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Linear synthetic inertia for improved frequency quality and reduced hydropower wear and tear

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ABSTRACT

The power system inertia is decreasing in many electrical grids as the share of production from directly connected synchronous generators decreases. Lower inertia increases the frequency deviations in normal operation, which leads to increased wear and tear in hydropower turbines and other units providing frequency control to the system. The predominant concepts for synthetic inertia from for example wind power does not address the frequency quality in normal operation, only the acute problem of frequency stability during large disturbances. This paper investigates how the frequency quality and frequency controlling hydropower units are affected by decreasing inertia and damping, using the Nordic power system as a case study. A new type of synthetic inertia (SI), which is linear and continuously active, is suggested as a means to mitigate the impacts on these units. It is shown that the suggested linear SI controller can effectively replace synchronous inertia and damping, improving frequency quality and reducing hydropower wear and tear. The controller includes an energy recovery feedback loop, to avoid depletion of the energy source behind the controller. The power and energy needed to provide linear SI is quantified, and the impact of the SI energy recovery integration time constant is investigated.

1. Introduction

The electricity production from variable renewable energy (VRE) sources is increasing all over the world. In addition to having a weather dependent power output, these production units are normally connected to the grid through inverters, which means that they do not supply the grid with natural inertia like synchronous machines do. As VRE is replacing production from synchronous machines, the inertia of the power system decreases and the number of units that can provide frequency containment reserves, FCR (also called primary control) and frequency restoration reserves, FRR (also called secondary control), without curtailment decreases. In the European Union, this development has prompted the transmission system operators (TSOs) to include obligations for large generators to provide FCR and some type of inertia in the draft of the new grid code [1,2]. Hydro-Québec in Canada and EirGrid in Ireland have already specified requirements on inertia emulation from wind farms in their grid codes [3,4].

Decreasing inertia can have an impact on several aspects of grid stability [5]. The aspect that has drawn most attention so far is the impact on the rate of change of frequency (ROCOF) and the lowest frequency (the nadir) after a sudden disconnection of the largest unit in the system (the $n-1$ disturbance). Early grid code requirements on synthetic inertia (SI), like the ones by Hydro-Québec [3] and EirGrid [4], are clearly focusing on this aspect, and commercial implementations of SI, such as GE's WindINERTIA [6] and ENERCON's IE [7] are designed to support the grid only during large frequency events.

Another aspect is the frequency quality during normal operation. Reduced inertia increases the amplitude and frequency of the grid frequency variations [8]. This changes the operational pattern of FCR, leading to more regulation and increased wear and tear of the units delivering frequency control reserves to the grid, for example hydropower [9,10], which may lead to increasing costs for frequency control. It also affects the worst case nadir for an $n-1$ disturbance, since the frequency may already be low when the disturbance occurs. The impact on normal operation has been overlooked in studies on synthetic inertia so far.

A third aspect is that reduced inertia and damping may impact the modes of electro-mechanical oscillations in the system. The conventional way to address electro-mechanical oscillations is to use power system stabilizers (PSSs) on synchronous generators. As an alternative,

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both synthetic damping [11] and specialized controllers using notch filters [12] have been suggested for systems with a high share of VRE.

A wide range of solutions to the problem of decreasing inertia has been investigated. One end of the spectrum is virtual synchronous machines/generator (VISMA, VSM, VSG) [13–16] or synchronverters [17], that aim at creating an interface between the VRE and the grid that totally emulates a synchronous machine with inertia, damping, voltage control, etc., which is continuously active. The other end of the spectrum is emulated inertia as defined by for example Hydro-Québec, i.e. a fixed power output for a certain time period, that is triggered by large frequency events but otherwise inactive. The terms synthetic/emulated/virtual inertia tend to be used for the types of grid support that are only active during large disturbances. They can be either fixed power profile [3,18] proportional to the grid frequency deviation (P-controller) [19] or proportional to the derivative of the grid frequency deviation (D-controller) [20,21]. Mathematically, D-control corresponds to inertia and P-control corresponds to damping, frequency dependent load or super fast droop control.

Synthetic inertia can be delivered by various sources, for example flywheels, superconducting magnetic energy storages [22], capacitors [23,24], batteries [13] or wind turbines [19,2]. In the case of wind turbines, it is the actual inertia of the unit that is the power source of the synthetic inertia, possibly in combination with extra power extracted from the wind, which is available if the wind speed is higher than the rated wind speed or if some power is being curtailed to create a margin for increase. The inertia can also be used to smooth the output power of the unit [25]. To maintain production efficiency, the wind turbine must be returned to its optimal rotational speed and pitch as soon as possible. This is one reason why research on SI from wind power is oriented towards temporary grid support during large disturbances, while continuously active VSM research normally assumes a large battery as the energy source. However, as long as the energy source is not inexhaustible, some type of energy recovery scheme will be needed. Such schemes has not yet been discussed in research on VSM.

