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Frequency stability analysis under consideration of virtual inertia emulation of converter-interfaced hydropower plants in the Nordic Transmission Grid

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SUMMARY

The stabilising influence of the rotating masses as an instantaneous reserve of kinetic energy is being lost due to the decommission of conventional power plants and the increasing penetration of intermittent renewable energy sources. The future Nordic grid with a sparsely meshed grid structure might be liable to frequency deviations as it can be characterised by higher dynamics and low physical inertia. In the Nordic grid hydropower plants have a great impact on the power system stability as they are carrying out most of the local frequency control.
One possibility to maintain frequency in transmission system with a high penetration of renewable energy sources and the resulting low inertia is the provision of additional inertia by virtual inertia emulation of synchronous generators of hydropower plants via converters. Recent research works have discussed the possibility of providing virtual inertia emulation using wind power plants for small grids. This paper presents a method to investigate the impact of the provision of virtual inertia by converter-interfaced hydropower plants besides their physical inertia given by the rotating mass in an extensive grid. Virtual inertia emulation might be a solution to provide spinning reserve in highly renewable power systems and leads to lower deviations of the frequency and a lower rate of change of frequency in case of disturbances in the Nordic transmission grid.

KEYWORDS

automatic generation control, frequency control, hydroelectric power generation, power system stability, virtual inertia emulation, Nordic transmission grid, frequency stability

INTRODUCTION

As part of a long term climate protection policy [1], nowadays an increasing amount of electrical energy is produced by intermittent renewable energy sources (RES) which are often connected to the grid via converts. This leads to a significant change in the generation structure: A decommission of conventional power plants is effectively reducing the capabilities to keep the system stable since synchronously coupled conventional power plants intrinsically have positive effects on power system stability. The stability of a power system can simply be described by the ability to achieve a technically permissible state of equilibrium after a disturbance. Because of this, the frequency as global reference variable of synchronous networks is of great importance. In general, frequency stability depends on whether a balance between consumption and generation can be maintained or recovered. The increasing power input via converters and the decrease of rotating masses of synchronous generators as an instantaneous reserve in the grid change its dynamic behaviour.
The high volatility and difficult predictability of renewable energies amplifies the need of a well-functioning frequency control mechanisms. One possibility to maintain frequency in a transmission system with a high penetration of RES is the provision of additional inertia by virtual inertia emulation of power plants coupled to the grid via synchronous generators. Recent research works have discussed the possibility of providing virtual inertia emulation using wind power plants for small grids [2][3][4].
In the Nordic grid the transmission system operators identified the high volatility of RES in combination with the reduction of the rotating masses as one main risk factor for system stability [5]. The future Nordic grid with a sparsely meshed grid structure might be liable to frequency deviations as it can be characterised by higher dynamics and lower physical inertia. In the Nordic grid hydropower plants have a great impact on power system stability since they are carrying out most of the local frequency control. Hence this paper presents a method to investigate the impact of the provision of virtual inertia by converter-interfaced hydropower plants besides their physical inertia given by the rotating mass in the Nordic transmission grid.

MODELLING

Due to the deteriorating grid frequency quality in transmission systems, RMS time domain simulations of the frequency stability under consideration of highly flexible hydropower plants are investigated in this paper. Therefore, the dynamic behaviour of all frequency-sensitive components in the Nordic transmission grid is modelled. Conventional generation units consist of individual components which exchange information such as synchronous generator, turbine, governor and exciter. The models of the synchronous generator and the exciter are briefly presented while the governor and turbine model are described in detail. Special attention is paid to the investigation of the provision of virtual inertia by converter-interfaced hydropower plants.

Synchronous generator and excitation system

The 4^{th} order synchronous generator model is based on Sauer-Pai [5] and Anderson-Fouad [7]. Electromagnetic transients and sub transient processes have been neglected. Due to the unneglectable voltage regulation of the conventional power plants the Simplified Excitation System (SEXS) is implemented which is recommended by the ENTSO-E [8]. The

SEXS model maps the most important dynamic features of modern excitation system without causing design limitations due to lack of information.

