Developing Voltage Droop/Compensation Controller for a Hydro Power Controller in Modelica

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Abstract

With the introduction of unregulated renewable energy such as wind, solar and tidal power, the operation of the electrical grid has become more and more challenging. The more dynamic production pattern requires more advanced control algorithms in order to maintain an acceptable voltage quality which is within the limits given by the electrical network regulators. Better tooling and improved simulation of different operation scenarios is required.

This paper presents the development of voltage droop/compensation controller as used in a typical hydro power controller. The controllers has been implemented using the Modelica language [4] and are according to the Norwegian Energy Regulatory Authority (NERA). Having the controller available in Modelica makes it possible to integrate them with hydro power system models build with the use of OpenHPL [7]. The behaviour of the controller have been tested against a verified generator model of the OpenIPSL [1].

1. Introduction

The electrical power demand is still increasing, and it leads to pushing the society to find a renewable source to produce electricity. Therefore the development of existing and new hydropower stations is still increasing. The development of hydropower plants focuses not only on larger hydropower plants but also on small-scale hydropower plants in order to utilise as much resource from nature.

A hydropower plant consists of several components such as a valve, turbine, generator, turbine-regulator, excitation system, switch gear, etc. The generator converts mechanical energy into electrical energy. A generator needs an excitation system to provide field current to the field winding in order to induce the voltage in the generator terminals. An excitation system contains mainly an exciter that produces field current and an excitation control system that consists of an Automatic Voltage Regulator (AVR), controllers, and protective limiters.

In order to keep the voltage quality within the limits of what the electrical network regulators allow, the government has developed requirements to the hydropower stations to adequate operation of power plants.

The legal requirement for excitation systems in Norway is given in the National Guide for Functional Requirements in the Power System, NVF 2020, [6]. It is a guideline for the power system administrators to build, maintain or operate their system in order to fulfil the functional requirements set by the Norwegian Energy Regulatory Authority (NERA). The NVF 2020 contains requirements for the Norwegian grids, production power plants, High Voltage Direct Current (HVDC), consumers, protections, and measuring equipment. The production power plant part in the NVF 2020 describes requirements for synchronous power plants and power parks. Several requirements are described under synchronous power plants, such as turbine regulation, excitation system, maximum reactive power, etc. Where the excitation system section describes the requirement for excitation system response time, VAR/PF control or regulation, voltage droop/compensation control, limiters, Power System Stabiliser, and reset functionality. This paper focuses on modelling and simulation of the voltage droop/compensation control function.

2. Theory

The voltage droop/compensation controller is an additional function that is required by NERA. The purpose of this controller is to maintain constant generator terminal voltage concerning additional measurement signals from the generator, such as reactive, active current, and frequency. The voltage droop/compensation controller influences the voltage reference in the AVR to obtain the desired terminal voltage output. This controller consists of four control functions, reactive current droop, reactive current compensation, active current compensation, and frequency droop, the characteristics of each control function are described below.

2.1. Reactive Current Droop Control

Reactive current droop control is one of the functionality implemented to stabilise the distribution of reactive load between two or more generators on the same busbar. Alternatively, to reduce the reactive load changes at a small generator that is connected to an unstable grid with high voltage variations. This control function has a negative droop that reduces the terminal voltage as a function of increasing reactive current (see Fig. 1, which gives the same effect as an inductor connected in series with the generator.

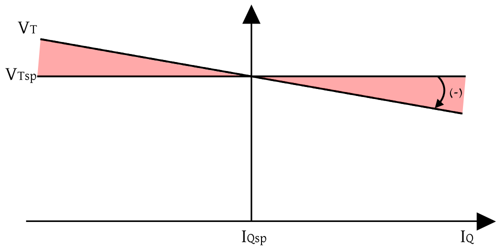

Figure 1: Characteristic curve of reactive current droop control function. V_T: Generator terminal voltage, I_Q: Generator terminal reactive current output, V_{Tsp}: Generator terminal voltage set point, I_{Qsp}: Reactive current setpoint.

2.2. Reactive Current Compensation Control

This control function is used to compensate for the voltage drop due to reactive components as transformers or transmission lines in the gird. The reactive current compensation control function is quite the opposite of the reactive current droop control function, as depicted in Fig. 2. This control function has a positive droop, meaning the terminal voltage increases for increasing reactive current.

