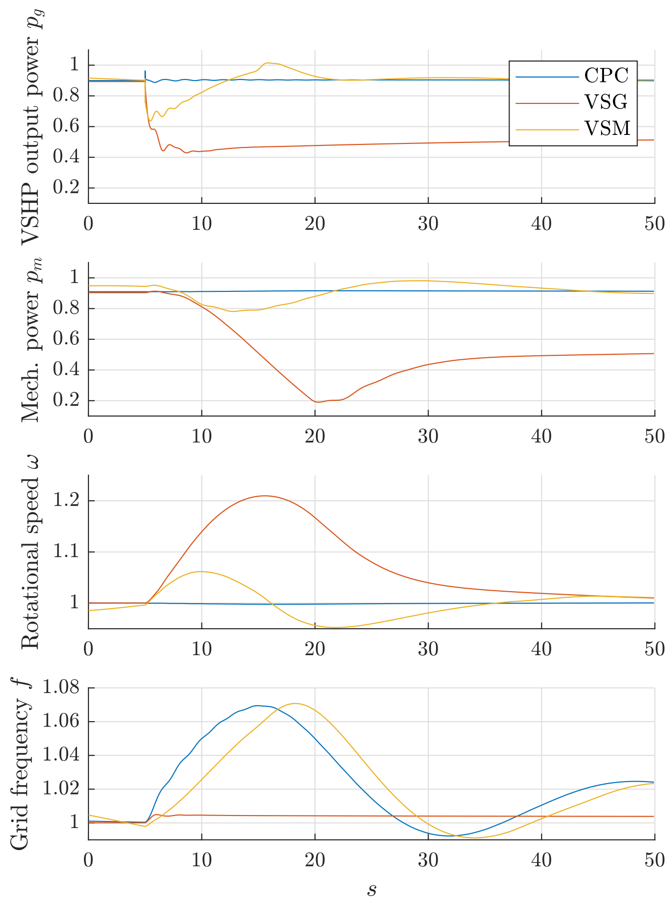

Figure 3: Responses to a load step change on Bus 7 for different VSHP control schemes

loss at Bus 7 are shown. The responses illustrate the difference between three different control schemes for power control of the grid-connected converter; the Constant Power Controller (CPC) that do not provide any frequency droop control, the VSM that provides an inertial response, and the VSG, providing both inertial response and frequency containment.

The VSG contributes with FCR since the droop characteristic of the VSG controller will cause the output power to stabilise at a lower value after the disturbance. With the VSM controller, the output power returns to its reference value since it has zero steady-state feedback from grid frequency. The maximal frequency deviation will be similar, or even higher, than with the CPC. The performance of the VSM can be improved by controlling the power reference to the VSM with a PD controller with feedback from grid frequency (VSM-PD) or a PID controller with permanent frequency droop (VSM-PID).

Fig. 4 shows the results for both the electric and hydraulic variables of the four most promising controllers, the VSG, VSG-PID, VSM-PD and VSM-PID. The main observation is that the VSG and the VSG-PID have the shortest response time and can reduce the maximum deviation in grid frequency f. This is due to a larger power reduction of the VSHP output power p_g with VSG-based inertia controllers compared to the VSM-based inertia controllers from $1 - 10s$ after the disturbance.

The oscillation in VSHP output power p_g is somewhat larger for the VSG-based inertia; however, they are small and well-damped. As seen in Fig. 4, the variables of the hydraulic system are mostly unaffected by the choice of VI controllers. The VSM-PC controller stands out because of its slower reaction to grid frequency deviations. The reduction in VSHP output power p_g is less, causing less deviations in turbine rotational speed ω, turbine power p_m, guide vane opening g and thereby turbine flow q and surge tank head h_{st}.

Two cases with load loss at different locations are compared in Fig. 5, showing the first $25s$ after the load loss and Fig. 6 is focused upon for the first $2s$ to show the difference in inertia response. The sizes of the load losses are similar and they are located, respectively, close to the VSHP (Bus 7 in Area 1) and far away from the VSHP (Bus 9 in Area 2).

From Fig. 6, we observe that the output power of the VSM-based VI controllers has the fastest response in the first milliseconds after the disturbance when the load loss is close to the VSHP. They, therefore, deliver more inertia than the VSG controllers. However, when the load loss appears at Bus 9 farther away from the VSHP, the situation is totally different, as discussed below.

