

Improving the Control System for Pumped Storage Hydro Plant

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Abstract. The operational flexibility of pump storage hydro-stations means that they are often used on a power system (grid) as a means of controlling system frequency and for load management. When used in this role, the response of the generator is determined by the behaviour of its control system (governor). The basic function of a governor is to control frequency variation of the grid where its droop characteristics ensure equitable load sharing between generating units in order to ensure satisfactory and stable operation. The governor setting and in particular the loop gains, are therefore critical to achieving optimum levels of performance. In this paper, a step-by-step procedure taken to construct the new governor is presented. The most relevant results on the evaluation of the governor are shown and its performance advantages compared to the current governor are highlighted.

Keywords: governor, pump storage, control

1. Introduction

The role of a governor is to control frequency variation of the grid due to dynamic load changes and produce stable operation. A normally governor consists of two feedback loops, a frequency control loop which has the frequency error as input and a power control loop in which the error between the set point and measured power is operated on by the 'droop' gain [1]. The governor output is then used to set the guide vane position [2]. Since the grid's unknown parameters such as the stiffness and the inertia are part of the frequency feedback loop, it is difficult to achieve optimum gain settings for all operating conditions with the current governor. The proposed scheme utilises the frequency error signal and the unit droop characteristics to determine the amount of power the unit needs to pick up or shed (this is called power target). Adopting such an arrangement separates the feedback loops and a single feedback loop to regulate the power target is implemented. An advantage of the scheme is that the grid unknowns (inertia and stiffness) are not included in the power control loop. The grid characteristics (effects) are embedded within the grid frequency signal, which is used to determine the power target signal. Therefore, it is feasible to optimise the governor performance for all operating conditions.

In the present study, the root-locus technique was used to design a new PI control system. The result shows that the actuator rate limits influence the unit response and should be included at the design stage. For this purpose the Matlab® nonlinear control blockset was used to re-evaluate the system loop gain for different operating conditions.

2. System model

As stated earlier, the unit governor consists of two feedback loops. During frequency control operation the unit will share load according to its droop characteristics. The droop gain is used to trim the frequency error signal in order to determine how much power the unit will pick up (power target). Hence, it is possible to calculate the amount of power that the unit is required to pick up or shed, depending on the frequency error signal. Fig. 1 shows the proposed control system where the power target is the only variable being

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controlled. The droop characteristics determine the amount of power the unit will share and this can be calculated as [3]:

$$P_{target} = (f_o - f_{grid}) \frac{P_{unit_rating}}{droop\% \times f_o} \quad (1)$$

where: P_{target} = Power target; P_{unit_rating} = Unit rated power MW; $droop\%$ = Droop setting; f_{grid} = Grid frequency and f_o = Nominal frequency (50Hz).

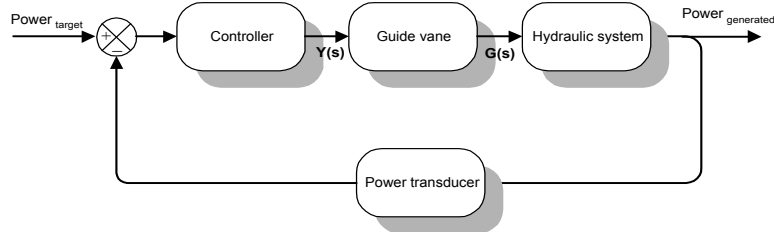


Fig. 1: System block diagram

During the investigation the guide vane dynamics were modelled as a two-stage actuator with an internal feedback loop using the transfer function of equation(2), which relates the desired and the actual positions.

$$\frac{G(s)}{Y(s)} = \frac{1}{(T_1s + 1)(T_2s + 1)} \quad (2)$$

The time constants T1 & T2 are determined by the pressure/flow characteristics of the guide vane and its actuator servomotors. A step response test was carried out on the guide vane to identify the system time constants. The result shows that T1 = 0.19 and T2 =0.4.

The penstock-turbine is modelled using the mathematical relationship of equation (3), which relates the turbine power increment to the guide vane position increment [4].

$$\frac{\Delta P_m(s)}{\Delta G(s)} = \frac{1 - \frac{T_w}{T_e} \tanh(T_e)}{1 + 0.5 \frac{T_w}{T_e} \tanh(T_e)} \quad (3)$$

Where: P_m is the power generated; G is the guide vane position; T_w is the water starting time; T_e is the wave travelling time and s is the Laplace operator.