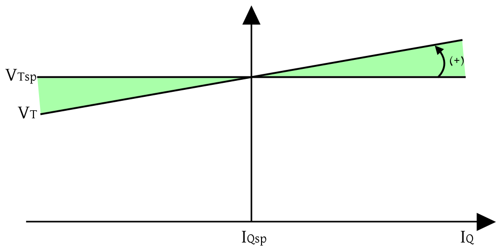

Figure 2: Characteristic curve of reactive current compensation control function. V_T: Generator terminal voltage, I_Q: Generator terminal reactive current output, V_{Tsp}: Generator terminal voltage setpoint, I_{Qsp}: Reactive current setpoint .

2.3. Active Current Compensation Control

The active current compensation control function is used to compensate for voltage drop over transformers or transmission lines due to active power consumption. This control function increases the terminal voltage as a function of increasing active current, see Fig. 3.

2.4. Frequency Droop Control

This control function can be used to help the turbine regulator to stabilise the frequency at the local grid. The frequency droop control function increases or decreases the terminal voltage as a function of increasing or decreasing frequency within a limited span (see Fig. 4). As a consequence, active power consumption in the resistive load increases if the generator runs at a higher speed. This control is only active if the circuit breaker is closed.

3. Modelling of Controller

The voltage droop/compensation controller varies the generator terminal voltage considering the changes in active and reactive current and frequency. The controller's output interacts with the summing point to modify the voltage reference signal V_{REF}, and consequently, the

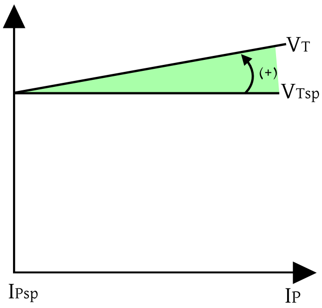

Figure 3: Characteristic curve of active current compensation control function. V_T: Generator terminal voltage, I_P: Generator terminal active current output, V_{Tsp}: Generator terminal voltage setpoint, I_{Psp}: Active current setpoint.

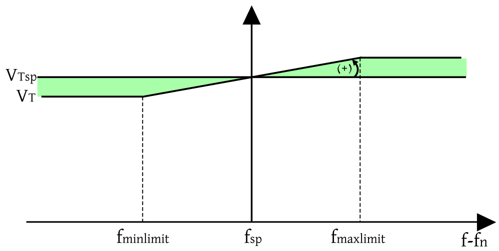

Figure 4: Characteristic curve of frequency droop control function. V_T: Generator terminal voltage, f: Actual frequency of the generator, V_{Tsp}: Generator terminal voltage setpoint, f_{sp}: Frequency setpoint.

generator terminal voltage will be regulated. The voltage droop/compensation controller consists of four control functions or three controllers. The modelling of the controllers is described below.

3.1. Reactive Current Droop and Compensation Controller

This controller inherent a combination of reactive current droop and reactive current compensation control functions. The controller is fundamentally modelled based on the formula given in (1) [5]. This formula is used to calculate the new generator terminal voltage setpoint considering the droop/compensation value and actual generator reactive current output. The E_{rr} obtained by subtracting the measured terminal voltage V_T from the calculated generator terminal voltage value V_{Tcal} and then the E_{rr} is applied through the PID controller to the output. Additionally, the droop (regulation) value should be given in percent, and most importantly, it should be a negative value "-" for the droop control function and a positive value "+" for the compensation control function. Fig. 5 illustrates the block diagram of the reactive current droop/compensation controller. The Boolean signal $IQ_{controller}$ should be "true" in order to activate the output of the controller, else the output will be zero.

$$V_{Tcal} = ((\frac{I_Q - I_{Qsp}}{I_{Qn}} \cdot \frac{R_{IQ}}{100}) + 1) \cdot V_{Tsp} \qquad (1)$$

where

R_{IQ}:	The droop (regulation) value	[%]
I_Q:	The actual generator reactive current output	[pu]
I_{Qsp}:	The generator reactive current setpoint	[pu]
I_{Qn}:	Generator nominal reactive current	[pu]
V_{Tcal}:	The calculated new generator terminal voltage setpoint	[pu]
V_{Tsp}:	The generator terminal voltage setpoint	[pu]