Governor
The task of the speed or frequency governor is to react to a frequency deviation resulting from a generation-consumption imbalance and to adapt the generated active power to the instantaneous demand. The model of the hydropower governor described here is shown in Figure 1 which is used in several hydropower stations in the Nordic power system. It has been developed in collaboration with projects partners within the HydroFlex project.
The governor is represented by a proportional-integral-controller (PI), a pilot valve and a main-gate servo. Additionally, it contains a lead-lag-element term. The electrical power is selected as a reference variable. The feedback of the PI-parallel structure is used as one reference variable, taking into account a permanent speed droop R_P. This approximation prevents oscillations in power and in waterways.
The pilot valve and the main gate servo are both modelled by a first order lag and its time constants. The output signal is the gate opening of the hydro turbine governor and corresponds to the input signal of the following turbine model.

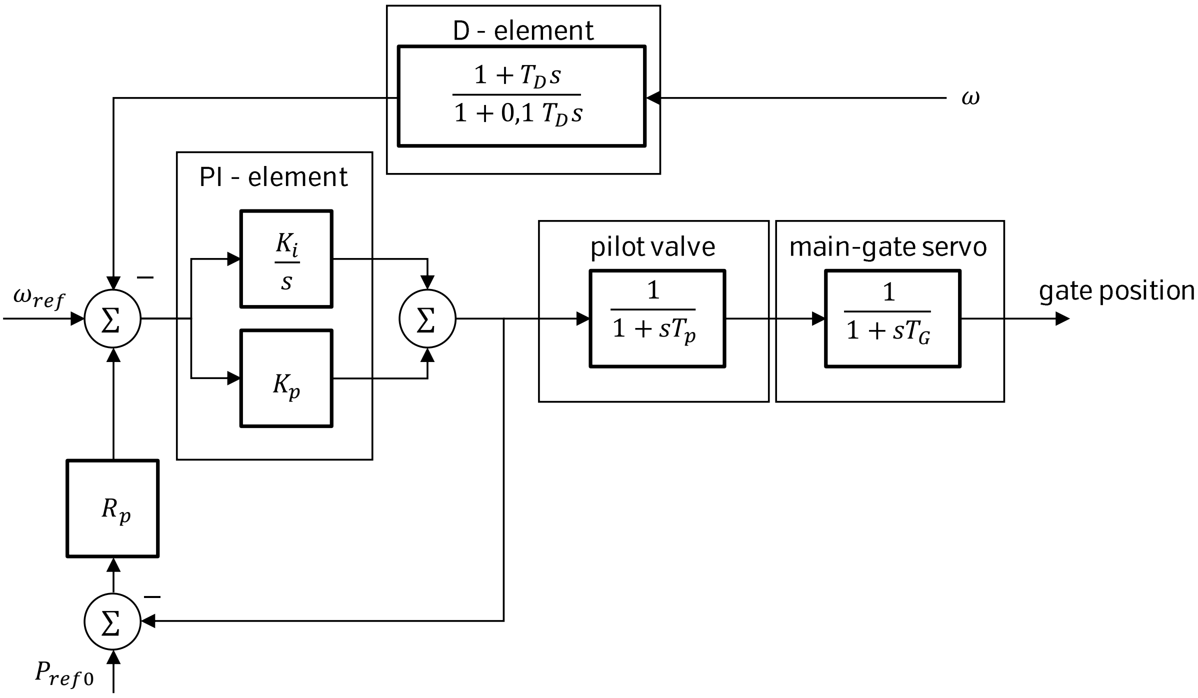

Figure 1: Model of hydro turbine governor

Turbine
The dynamic transfer behaviour of a hydraulic system is significantly influenced by the characteristics of the turbine and the penstock. In this paper a nonlinear inelastic model, shown in Figure 2, is used [9]. The nonlinearity of the model results from the nonlinear relationship between the valve position and the mechanical turbine power. The gain factor A_t transforms the real valve position to a relative gate position. T_W is defined as water run-up time necessary to accelerate the flow in the penstock from standstill to nominal velocity. In

addition, the stationary head and the offset resulting from the rate of flow at idle are taken into account.