Forming the lumped parameter approximation modifies the representation of equation(3) by expanding the transfer function into the general nth-order model, using the relationship; $\tanh(x) = \frac{e^{2x} - 1}{e^{2x} + 1}$, which leads to the finite approximation [5].

$$\tanh(T_e s) = \frac{s T_e \prod_{n=1}^{n=\infty} \left[1 + \left(\frac{s T_e}{n\pi} \right)^2 \right]}{\prod_{n=1}^{n=\infty} \left[1 + \left(\frac{2s T_e}{(2n-1)\pi} \right)^2 \right]} \quad (4)$$

For n=1 equation (4) can be written in the form of an equation which represents an elastic water column. For most power system stability studies the approximate transfer function (5) is adequate.

$$\frac{\Delta P_m(s)}{\Delta G(s)} = \frac{1 - T_w s + \frac{4}{\pi^2} T_e^2 s^2 - \frac{T_w T_e^2}{\pi^2} s^3}{1 + 0.5 T_w s + \frac{4}{\pi^2} T_e^2 s^2 + 0.5 \frac{T_w T_e^2}{\pi^2} s^3} \quad (5)$$

The root-locus of Fig. 2a shows how changes in the system's characteristics influence the closed loop pole locations, which largely determine its time response. Matlab® software [6] was used to plot the root locus for the system based on single unit operation. Plotting the system root locus for variable loop gain reveals that increasing the system gain (Kloop) causes the root to cross over to the right hand side of the s-plane (unstable region). Thus, there is a limit to how much the gain can be increased before the system becomes unstable. The design criterion was to set the system damping to ~ 0.7 and that is achieved by setting the gain to 0.02. The corresponding Nichols chart is used to plot the system closed loop frequency response and is shown in

Fig. 2b. For this gain value, the gain margin is 11.2dB and the phase margin is 64.4o, which are within the stability limits.

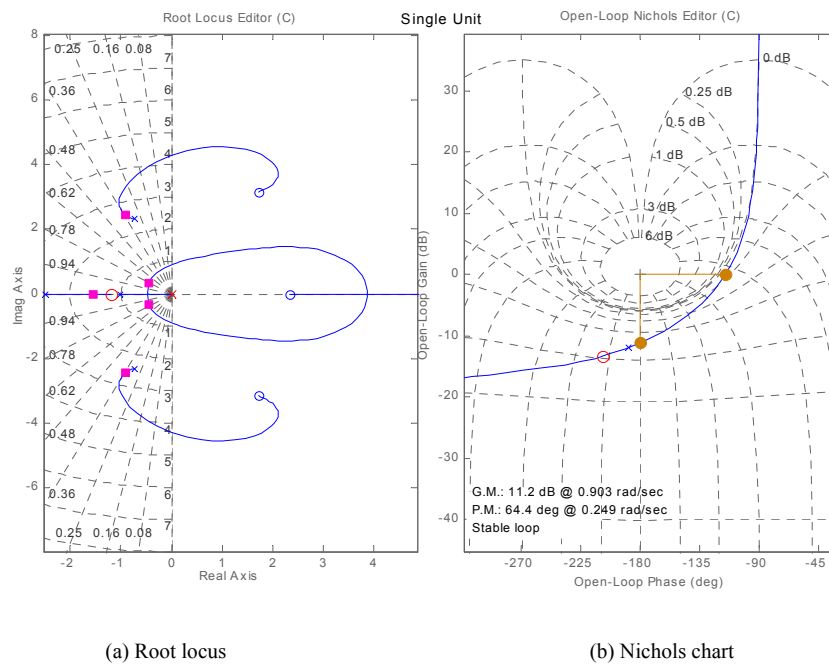


Fig. 2: Control system design for a single Unit

Because the Dinorwig plant that was used as a case study consists of six units and each has its own penstock, which is connected to the upper reservoir by a single tunnel. Consequently, the water inertia will change according to the number of units on line. Hence, it is necessary to investigate the effect of changes in water inertia on the performance of the new governor. As before, the root locus technique was used to establish the loop gain for different operating points: two units, three units active and so on. Table 1 shows the loop gain and gain margins for each operational condition.

