Development of Models for Hydro Power Plants with Shared Penstock for Grid Compliance Study

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***Abstract*— Trustpower (TP) own and operate the Waipori Hydro Scheme. The scheme is relatively fragmented and consists of four generation stations as follows: G1A, G2A (G2A-1/G2A-2/ G2A-3), G3 and G4. TP contracted SKM to develop station plant models for the Waipori Hydro Scheme and undertake validation simulations using the available test data provided by TP. SKM developed two different frame/plant models (including generator, AVR, governor, turbine and penstock models) for the units at the Waipori hydro station. One plant/frame model was built for the units with single/individual penstocks (G1A, G3 and G4), and another plant/frame model was built for the units with a shared penstock (G2A-1, G2A-2 and G2A-3). The outcome of this work forms part of the Asset Capability Statement (ACS) information that TrustPower are required to provide to the NZ System Operator.**

***Index Terms*— Governor Model, Grid Compliance, Hydro Power Plant, Shared Penstock.**

I. Introduction

The Waipori River is located about 64 km to the west of Dunedin, rising in the Lammerlaw Mountains. After winding through a course of about 24 km the River emerges into a valley 1.5 km wide and 27 km long, with a drop of only 30-metres. Following the first steps towards generating electricity from the Waipori River in May 1900, on 27th April 1907 the Waipori Hydro-Electric Power Station was commissioned. This hydro scheme consists of four generation stations as follows:

- Station 1A:
  - Unit G1A: 12.88 MVA, 0.75pf.
- Station 2A:
  - Unit G2A-1: 23.00MVA, 0.91
  - Unit G2A-2: 26.15MVA, 0.90pf
  - Unit G2A-3: 26.15MVA, 0.69pf
- Station 3:
  - Unit G3: 8.0MVA, 0.80pf
- Station 4:
  - Unit G4: 9.0MVA, 0.80pf

Each one of the G1A, G3 and G4 units has its own/separate penstock. However, the G2A-1, G2A-2 and G2A-3 units share a common penstock. SKM developed DIgSILENT models for this hydro scheme and undertook validation simulations using the actual test data. The governor test results for units G2A-1, G3 and G4 were supplied to SKM.

The main focus of this work has been on the governor performance assessment and in the absence of any information regarding the excitation systems SKM has used a simple IEEE SEXS type model to represent the excitation systems (AVR) of the units at the Waipori station. We tested the SEXS AVR model in order to ensure that it provided sensible AVR action.

SKM developed a governor model for this hydro power station. The lengths of individual sections (the section between the main bifurcation to each unit) are not the same for all the penstock-sharing units (units G2A-1, G2A-3 and G2A-2).

II. Network Model

Figure 1 illustrates the network model that SKM has developed to represent the Waipori station.

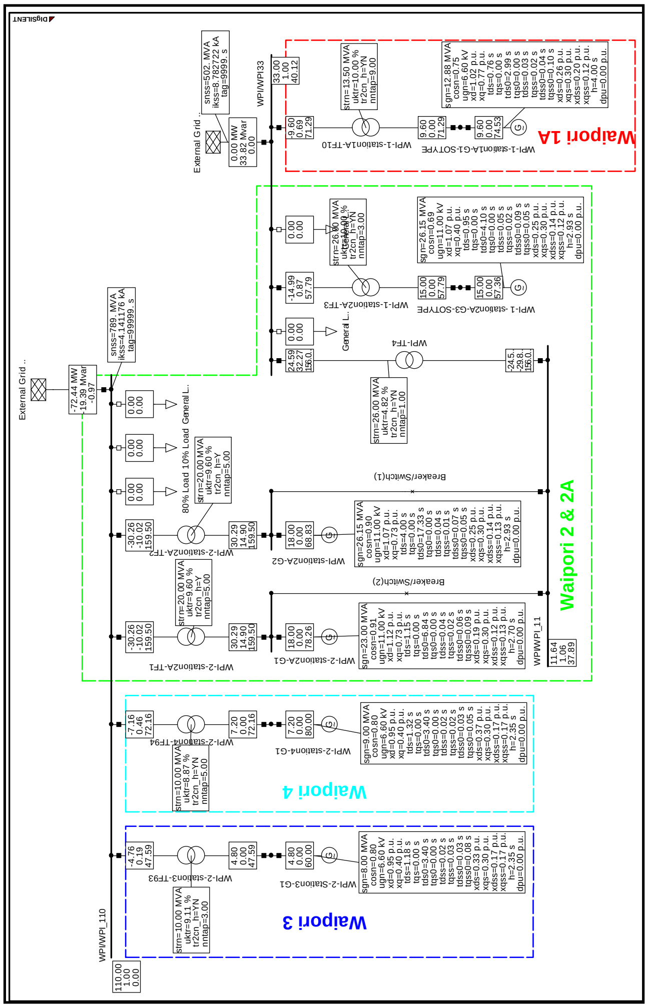

Figure 1. Waipori Power Station: Network Model: Power Flow

III. PLANT/FRAME MODEL

SKM used two different plant/frame models for the different units at the Waipori station.

Figure 2 illustrates the plant/frame model for the units with single/individual penstocks (G1A, G3 and G4). The model includes the following "slots":

- Generator (ElmSym).
- Governor (ElmPcu).
- Turbine/Penstock (ElmPmu).
- Excitation System / AVR (ElmVco).
- Power System Stabiliser (ElmPss) (not used for Waipori).
- Data File for importing test data.
- Voltage Sensor for measurement of local bus voltage.