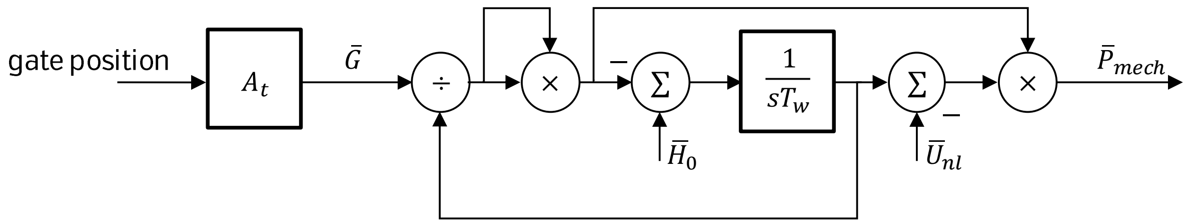

Figure 2: Nonlinear turbine model with inelastic water column [9]

Load

Generally speaking, the consumers can be described as ohmic-inductive dominated. The frequency dependence of loads has decisive influence on system stability – particularly in studies investigating generation deficits or load shedding.
To model the active power dependence the Exponential Load Model is used [10]. It takes the non-linear dependencies of active and reactive power to voltage and frequency into account. Hence the power consumption is modelled as a function of the voltage and the frequency.

Virtual inertia emulation

The main idea of using virtual inertia emulation is the provision of additional virtual inertia by slowing down the rotor even further than by intrinsically provided inertia. This is possible by using a converter between the synchronous generator and the grid.
The model used for the provision of virtual inertia by rotating masses of synchronous machines of hydropower plants is shown in Figure 3. Depending on the deviation between reference and grid frequency additional inertia is provided via the converter by slowing down the rotating mass of the synchronous generator even further than in the case of intrinsically provided inertia.

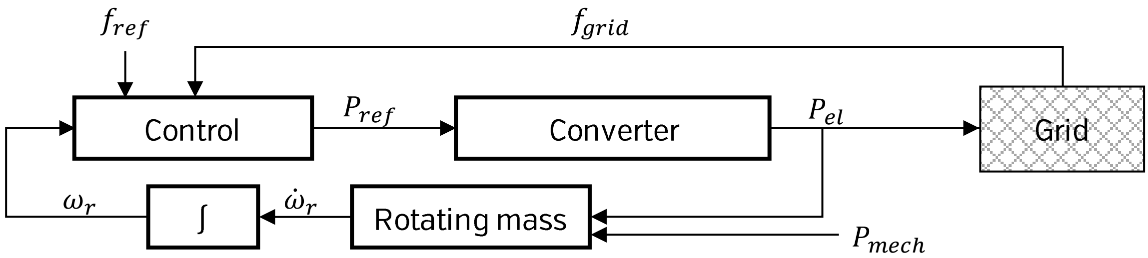

Figure 3: Model of virtual inertia emulation

The model used for virtual inertia control is shown in Figure 4 and is a modification of the model proposed in [4]. The rotor speed is the input for the model of the synchronous machine which has a reference power as output. There are two paths defining the reference power of the virtual inertia emulation. One has a droop characteristic depending on the difference between grid and reference frequency, the other one depends on the derivative of the grid frequency. By gain factors K_{in} and K_f the reaction of the virtual inertia emulation can be weightily changed by rate of change of frequency or by deviation from a reference frequency. Limiters assure that the rotor speed will not be slowed down too much since this might damage the synchronous machine.