Table 1 system loop gain and margins

Units on line	Loop gain (K_{loop})	Gain margin (dB)	Phase margin (deg.)
One	0.02	11.2	64.4
Two	0.017	11.7	66.8
Three	0.015	10.6	64.3
Four	0.0125	10.5	64.4
Five	0.011	10.2	63.5
Six	0.01	10.8	65.3

It can be seen that, as predicted, the required loop gain depends on the operating condition (water inertia) and to comply with the design criterion the loop gain must be reduced as the number of units on line increased.

2.1. Matlab nonlinear control design blockset

The plant has a rate limit on the main actuator and the rate limit has a large influence on the unit response it is crucial to include it in the design process. Fortunately, Matlab software has a non-linear control blockset, which can be used for this purpose. The tool provides a time-domain-based optimisation approach to system design. It is designed for use with Simulink block diagrams and automatically tunes parameters, based on user-defined time-domain performance constraints. The Blockset provides an interactive GUI for modifying system parameters and specifying performance constraints. The Simulink system, time-domain constraints, tuneable variables and parameter uncertainty are formulated as a constrained optimisation problem. The optimisation performs successive simulations on the Simulink system and changes the tuneable variables in an attempt to better meet the time response specifications.

As before, the investigation involved tuning the loop gain at different operating conditions. The maximum power target considered during system tuning was 150MW to minimise the power variations (between minimum 0MW and maximum 150MW in this case). This is justifiable because the maximum amount of power that any unit can pick up during frequency control is 150MW (this occurs only during extreme circumstances such as losing a large generating unit on the grid). The aim is to minimise the error between the output and the input signal for all time steps, thus producing a multiobjective function (one function for each time step). The tuneable variable for optimisation, the loop gain (K_{loop}) should ensure that the closed loop system meets or exceeds the following performance specifications:

- The maximum percent of overshoot is 5%.
- The maximum rise time is 10 second.
- The maximum settling time within 1% is less than 25 second.

The results of the optimisation are shown in Table 2. Compared to the gains obtained previously (Table 1) it is evident that reductions in the gain values are required, even when operating with a light hydraulic system (small water starting time). However, the results as previously indicate that a gain-scheduling regime should be implemented to achieve an optimum response for all operating conditions.

Table 2: System loop gain

Number of Units on line	Loop gain (K_{loop})	Number of Units on line	Loop gain (K_{loop})
One	0.016	Four	0.0125
Two	0.0138	Five	0.011
Three	0.0128	Six	0.01

3. Performance of the new control system

In this section the response of the new governor is determined for two relevant conditions, variation of Grid parameters and part load response.

3.1. Grid parameters

The effects of power system parameters, specifically the Grid inertia and stiffness, on the stability of the new governor as depicted in Fig. 1 (with the rate limit included) are investigated. The grid inertia “M” corresponds to the total inertia of rotating machines on the Grid (which includes the inertia constant of the generators and the load). Therefore the inertia constant is large when the number of generating units is high. To investigate the stability of the new governor scheme (tuned using the nonlinear blockset) to changes in the Grid inertia, simulation tests were conducted using two units responding to load deviation on the Grid. Both units were operating with 1% droop –the first unit was controlled using the new governor ($K_p=10$ $K_i=12$ and $K_{loop}=0.016$) while the current governor ($K_p=10$ $K_i=12$ and $K_d=2$) controlled the second unit.

The first test was conducted using an inertia constant of $M = 10 \frac{MW.s}{MVA}$ on a 30GVA base, and then the test was repeated for $M = 5 \frac{MW.s}{MVA}$ on a 30GVA base.

The results shown in Fig. 3, illustrate that the inertia constant will influence the speed at which the unit picks up the load. For both governors, low inertia results in the unit responding faster and the reason for that is the higher rate of frequency change due to low grid inertia. It can be seen that the new governor performance is stable as predicted and is superior to the current governor in both cases. For the case of inertia equal to 5, it can be seen that the unit picks up an extra 12MW after 10s compared with the current governor. Moreover at high inertia ($M = 10$) the new governor once again picks up an extra 12MW after 10s. It is clear that the new governor scheme will enhance the unit response regardless of grid inertia.

