IOP Conference Series: Earth and Environmental Science

Measurements and simulations of turbines on common grid

To cite this article: T K Nielsen and P-T Storli 2014 *IOP Conf. Ser.: Earth Environ. Sci.* **22** 042018

Measurements and simulations of turbines on common grid

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Abstract: Speed droop control is of basic importance for the primary governing in the Nordic grid. The speed droop control, a mandatory and build-in regulatory loop on all larger units, is automatically changing the produced power on synchronous units as the grid frequency changes. This part of the governor allows a certain deviance from the nominal 50 Hz grid frequency. If the grid frequency is decreasing this means that the load on the grid is greater than the power delivered into the grid, and the local speed droop regulatory loop on each unit then autonomously increases the production to obtain a new balance between load and production, which will be at a lower frequency than 50 Hz. If the power delivered into the grid is greater than the load, the rotating masses will be accelerated (thus increasing the grid frequency) and the speed droop operation will act to reduce the power produced to obtain a new balance, this time at a higher frequency than 50 Hz. The frequency in the Nordic power grid has in recent years for increasing duration been outside the allowed steady state frequency band of 50 ± 0.1 Hz. In order to study the behaviour of a turbine operating on a common grid, measurements have been done at site. The measurements performed are the generator power, main servo motor position, the rotational speed of the unit and the grid frequency. The purpose of the measurements was to see if it is possible to observe the behaviour of the machine as it is linked together with all the other machines on a synchronous grid. It is interesting to observe the response to deviations in the frequency due to the speed droop operation. In order to better understand the behaviour, a simulation model of two power plants, complete with individual conduit system, turbine and generator, connected to the same grid was used.

1. Introduction

The Scandinavian grid, previously called NORDEL, but now a part of ENTSO-E, connects Norway, Sweden and Finland on a common AC-grid, which is only connected to the grid in Central Europe by HVDC cables. The power and frequency regulation in Scandinavia is dominated by hydro power generators. The requirements for operating power stations on the grid are given by each country's Transmitting System Operator (TSO), which in Norway is Statnett [2]. However, the requirements are common in the whole of Scandinavia.

The permanent speed droop defines the power output on each turbine and in what extent the turbine shall participate with primary governing, which is a marked issue. The utility companies decide on how much regulating power they will offer on the marked, and at which price. The turbines will participate in keeping frequency according to the set permanent speed droop with a maximum of 6%.

The frequency deviation in the Scandinavian grid is, according the requirement, 50 ± 0.1 Hz, which is a rather high frequency deviation compared with the main grid in continental Europe.

As mentioned, the permanent speed droop is essential in order to properly define each of the turbines operational points when the frequency varies. If one turbine has permanent speed droop equal to zero, this aggregate will take the whole governing alone. If two (or more) turbines have zero permanent speed droop, the operational points will be undefined; hence it is not allowed to set the permanent speed droop zero. On the other hand, if the permanent speed droop is set extremely high, the turbine will not participate on the frequency governing. The TSO, which is the authority in these matters, requires a permanent speed droop on the range of 1 – 6 %. The Figure 1 below illustrates how the permanent speed droop effects the power distribution on two aggregates connected to the same grid. All synchronous machines connected to the grid, operates of course with the same rotational frequency. If initially, the grid frequency is according to the read line in the figure below, a change in the grid frequency, blue line, will give a new load distribution for all aggregates according to each permanent speed droop.