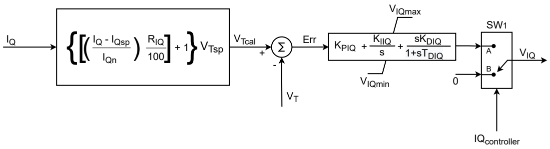

Figure 5: Block diagram of reactive current droop/compensation controller

3.2. Active Current Compensation Controller

The active current compensation control function model uses the formula given in (2) to calculate the new generator terminal voltage setpoint [35]. This controller regulates the voltage only if the actual active current I_P is higher than the active current setpoint I_{Psp}. Meaning, if the I_P is less than the I_{Psp} the active compensation controller will not react. Further, the E_{rr} is calculated by subtracting the V_T from V_{Tcal} then applied to the output through the PID controller. The regulation value R_{IP} should be a positive value to obtain the compensation function. Otherwise, the controller will behave on the contrary. The block diagram of the active current compensation controller is presented in Fig. 6. The Boolean signal $IP_{controller}$ should be "true" to change the position in the switch SW_1 to enable the output of the controller, otherwise the it will be zero.

$$V_{Tcal} = ((\frac{I_P - I_{Psp}}{I_{Pn}} \cdot \frac{R_{IP}}{100}) + 1) \cdot V_{Tsp} \qquad (2)$$

where

R_{IP}:	The droop (regulation) value	[%]
I_P:	The actual generator active current output	[pu]
I_{Psp}:	The generator active current setpoint	[pu]
I_{Pn}:	Generator nominal active current	[pu]
V_{Tcal}:	The calculated new generator terminal voltage setpoint	[pu]
V_{Tsp}:	The generator terminal voltage setpoint	[pu]

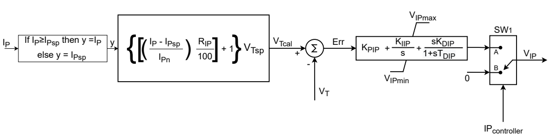

Figure 6: Block diagram of active current compensation controller

3.3. Frequency Droop Controller

This controller model is modelled based on (3) to determine the new generator terminal voltage setpoint. This controller behaves similarly to the latter controllers, where the E_{rr} is obtained by comparing the V_T and V_{Tcal}, then applying this through the PID controller to the output. The droop (regulation) value should be a positive value to obtain the compensation function. Besides, this controller has an additional function limiting the voltage support when the frequency exceeds the maximum and minimum limit, f_{maxlimit} and f_{minlimit}, respectively. This means that the frequency droop controller will not increase or decrease the V_T when the frequency exceeds the latter limits. The Boolean signal $f_{controller}$ should be "true", and the circuit breaker should be closed in order to activate the output of the controller, else the output is zero. The block diagram of the frequency droop controller is depicted in Fig. 7.

$$V_{Tcal} = ((\frac{f - f_{sp}}{f_n} \cdot \frac{R_f}{100}) + 1) \cdot V_{Tsp} \qquad (3)$$

where

R_f:	The droop (regulation) value	[%]
f:	The actual frequency	[pu]
f_{sp}:	The frequency setpoint	[pu]
f_n:	Nominal frequency	[pu]
V_{Tcal}:	The calculated new generator terminal voltage setpoint	[pu]
V_{Tsp}:	The generator terminal voltage setpoint	[pu]