Since most of the FRC is delivered by the VSHP, the power from Area 1 to Area 2 will decrease in the case of load loss in Area 2 and trigger power oscillations between the two areas. Due to these power oscillations, there will be higher oscillations in both the output power of the VSG- and VSM-based VI controllers when the load loss is far away from the VSHP. This is related to inter-area power oscillation between the two areas of the system, as also observed in the nearby

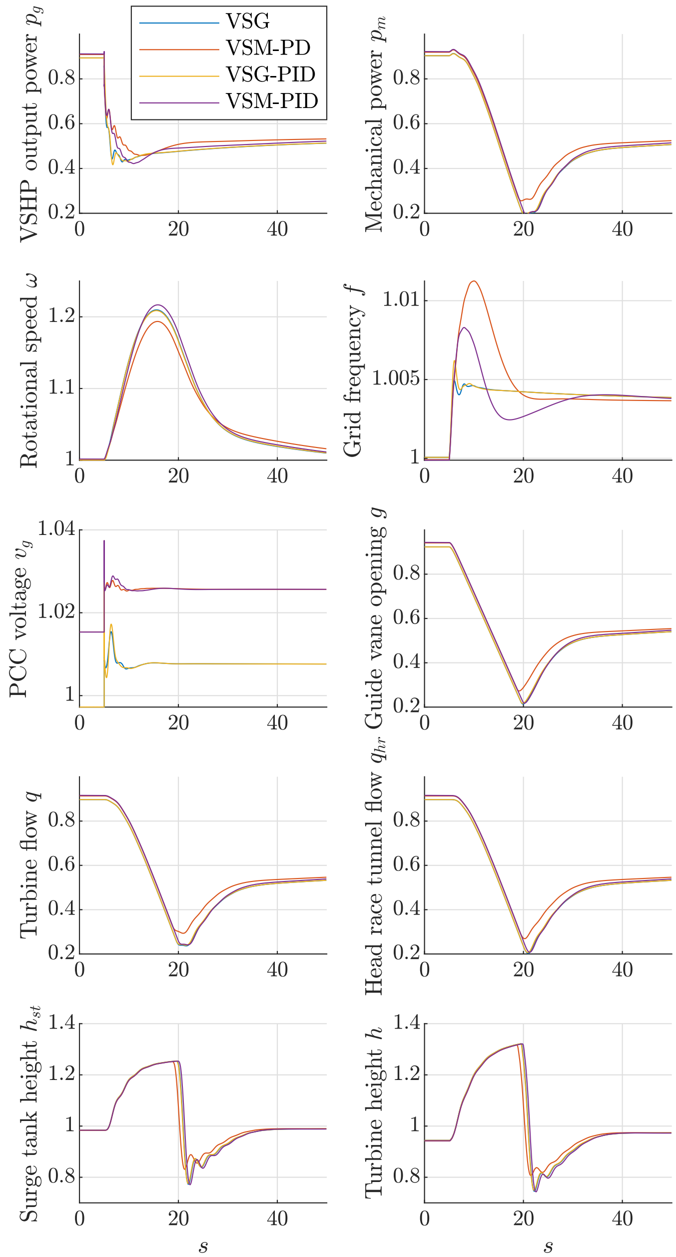

Figure 4: Responses to a load step change on Bus 7 for different VSHP control schemes

generators. In particular, these power oscillations affect the VSM-based VI controllers since they are dependent on the voltage angle. In the case of load loss at Bus 9, the power output of the VSM-based VI controllers actually increases immediately after the load loss, causing a higher deviation in grid frequency f. The dependence on the voltage seems to be a major disadvantage by emulating a synchronous machine, and the use of VSM might cause problems in a system with large power oscillations.

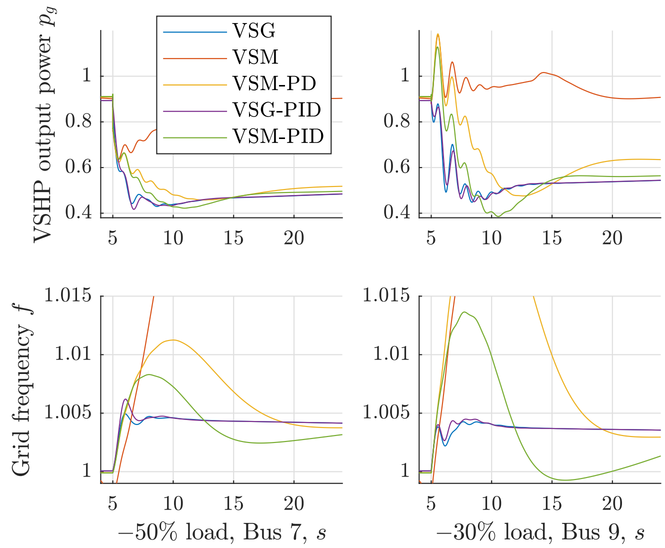

Figure 5: Responses to a load step change at, respectively, 50% on Bus 7 and 30% on Bus 9

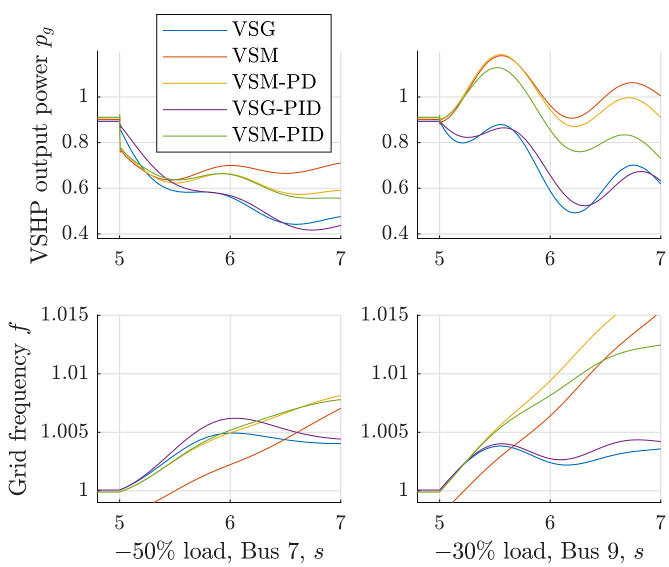

Figure 6: Responses to a load step change at, respectively, 50% on Bus 7 and 30% on Bus 9