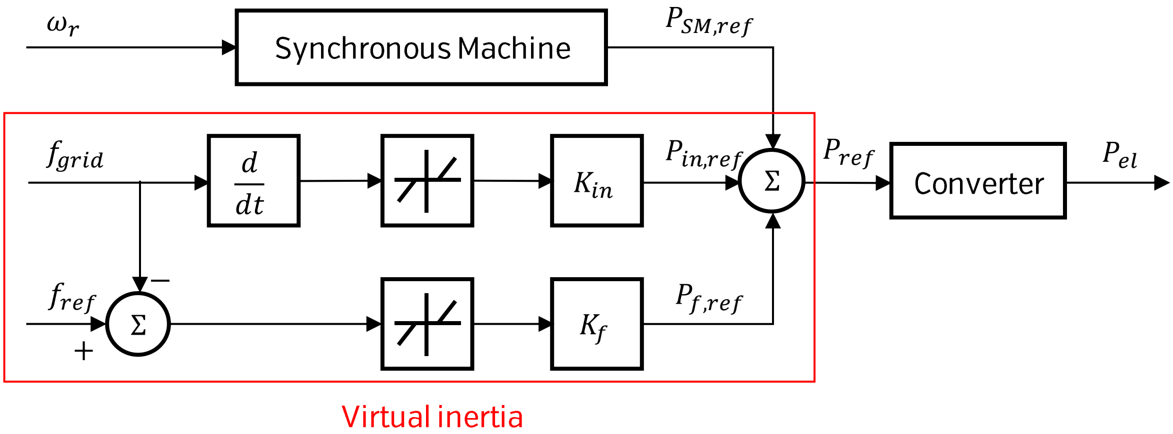

Figure 4: Model of virtual inertia control

VALIDATION OF MODELS

The functionality of the developed model was demonstrated using a modification of the IEEE 39-bus system. It is assumed that the generation units of the IEEE 39-node grid only consist of hydroelectric power plants of one type.
Figure 5 shows that ten synchronous generators are connected to the grid as well as 18 frequency-dependent consumers. Nodes 1 to 29 are defined as PQ nodes, nodes 30 to 39 as PV nodes and node 31 with generator 2 (G2) as slack node. The total power of the power plants is 6134.3 GW and the total load is 6087.9 GW. For the following investigations RMS time domain simulations are performed. To initialise the power system a power flow calculation based on the Newton-Raphson method is used. In contrast to the Nordic grid the frequency of the test system is 60 Hz. However, this is not relevant for the validation of the model for virtual inertia emulation as the results are displayed and evaluated in per unit values. Thus a frequency equal one represents the nominal frequency.
The investigation of a sudden rise of a load in the small test grid is useful in order to consider the behaviour of the hydropower plants in isolation. The following section focuses at the effects on the frequency response when modelling the power plants without virtual inertia emulation in comparison with the frequency response when using virtual inertia emulation.
The gain factors K_{in} and K_f used for the following investigations are set to 10,000 to enable a highly stabilising effect by virtual inertia emulation even for small frequency deviations.