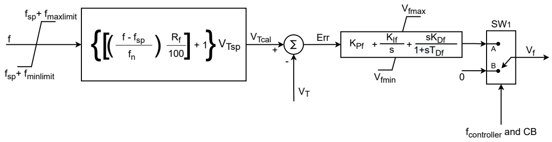

Figure 7: Block diagram of the frequency droop controller

3.4. Final Combined Controller

All three controllers mentioned in Section , , and are added together into a voltage droop/compensation controller model as shown in Fig. 8). The checkboxes III, V, and VII in Fig. 9 shall be selected in order to enable the outputs of the reactive current droop/compensation, active current compensation, and frequency droop controllers, respectively. These checkboxes are associated with the switches, `SW1_IQ`, `SW1_IP`, and `SW1_f`. Thus, the controllers can either be used alone or in combination with others to regulate the voltage. All the setpoint values can be chosen as constant or variable setpoints by choosing the checkboxes indicated with II, IV, VI, and VIII in Fig. 9. When the checkboxes II, IV, VI, and VIII are checked, variable setpoint inputs such as terminal voltage setpoint V_{Tvsp}, reactive current setpoint I_{Qvsp}, active current setpoint I_{Pvsp}, and frequency setpoint f_{vsp} will be enabled to connect, respectively. Simultaneously, when those are activated, the associated constant setpoints will be disabled. Moreover, conditional connections are visibly indicated with dashed lines in Fig. 8. Note that the controller's parameters are placed in individual tabs as indicated with (I) in Fig. 9, while the common terminal voltage setpoint options are placed in the tab called "General". Further, in active compensation and frequency droop control functions, an absolute block is used to assure that a given negative droop (regulation) value (R_{IP} and R_f) does not change the characteristics of the control functions. Be aware of the named parameters in the controller's block diagram and the model because they are changed due to modelling purposes.