The VSG-based VI controllers only consider the frequency, and not the angle, when controlling the VSHP output power. Therefore, the power oscillation will have less impact, and the response to a load loss in Area 2 will be almost as fast as if the load loss occurred in Area 1, albeit with more oscillations. Moreover, the VSG-based VI controllers reduce the frequency deviation by a larger reduction in VSHP output power between $1-3s$ after the load loss.

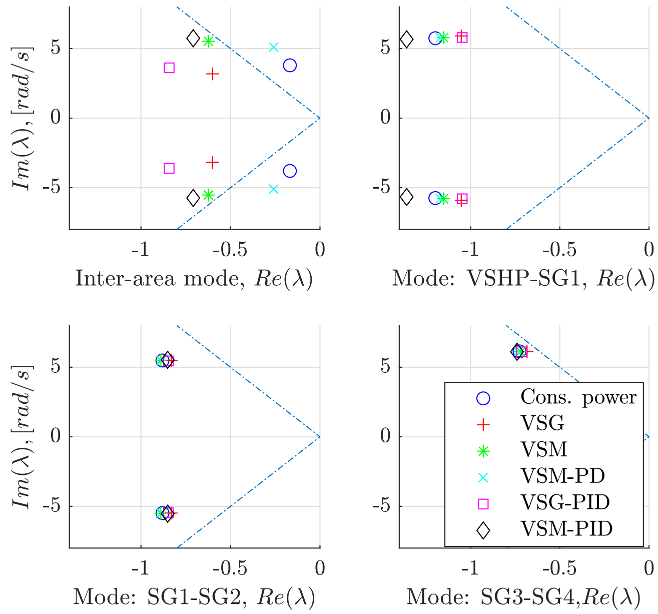

Figure 7: Power oscillation modes for different VSHP control schemes

5. Eigenvalue Analysis

In this chapter, the most important results from the eigenvalue analysis are presented. In the Kundur Two-Area system, an interarea mode exists between Area 1 and Area 2 and a local mode in each area, between, respectively, SG1-SG2 and SG3-SG4. As the VSHP is connected on Bus 5, close to SG1, a new local mode appears between the VSHP and SG1. Fig. 7 shows these four modes for the different control schemes of the VSHP.

The inter-area mode is the mode most dependent on the VSHP control scheme. Compared to the case with constant power control, the modes of the VSM and its variants have a higher frequency and higher relative damping. The damping of this mode for the VSM-PD is still poor. The relative damping of the inter-area mode is doubled when the VSG control of the VSHP is introduced. In addition, the frequency of the oscillation is reduced. The relative damping is slightly better for the VSG-PID than for the VSG.

The relative damping of the mode between the VSHP and SG1 is slightly better for the VSM-based control schemes than the VSG-based control schemes. The local modes between the generators are more or less independent of the VSHP control scheme.

6. Conclusion

Two VI controllers, the VSG and the VSM, have been further developed in this paper to increase the contribution of instantaneous and primarily frequency resources, which are the main objectives for grid support control. At the same time, the objectives of internal control of the VSHP have to be considered in order to limit water hammering, mass oscillations and guide vane operation and to ensure that the turbine rotational speed is regained within an acceptable time.

The VSM topology shows the fastest response when simulating a disturbance and thus delivers the best inertial response. However, since it has zero steady-state feedback from grid frequency, the output power returns to its reference value, and the VSM is not contributing to the frequency control. Frequency control is added by controlling the power reference to the VSM with a PD controller with feedback from grid frequency (VSM-PD) or a PID controller with permanent frequency droop (VSM-PID).

The VSG-based control structures do not have an instantaneous response to the load loss; however, the power response is larger from $200ms$ to $5s$ after the disturbance. In addition, the VSG-based controllers damp oscillations against other generators more effectively, resulting in lower frequency deviation.

Although the VSM controller shows the fastest response during the first $200ms$ after a disturbance, the VSG controller provides better frequency regulation for the next $5s$. In cases where the disturbance is far away from the VSHP, the performance of the VSM controller is reduced, and the VSG performs more effectively regarding the instantaneous power response and permanent frequency droop control.

The dynamic analysis clearly shows that the VSG has the best performance from a grid-integration point of view. However, since the VSM controller is based on emulating the response of a synchronous generator, the PLL is not needed. This makes the VSM capable of working in islanded systems without changing parameters and control structure.

The transient behaviour of the hydraulic system is more or less equal for the VSG, VSG-PID and VSM-PID. The VSHP output power response of the VSM-PD is marginally smaller, causing smaller deviations in the hydraulic system variables.

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