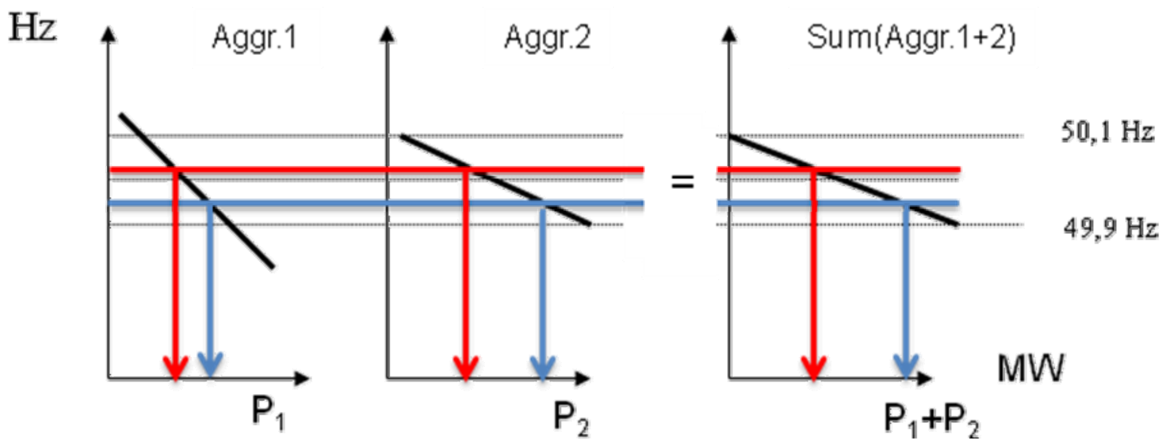

Figure 1: The permanent speed droop defines the power output on each turbine as the grid frequency changes.

The power of regulation on the grid, Figure 1 fare right, is a sum effect the permanent speed droop on each of the connected machines. If the load changes, the frequency change on the grid, according to the grid characteristic, lead to a change in load on each connected turbines.

In order to raise the grid frequency, the power out put on one or several turbines must be raised. This is what we call the secondary governing, illustrated in Figure 2.

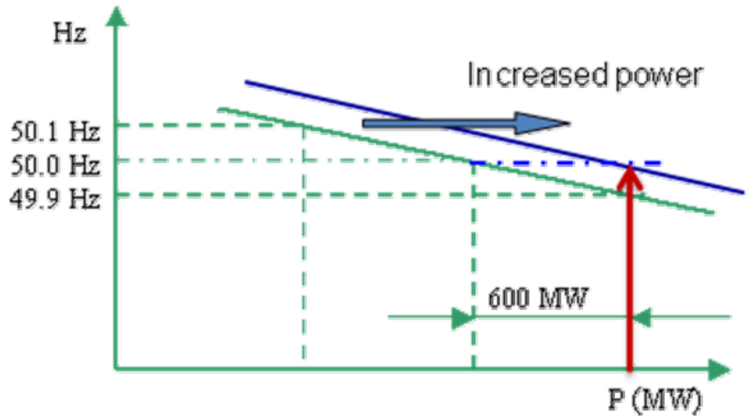

Figure 2 Secondary governing.

The TSO requirements also imply that the total producing power on the grid shall give a power of regulation of at least 6000 MW/Hz, i.e. 600 MW for a frequency deviation of 0.1 Hz. In other words, the grid acts as a sort of reservoir of power which is immediate available.

2. Simulation model

A simulation model is made in order to investigate the individual behaviour of turbines operating on a common grid. Two power plants complete with reservoirs, conduit systems and surge shafts, turbine and generators are connected to a simplified grid. The simulation model is previously published at the IAHR conference in Valencia some years back [1]. In this paper, the mathematical model is described in detail. The elements in the model are briefly described below.

2.1. Hydraulic system

The pressure shaft is modelled with elastic properties using a discreet lumped model. The tunnel and surge shaft is modelled by means of Newton's 2. law and the continuity equation.

2.2. Turbine model

The turbine characteristics are simulated based on the Euler turbine equation. In this case, the geometry of a high head Francis is used, which is the most common turbine used for primary governing in the Scandinavian grid.

2.3. Generator model

The generator is modelled by assuming proportionality between speed of rotation and voltage. The proportionality coefficient is the magnetic field. As the power output increases, the angle (in a rotating frame of reference) between the stator and rotor will increase [3]. The magnetic field forms a flexible element between the stator and rotor. A voltage governor (PID) is connected, manipulating the magnetic field.

2.4. Frequency governor model

The governor is modelled as a conventional PI-governor with permanent speed droop. The permanent speed droop is a feed back from the guide vane position allowing a deviation in the speed of rotation and defines the grid characteristic. b_p is a constant which is adjustable and defined by the operator of the power plant. The result is that the frequency is inverse proportional with the power, see Figure 4.