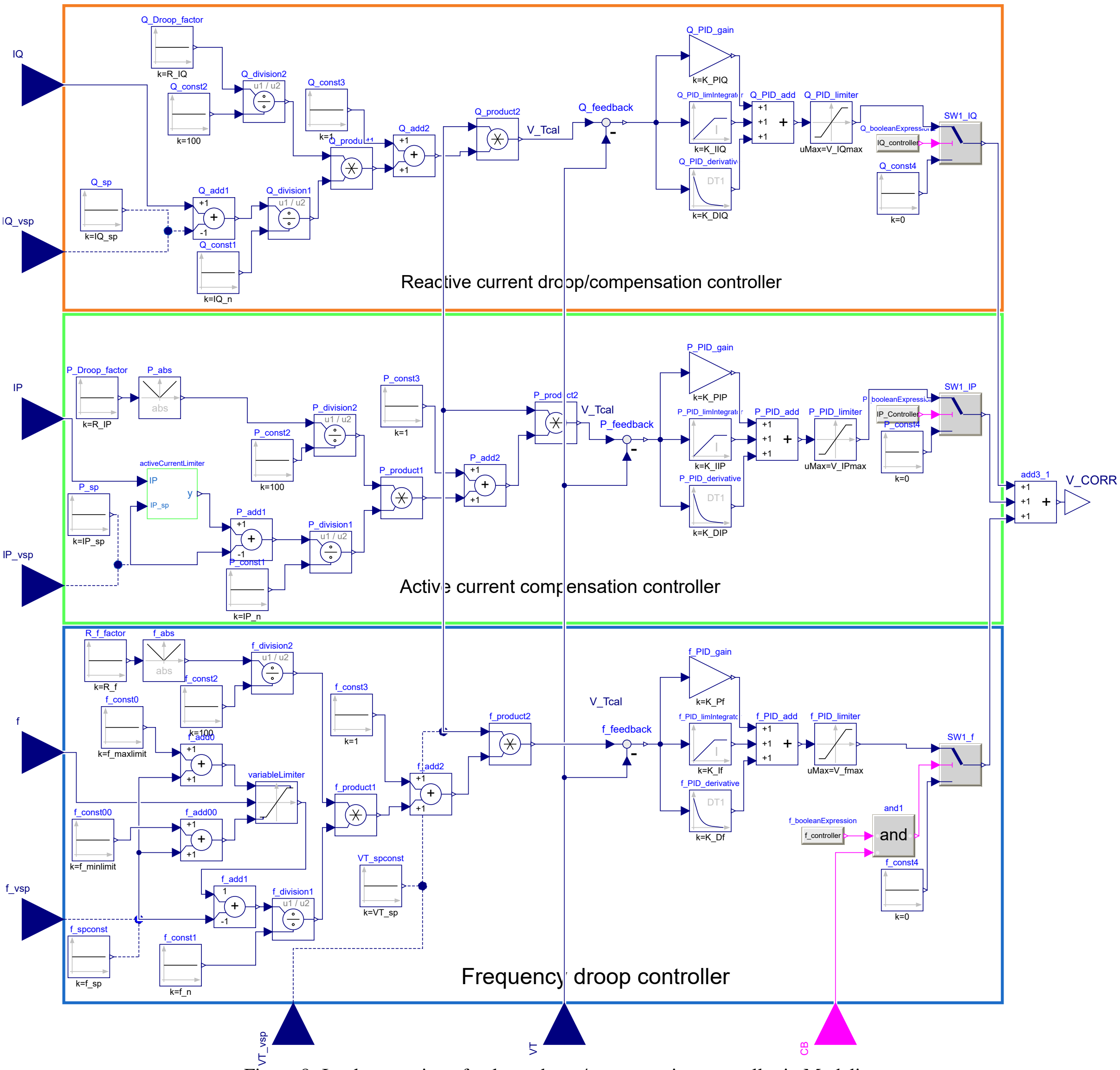

Figure 8: Implementation of voltage droop/compensation controller in Modelica

4. Simulation Results

This section presents simulation results of voltage droop/compensation controller. A test setup of the voltage droop/compensation controller is portrayed in Fig. 10. The test setup is created using a GENSAL generator, transmission line, infinite grid, and excitation system type*ST7C* from the OpenIPSL version 2.0.0 [1], as shown in Fig. 10. The system power base and frequency for all the components are set to $10\,MVA$ and $50\,Hz$, accordingly. The generator is initialised, as presented in Table 1, during the various simulations. Also the voltage setpoint V_{Tsp}, reactive current setpoint I_{Qsp}, active current setpoint I_{Psp}, and frequency setpoint f_{sp} are varied to examine the controller. The simulation is performed individually for each controller by changing the controller's latter setpoints at 1200 s and the voltage setpoint at 2200 s.

4.1. Reactive Current Droop and Compensation Controller

There are performed two tests with this controller, first with the droop function and the second with the compensation function. The generator reactive current setpoint I_{Qsp} is changed from zero to 0.5 pu at 1200 s, and the voltage setpoint V_{Tsp} is changed from 1 to 1.05 pu at 2200 s. Initially, the controller starts to influence the AVR to reduce the terminal voltage equal to the predefined voltage setpoint, as shown in Fig. 11. Please note that when the AVR influences, the field voltage applied to the generator will be affected. Consequently, the reactive power or current output is affected to obtain the desired

Table 1: Initialisation of GENSAL generator for simulation

Name	Description	Value	Units
P_0	Initial active power	2	MW
Q_0	Initial reactive power	1	Mvar
v_0	Initial voltage magnitude	1	pu
$angle_0$	Initial voltage angle	0	$\circ$
ω	Initial generator speed	0	pu

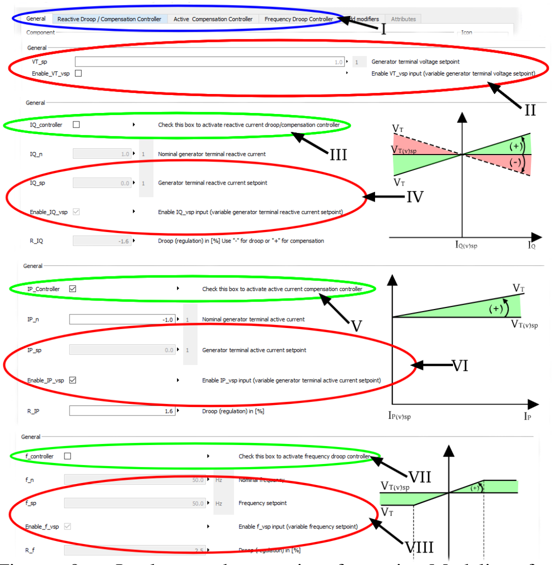

Figure 9: Implemented user interfaces in Modelica for voltage droop/compensation controller. I: Tabs for each controller. II: Checkbox to enable the variable generator terminal voltage setpoint. III: Checkbox to enable Reactive current droop/compensation controller. IV: Checkbox to enable the variable generator terminal reactive current setpoint. V: Checkbox to enable Active current compensation controller. VI: Checkbox to enable the variable generator terminal active current setpoint. VII: Checkbox to enable the Frequency droop controller. VIII: Checkbox to enable the variable frequency setpoint.