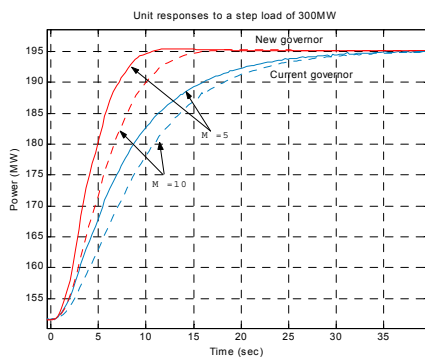


Fig. 3: The effect of changes the grid inertia (M) on unit response

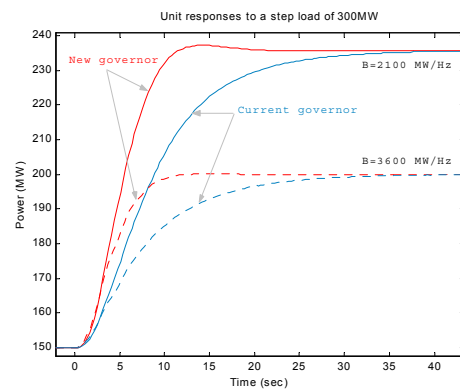


Fig. 4: The effect of changes the grid stiffness (β) on unit response

The second parameter to be examined was the power system frequency response characteristic “ β ” which is referred to as the stiffness. The physical significance of β can be stated as follows: if a power system was subject to a step load change, it would experience a static frequency drop inversely proportional to its stiffness. The smaller the change in frequency for a given load change the stiffer the system.

In this context, an experiment was carried out to compare the responses of both governors using a grid operated with $\beta = 2100 \frac{MW}{Hz}$, and then repeated using a stiffer grid $\beta = 3600 \frac{MW}{Hz}$. The test was conducted

by applying a step load of 300MW on the system, while the grid inertia was set to $M = 10 \frac{MW.s}{MVA}$ on a

30GVA base. Fig. 4, shows the results, which, as expected, show that the load has less impact when operating on a stiff grid. Both units pick up the extra load of 50MW in steady state but once again the unit operating with the new governor picks up the load much faster than the unit operating with the current governor. This is also true for the lighter grid where both units pick up an extra load of 85 MW, but the new governor achieves this in 10s while the current governor requires up to 25s to do so.

4. Conclusions

A new control scheme is developed to enhance the performance of the Dinorwig plant. Adopting such a scheme enables us, to discard the unknown parameters in the power system during the design stages, because they are not part of the control loop. However, their effects are embedded in the Grid frequency signal, which is used to determine the power target signal. The results of the simulations suggest that there are significant possibilities for improved performance based on the introduction of a revised governor for the Dinorwig plant. The new governor scheme responds to variation of grid parameters in a stable manner and the results demonstrate the advantage of the new scheme, as the plant is more responsive to frequency variation on the grid. The study has highlighted that the plant is nonlinear and that operating with a fixed gain governor is not the way forward because conservative gain settings are chosen to cover the whole operating range. Gain scheduling accommodates all operating conditions, which results in better-tuned governor.

4. References

- [1]. Mansoor, S. P., Jones, D. I., Bradley, D. A., Aris, C., and Jones, G., "Reproducing oscillatory behaviour of a hydroelectric power station by computer simulation", *Control Engineering Practice*, 8, 1261-1272, 2000.
- [2]. Mansoor, S. P., Jones, D. I., Bradley, D. A., Aris, C., and Jones, G., "Stability of a Pump Storage Hydro-Power Station Connected to a Power System", *IEEE power Winter Meeting 1999, New York*, vol. pp. 646-650, 1999.
- [3]. Mansoor, S. P., "Behaviour and Operation of Pumped Storage Hydro Plants", PhD Thesis University of Wales, 2000.
- [4]. Working Group on Prime Mover and Energy Supply Models for System Dynamic Performance Studies, "Hydraulic Turbine and Turbine Control Models for System Dynamic Studies", *IEEE Transaction on Power Systems*, vol. 7, pp. 167-179, 1992.
- [5]. Goodson, R. E., "Distributed System Simulation Using Infinite Product Expansions", *Simulation*, vol. 15, pp. 255-263, 1970.
- [6]. "MATLAB System Toolbox User's Guide", MA, USA: The Math Works Inc., 2010.