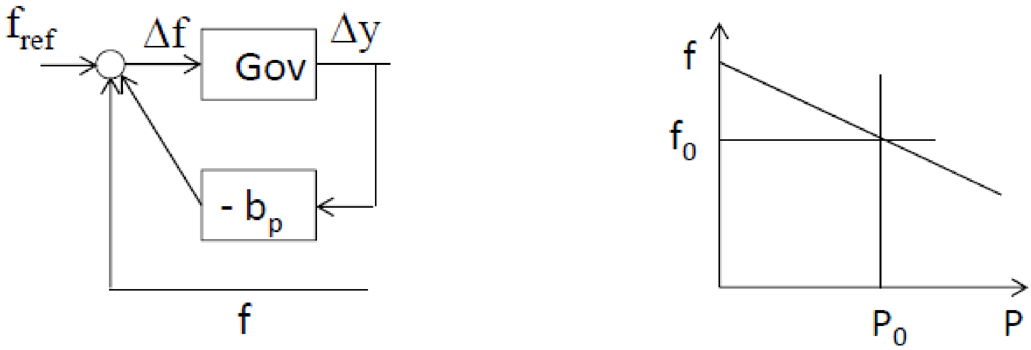

Figure 3: Permanent speed droop.

2.5. AC grid model
The AC-grid is modelled with impedance, which for this paper is not entirely relevant.

3. Simulation results
The simulation shows that the grid speed of rotation is the same for both aggregates, which is of course how it must be. In transient periods, the grid frequency has a deviation from the rotational frequency of the turbines. This is because the pole angle will change in a transient manner.

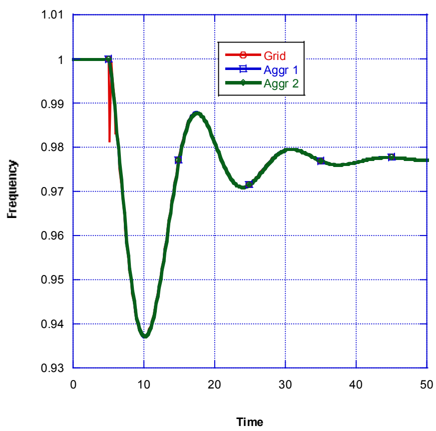

Figure 4: In transient period the rotational frequency and the grid frequency deviates due to the pole angle.

The two power plants have different conduit geometry and governor settings. The guide vane position will therefore have individual transient behaviour and end up at different positions, which is a direct result of the different permanent droop setting.