terminal voltage. Hence, the terminal voltage is stabilised at 1 pu before I_{Qsp} changes. When I_{Qsp} changes, the reactive current increases, hence the voltage increases. The stabilised voltage ends up at 1.00748 pu, which is similar to the calculated value. Simultaneously, when the V_{Tsp} increases, there is a significant change in terminal voltage due to an increase in the reactive current. The deviation between the calculated value and the simulated value is found to be about $1.97 \cdot 10^{-6}$, which is reasonable. Note that the steady-state terminal voltage after a setpoint change can be calculated using (1) to verify the results.
Since the initial terminal voltage is higher than the preset setpoint, the controller reduces the terminal voltage, as shown in Fig. 12. The voltage is finally stabilised at 0.9999 pu before any setpoint changes, which is corresponds to manually calculated terminal voltage using (1). After the increase in I_{Qsp} at 1800 s, the reactive current and the terminal voltage are decreased to roughly -0.0489 pu and 0.9912 pu, respectively. Whereas change in V_{Tsp} is causing the voltage to rise again to 1.0453 pu, as expected.

4.2. Active Current Compensation Controller

The results from the active current compensation controller simulation are presented in Fig. 13. Where the generator active current setpoint I_{Psp} is changed from 0.5 to 0 pu at 1200 s, and the voltage setpoint V_{Tsp} is changed from 1 to 1.05 pu at 2200 s. At the initial stage, when the setpoint is at 0.5 pu, the generator active current output I_P is at 0.1996 pu, thus the controller does not react on I_P. It will rather consider the setpoint as an actual active current output, and it compensates for it because the controller does not operate for any I_P below the setpoint. Thus, the terminal voltage is reduced to 1 pu by regulating the generator's reactive power or current. Later, the setpoint

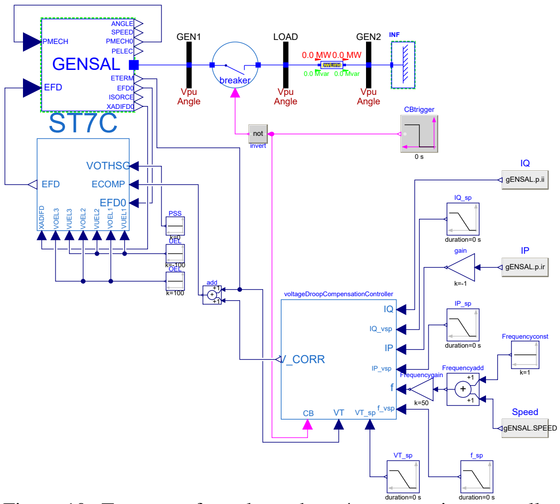

Figure 10: Test setup for voltage droop/compensation controller model

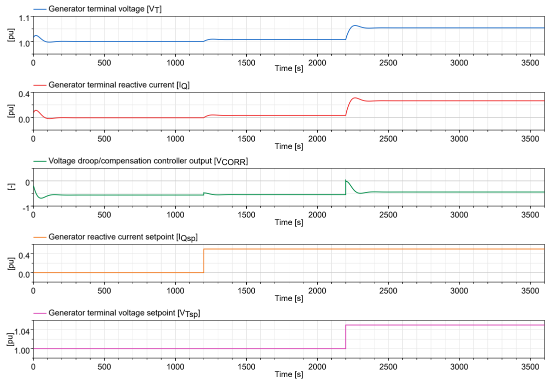

Figure 11: Performance of voltage droop/compensation controller when the reactive current droop function is activated.

reduces to zero, then the controller starts to compensate for the actual active current output. Hence, I_P is higher than the setpoint, the terminal voltage increased and stabilised at 1.0048 pu, as expected. When the voltage setpoint increased, as a result, the terminal voltage increased to 1.0498 pu, which is equal to the manually calculated value, where the manually calculated value is acquired by using (2).

4.3. Frequency Droop Controller

Fig. 14 illustrates the simulation results of the voltage droop/compensation controller using the frequency droop function. Since in the beginning, the nominal frequency and the frequency setpoint is at 50 Hz, and terminal voltage is higher than V_{Tsp}, the controller tries to reduce the voltage to 1 pu. Afterwards, when the frequency setpoint is reduced to 48 Hz, consequently the voltage is increased to 1.001 pu as expected. And, when the voltage setpoint V_{Tsp} is increased to 1.05 pu at 2200 s, the terminal voltage rises again and stabilises at roughly 1.05 pu as desired.