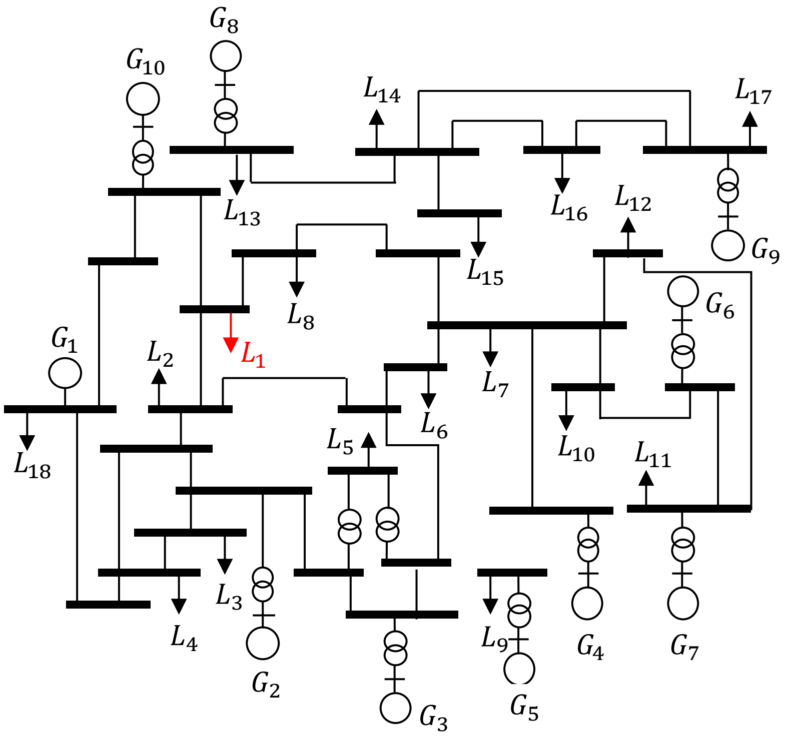

Figure 5: IEEE 39 bus system

At time t = 0.5 s load 1 (L1, see Figure 5) increases by 50 % to 483 MW and it's set back to its initial value of 322 MW at time t = 1.5 s. The left diagram of Figure 1Figure 6 presents the frequency response over time for two different models of synchronous generators: The grey line represents the frequency with only intrinsic spinning reserves while the black line represents the frequency with additional virtual inertia emulation. As the frequency nadir in the test system without virtual inertia emulation is 0.9989 p.u. at t = 0.53 s the frequency nadir in the test system with virtual inertia emulation is 0.9992 p.u. at t = 0.52 s. In the following seconds the frequency in the case of using virtual inertia is almost on the constant level of 1.0 p.u. while in the case without using virtual inertia the frequency decreases to approx. 0.995 p.u. This result shows the positive effect of virtual inertia emulation on the frequency in the test system.

The right diagram of Figure 6 shows the rotor speed over time of generator G1 connected to the grid synchronously. Rotor speed decreases more significantly when using virtual spinning reserve. While in the case without virtual inertia emulation the minimum of rotor speed is 0.995 p.u. the minimum of rotor speed in the case with virtual inertia emulation is lower than 0.988 p.u. Since virtual inertia emulation removes more kinetic energy from the rotating mass of the generator this behaviour is reasonable. It is also shown that the speed governor is able to accelerate the rotor after the load recovered.

The comparison of both diagrams presents one main effect of virtual inertia emulation: While grid frequency and generator speed show similar developments over time when not considering virtual inertia emulation the frequency and rotor speed behave differently since grid frequency and rotor speed are decoupled by the converter when using virtual inertia emulation.

These results show the fundamental effect of virtual inertia emulation and shall be carried out to a larger power system.