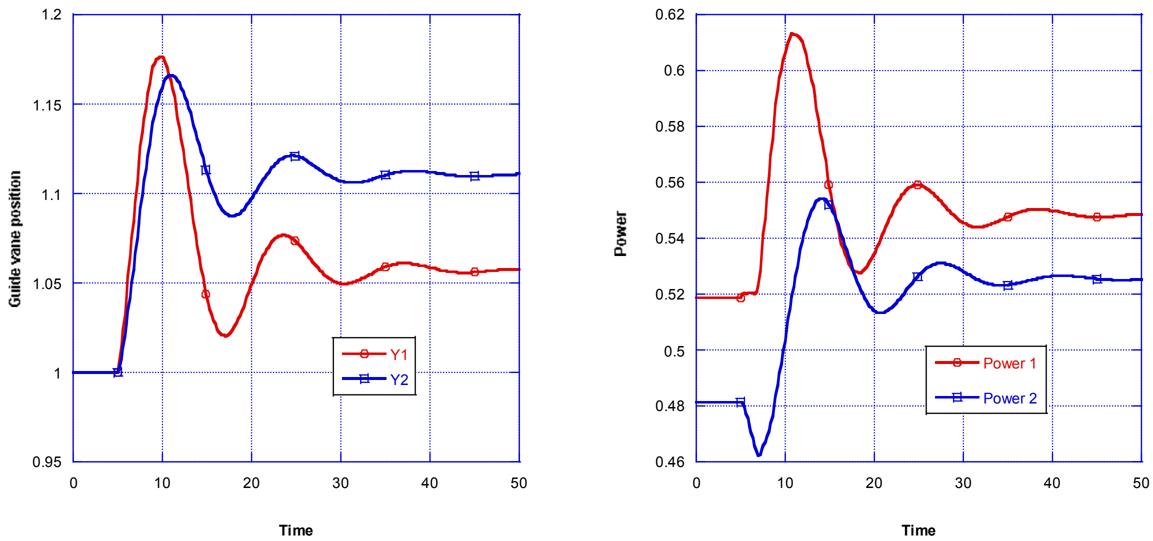

Figure 5: Wicket gate position (left) and power output (right).

Plotting the Power – Frequency for the two aggregates, the transient behaviour will be as shown in Figure 3. In the simulation, the turbines start at normalized frequency at a given load and end up on a lower frequency on the line that defines the permanent speed droop of each turbine. The trace will be different because of the wicket gate movement, which is almost proportional to the power output. In the simulations, the speed droop is exaggerated in order to better illustrate the behaviour.

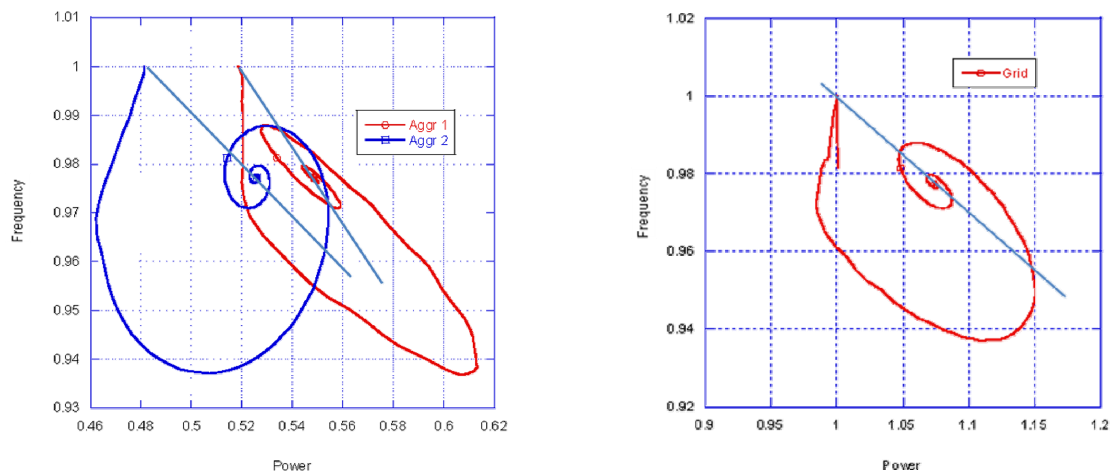

Figure 6: Frequency vs Power in a transient performance when load increase.

4. Measurements

Of course it is impossible to isolate two hydro power plants in a similar performance as the ones in the simulations. However, we have done measurements on two power plants, simultaneously measured power, grid frequency, rotational frequency and guide vane position with a sampling frequency of 250 Hz with 1 sec. averaging time. We logged the performance during 3 days of operation. The turbine performance is constantly varying, as can be seen on Figure 5.