This paper presents a new, linear SI controller which is continuously active, automatically recovers the energy of its energy source and can emulate both inertia and damping. The impact from reduced inertia and damping on the system during normal operation is described, and compared to a scenario where the lost inertia and damping are replaced with active control by the suggested linear SI controller. Furthermore, the impact of the energy recovery time constant of the SI is investigated, both in terms of linear and non-linear (limit cycle) aspects. Energy recovery schemes have previously been studied for temporarily active SI, but not for any of the continuously active concepts like VSM. To the best of our knowledge, the consequences for units delivering frequency control services to the system have not been previously been studied in relation to SI or VSM.

2. Method

In this paper, the Nordic synchronous grid is used as a case study. The system is dominated by hydro and nuclear power, and almost all FCR is delivered by hydropower. Onshore and offshore wind power is growing, at the same time as some nuclear power is scheduled for decommissioning. The organisation for European TSO:s, Entso-e, estimates that in 2020 the kinetic energy of the Nordic system during low load and high wind will be 124 GWs, which is only half of today's normal value, and as low as 80 GWs in 2025 [26]. It is also expected that the frequency dependency of the load will continue to decrease, as more and more loads are connected to the grid via inverters. The Nordic system is sensitive to changes in inertia and damping since the FCR is provided by hydropower with non-minimum phase response. There are already concerns about a very low frequency oscillation in the system [27]. This paper will compare normal operation in today's system with two scenarios: (1) System inertia and damping reduced by half and possibly replaced by synthetic reserves that are triggered at major frequency events, meaning that there is no support in normal operation, and (2) System inertia and damping reduced by half but replaced by continuously active synthetic reserves provided by the suggested linear SI controller, supporting normal operation. Both synthetic inertia (D-control) and synthetic damping (P-control) are investigated in this paper. For simplicity, the controller that provides these two types of grid support will be denoted SI-controller, and which type of service it provides is specified case by case.

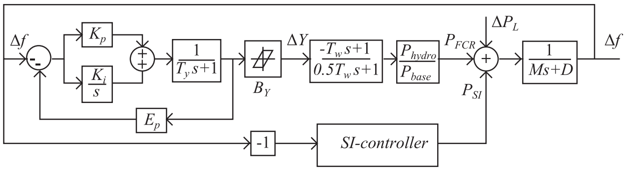

Fig. 1. One-area model of the Nordic synchronous system, where FCR is delivered by hydropower. The signal Δf is the grid frequency deviation, ΔY is the guide vane opening deviation, P_{FCR} is the FCR power output, P_{SI} is the power output from the SI controller and ΔP_L is the load disturbance. Parameter values are given in Table 1, where K_p,K_i and E_p are the governor parameters, T_y is the servo time constant, $\pm B_Y$ is the backlash in the guide vane regulating mechanism, T_w is the water time constant, M is the system inertia constant and D is the frequency dependency of the load (the system damping).

2.1. System

Since this study is focused on the impact on frequency control in normal operation, the power system can be modelled as a one-area model according to Fig. 1, with parameters according to Table 1, c.f. [27]. All the hydropower units delivering FCR are lumped into one unit, governed by a PI controller with droop. Backlash in the guide vane regulating mechanism after the feedback measurement of the guide vane position is included in the model. Measurements on Swedish hydropower units have shown that this type of backlash greatly impacts the performance of the FCR delivered in normal operation [28]. In the Entso-e scenario for 2020, the Nordic hydropower production in the low inertia scenario is 14.5 GW. If the hydropower is assumed to operate at 80% loading (typical best efficiency point), this means that the installed hydropower in operation, P_{hydro}, is 18 GW. Normally, the TSO:s in the Nordic system acquire a total FCR power $P_{FCR} = 7530$ MW/Hz FCR from the power producers. This corresponds to a per unit droop

$$E_p = \frac{1}{P_{FCR}}\frac{P_{hydro}}{f_{base}} = 0.048 \tag{1}$$

in the lumped model. The governor proportional and integral gain K_p and K_i are scaled with the droop E_p so that the dynamic response of the governor is the same as in the previously published model of today's system [27].

2.2. Linear SI controller

A block diagram of the suggested linear SI controller is drawn in Fig. 2. This is the top-level controller, and it is assumed that the delay of the actuation of the requested power output from the SI controller, P_{SI}, is fast enough to be negligible. This is reasonable if the energy source is

Table 1
System parameters in per unit with $P_{base} = 50$ GW. Low load case with total production 29 GW. $P_{hydro} = 20$ GW, cf. Fig. 1.

Scenario	M	D	T_w	B_Y	T_y	E_p	K_p	K_i
Nominal	14.6	0.57	1.01	0.001	0.2	0.048	4.2	0.38
$M = 0.5M_{nom}$	7.3	0.57	1.01	0.001	0.2	0.048	4.2	0.38
$D = 0.5D_{nom}$	14.6	0.285	1.01	0.001	0.2	0.048	4.2	0.38
Both	7.3	0.285	1.01	0.001	0.2	0.048	4.2	0.38