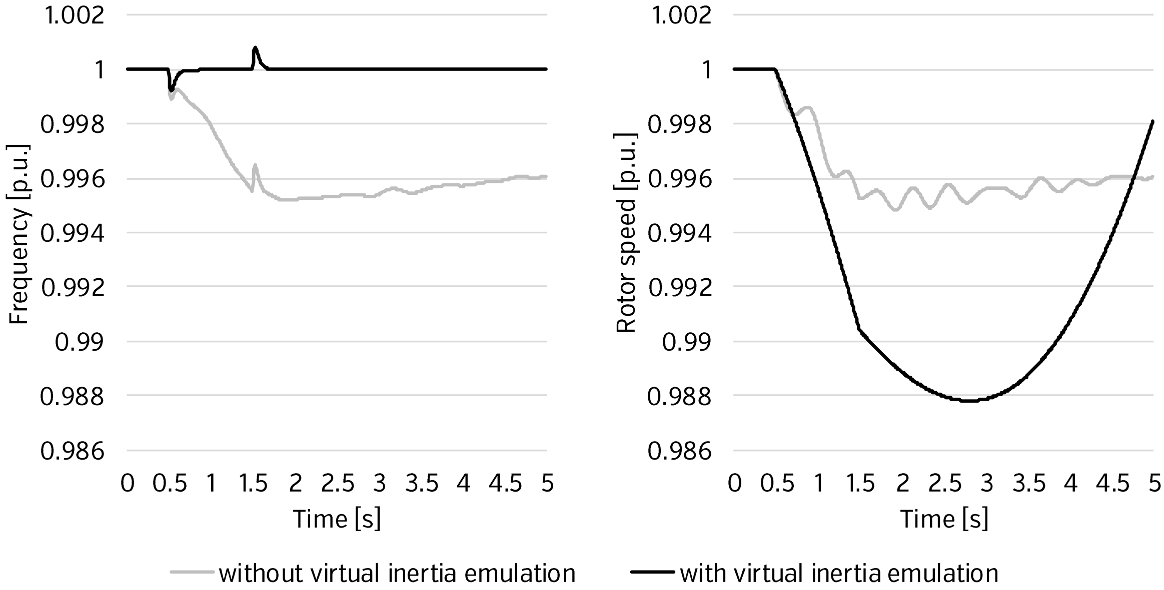

Figure 6: Frequency at node of load 1 (left); Rotor speed of generator G1 (right)

FREQUENCY STABILITY ANALYSIS IN THE SCANDINAVIAN TRANSMISSION GRID

In the following a rise of load and its impact on the frequency in the Nordic grid are analysed. The node-precise grid structure is visualised in Figure 7.

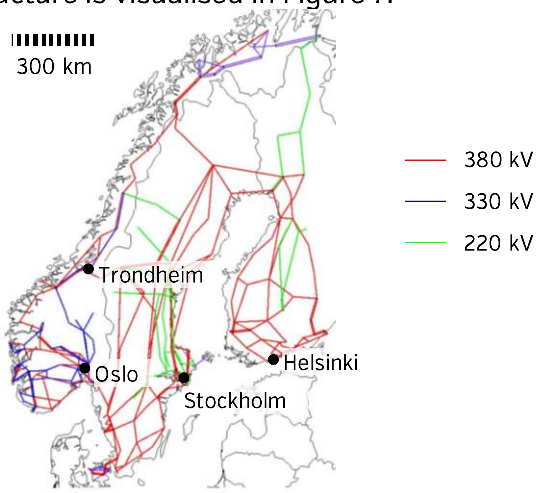

Figure 7: Focus part of Nordic transmission grid

The different voltage levels of the transmission network are highlighted in colour. The nominal grid frequency is 50 Hz and a total of 1064 power plants with a total power of 27.1 GW are modelled. The initialisation of the devices in the power system bases on the infeed of the power plants and the consumption of loads calculated by a market simulation and a power flow calculation. For time domain simulations a distinction is made within the power plants according to the generation technology. There are 1033 hydropower plants and 31 steam power plants which are represented by the TGOV1-Model [11]. Furthermore, there are 946 frequency dependent loads with a total power of 24.7 GW in the grid. In this paper hydropower and steam power plants are set up with a parametrisation that can be seen as common in literature [12]. Small generating units as well as hydropower plants which are in pump operation and therefore have a negative output from a grid point of view are also modelled as frequency-dependent consumers without any explicit governor mechanism.

As described before frequency stability essentially depends on an equilibrium of generation and consumption. Therefore, a load surplus is analysed as exemplary change within the grid. This rise of all loads to 150 % is triggered at time t = 0.5 s until t = 1.5 s. The frequency over time at one node in the grid is shown in the left diagram of Figure 8. The course of the frequency is similar to the course in the test grid (see Figure 6. The frequency drops to approx. 0.998 p.u. in case of using virtual inertia emulation and to approx. 0.995 p.u. in case of no virtual inertia emulation. In this case the frequency nadir can be approx. divided in half when considering virtual inertia. This results in a rate of change of frequency which is divided in half, too.