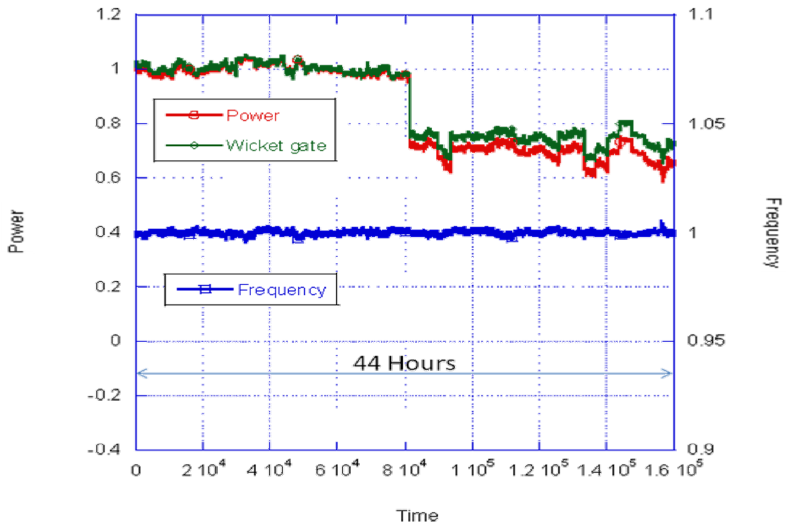

Figure 7: Measured Power and Frequency at Brattset power plant.

Figure 7 shows a typically period with no secondary governing. The first period, which is a typical period with primary governing, the power plant will continuously change the wicket gate position as the grid frequency changes. The typical trend is that when the power increases, the frequency decreases and vice versa.

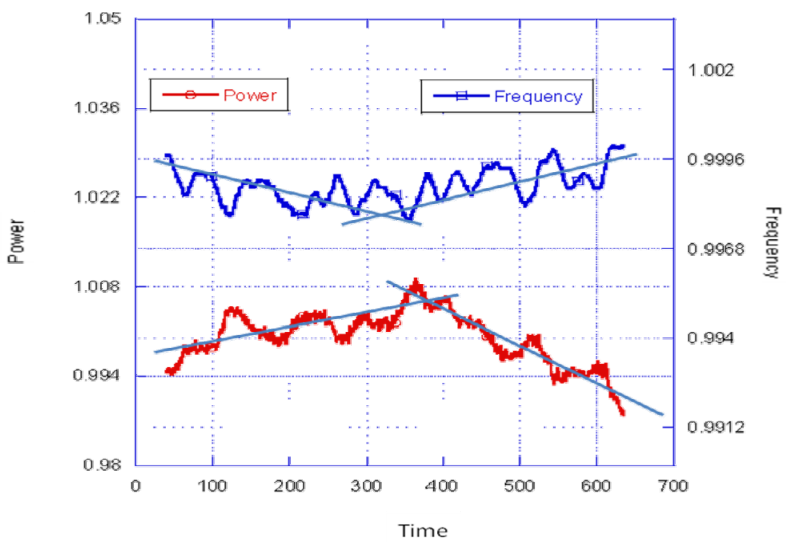

Figure 8: Typical behaviour in a period of primary governing.

The same period is plottet as frequency vs Power on Figure 9. One can se that the turbine works along the power – frequency characteristics, but will deviate from the line due to wicket gate movement causing power variation trying to govern the frequency.

IOP Conf. Series: Earth and Environmental Science **22** (2014) 042018 doi:10.1088/1755-1315/22/4/042018

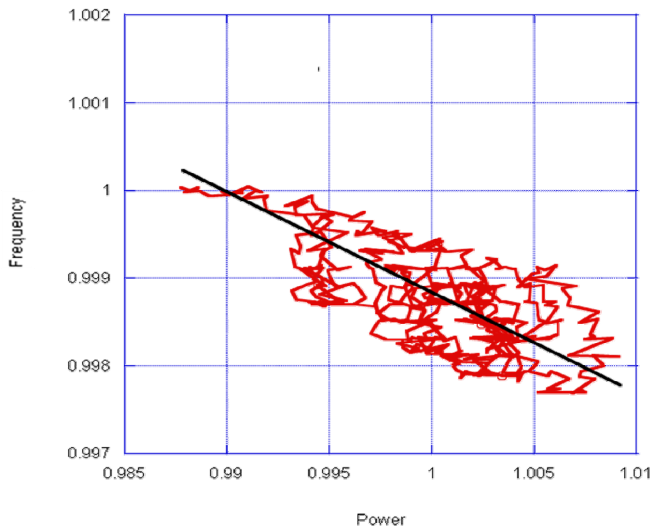

Figure 9: The turbine is working along the power frequency characteristic.

In the periode marked on Figure 9, a secondary governing is taking place. The turbine wicket gate is forced closed to meet the increase in frequency by reducing the power on the grid.