5. Discussion

This paper aims to model voltage droop/compensation controller in the Modelica modelling language. Fundamentally, the controller is modelled based on

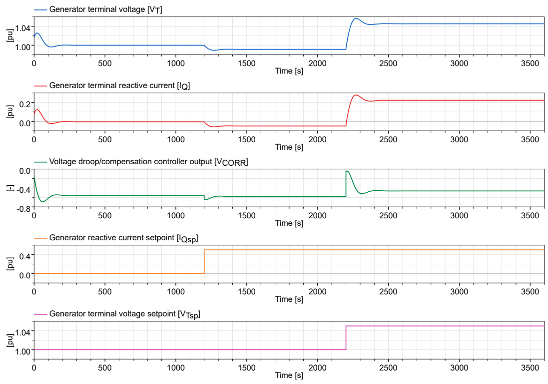

Figure 12: Performance of voltage droop/compensation controller when the reactive current compensation function is activated.

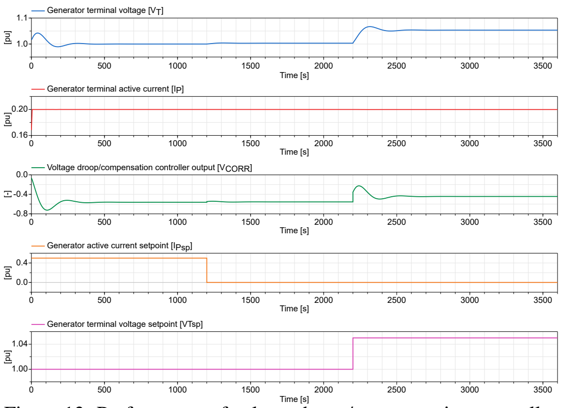

Figure 13: Performance of voltage droop/compensation controller when the active current compensation function is activated.

the requirements in NVF 2020; however, the models have been modified slightly for modelling purposes. The excitation system, type ST7C, is obtained from the OpenIPSL library.
Since the primary focus of this paper is to model the voltage droop/compensation controller, the test setup modelling is kept simple as possible to analyse the model performance.
The overall behaviour of the model was reasonable to compare to the theoretical behaviour. However, the simulation results should be compared with the real controller to verify the model performance. The controller models have a switch at the output to disable the control function. These switches may cause a sudden increase in the control signal, consequently, an overshoot in terminal voltage output may occur. It can be eliminated by adding a self-reset function for the PID controller to reset when the output is re-enabled.

6. Conclusions

In this paper, the voltage droop/compensation controller is mainly object-oriented modelled in Modelica modelling language using Dymola software. The models are fundamentally modelled with reference to requirements in the National Guide for Functional Requirements in the Power System, NVF 2020, [6].
The voltage droop/compensation controller modelled separately from scratch, except the AVR, obtained from the external library OpenIPSL. Later, the model was simulated separately and then compared to these

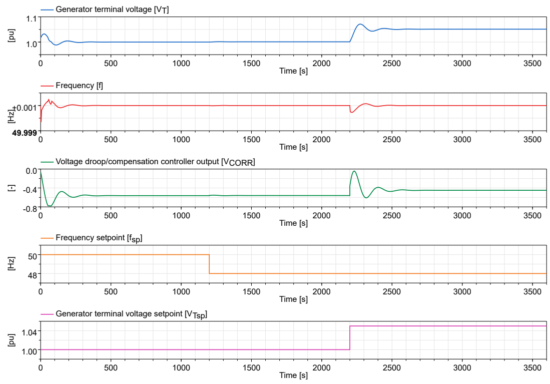

Figure 14: Performance of voltage droop/compensation controller when the frequency droop function is activated.

controller's theoretical behaviour.
In conclusion, the model performed as desired but still need proper tuning and further development to enhance the performance. For the future it is planned to run further tests with real power plant data in order to improve and verify the behaviour of the limiter models.

Acknowledgement

This paper is the result of the Master's Thesis of Luxshan Manoranjan, with the title "Modeling the Excitation Control System of a Hydropower Controller in Modelica" [2]. The thesis also covered the modelling of limiters which has been published in [3].

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