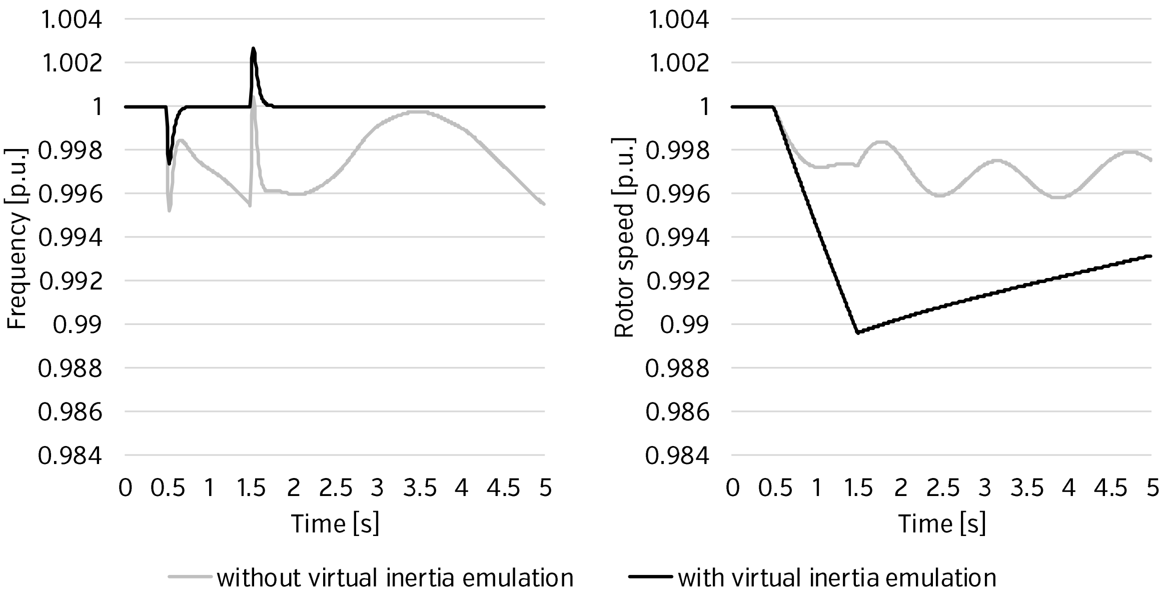

Figure 8: Frequency at node of load 1 (left); Rotor speed of generator near location of load (right)

The right diagram of Figure 8 shows the rotor speed of a generator near to the node of the frequency measurement. Between t = 0.5 s and t = 1.5 s the rotor speed drops down from 1.000 p.u. to approx. 0.990 p.u. in case of using virtual inertia emulation and it is accelerated to 0.993 p.u. after the load recovered. If there is no virtual inertia emulation the rotor speed only drops down from 1.000 p.u. to approx. 0.997 p.u. within the same time interval. In the considered case there is a reduction of frequency nadir and rate of change of frequency at cost of slowing down the rotation speed of the generator by 1 %, from 50 Hz in the initial state until t = 0.5 s to 49.5 Hz at the end of the inequilibrium at t = 1.5 s.

CONCLUSION AND DISCUSSION

In this paper the effect of virtual inertia emulation by water turbines is investigated. All components that are involved in frequency stability are modelled with respect to their

dynamic behaviour. The implemented excitation systems, prime mover and governors are shortly described. The developed model for virtual inertia emulation is validated using a test system. Subsequently the developed dynamic model is applied to the Nordic grid. The resulting frequency characteristic from a sudden rise of load is analysed.
The investigated rise of load clearly shows that virtual inertia reduces the frequency nadir and the rate of change of frequency. The results indicate that frequency stability of the Nordic grid is guaranteed for the considered load case, even without using virtual inertia emulation. Hydropower plants are able to serve as predictable RES which secure the frequency stability in a generation-driven system with low physical inertia by providing both intrinsic spinning reserve and, if necessary, virtual spinning reserve by virtual inertia emulation presented in this paper.

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