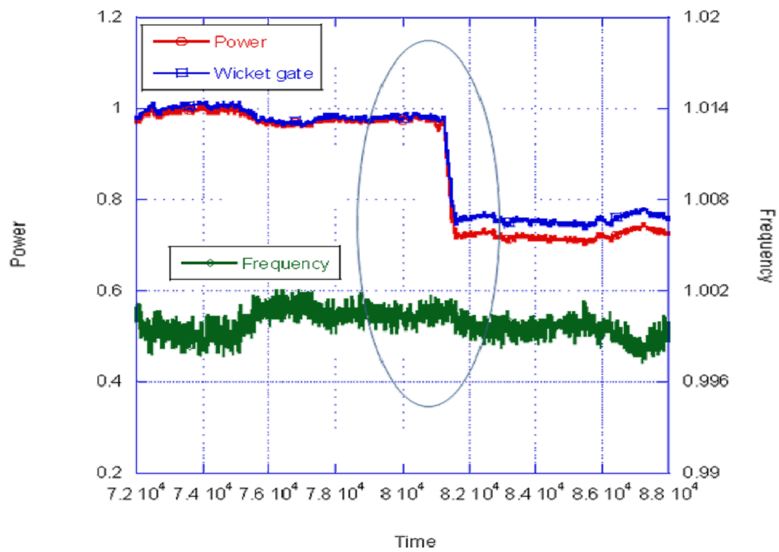

Figure 10: Periode of secondary governing to reduce the power in the grid and thereby adjust the frequency.

Figure 10 shows the same time period plotted as Frequency vs Power. One can see that the turbine works along the power – frequency characteristic just before the governing at high frequency. Then the wicket gate position is reduced more or less linearly and hence reduces the power out put.

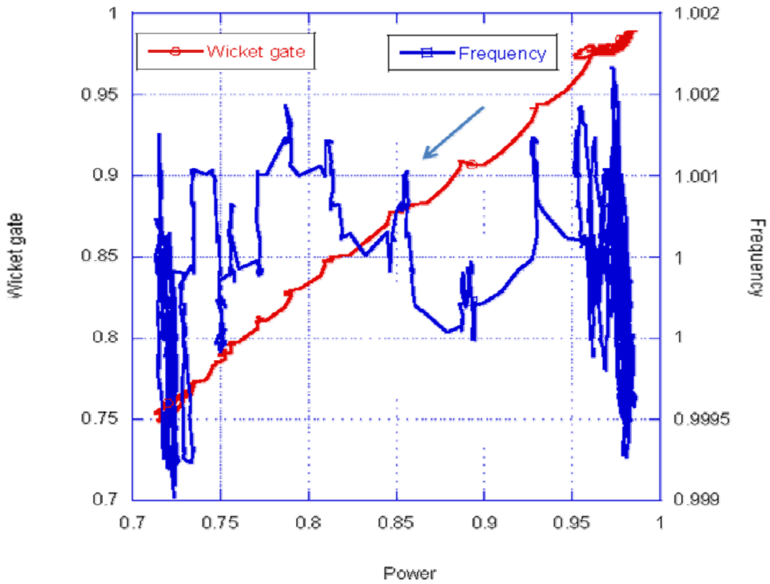

Figure 11: The wicket gate position is reducing and ends up in a new position and the primary governing continues

5. Conclusion

A turbine never experience steady state operation. The continuously varying primary governing, expose the turbine runner to varying hydraulic performance and torque variations. Secondary governing exposes the runner to even higher transients.

The hydro turbines are, at least in the Scandinavian grid system, the main (if not only) source of governing. As the amount of unregulated power increases, the demand on the existing water power increases. In Norway, which does most of the governing in the Scandinavian grid, the main power plants are built in the 1970's when the situation was quite different. They were design for optimal power production at peak efficiency, meaning mostly running at BEP. Now a day, the power plants are run by the economists who don't really bother about the original design criteria. This is a challenge we will meet with enthusiasm, seeking to improve the control algorithms.

6. References

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