Figure 3 illustrates the plant/frame model for the units with a shared penstock (G2A-1, G2A-2 and G2A-3). The model includes the following "slots":

- 3 × automatic voltage regulators (AVR) slots (VCO 1, VCO 2 and VCO 3),
- 3 × governors slots (PCO 1, PCO 2 and PCO 3),
- 3 × turbine slots (Mechanic 1, Mechanic 2 and Mechanic 3),
- 1 × Hydraulic/Penstock slot (Hydraulic),
- An input file slot for importing test data.

Additional details associated with the models that fit into these slots are discussed in the following sections.

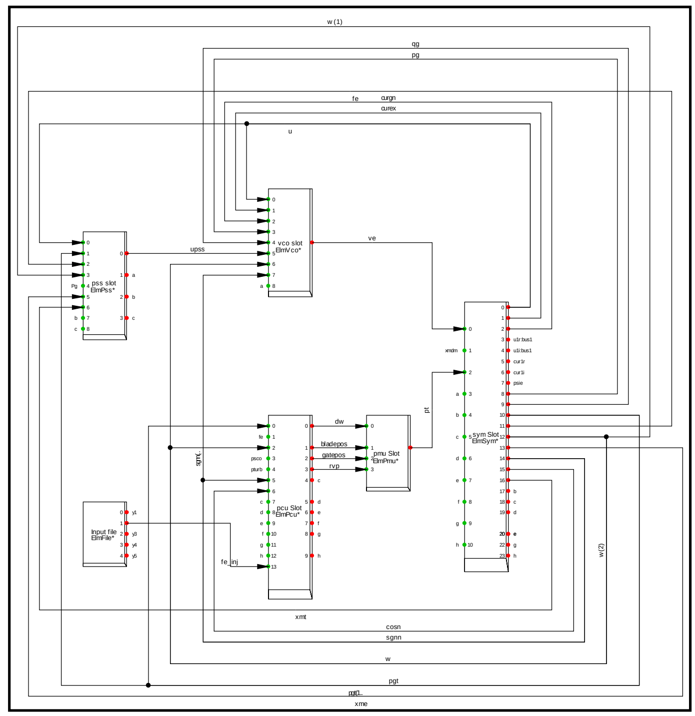

Figure 2. Plant/Frame Model for Individual Penstock Units (G1A/G3/G4)

IV. EXCITATION SYSTEM MODEL

SKM used a typical AVR model (IEEE SEXS type exciter as illustrated in Figure 4) to represent the excitation systems of the units at the Waipori station.

SKM tested the existing AVR model in order to ensure that it provided sensible AVR action. The off-line response to a 5% step change in voltage set-point was examined and was stable and damped.

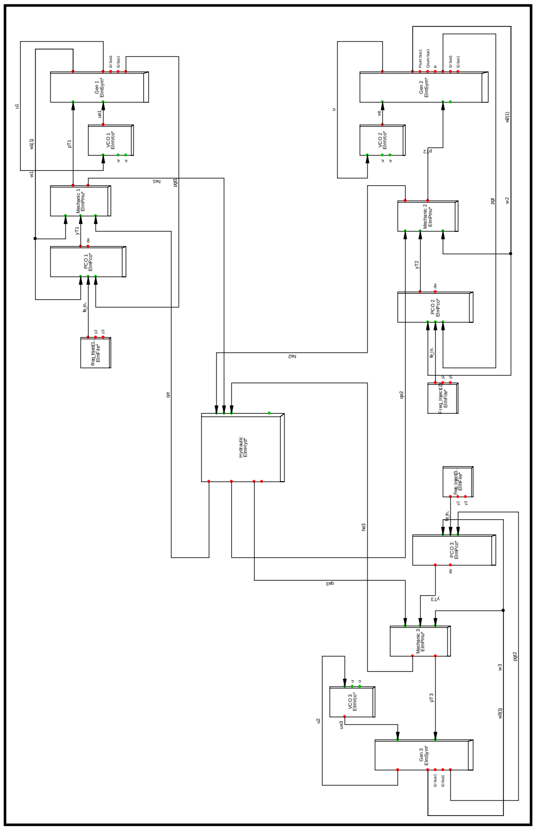

Figure 3. Plant/Frame Model for Shared Penstock Units (G2A-1, G2A-2 and G2A-3)

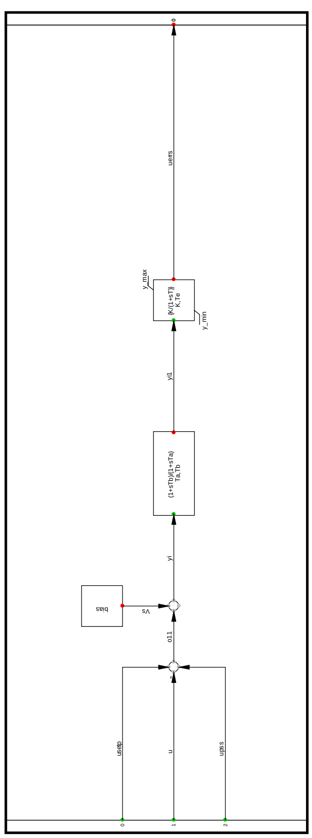

Figure 4. Excitation System Model: IEEE SEXS

V. PRIME-MOVER/TURBINE MODEL

In light of available information and tests undertaken SKM implemented a non-linear turbine model. Each one of the G1A, G3 and G4 units has its own/separate penstock/tunnel. However, we note that the G2A-1, G2A-2 and G2A-3 units share a common penstock/tunnel. Thus we used a common penstock model for these units which is based on published literature [1].

Figure 5 illustrates the turbine and penstock model used for single penstock units (G1A, G3 and G4). Figure 6 and Figure 7 illustrate the turbine and common penstock models for the units sharing a penstock (the G2A-1, G2A-2 and G2A-3).

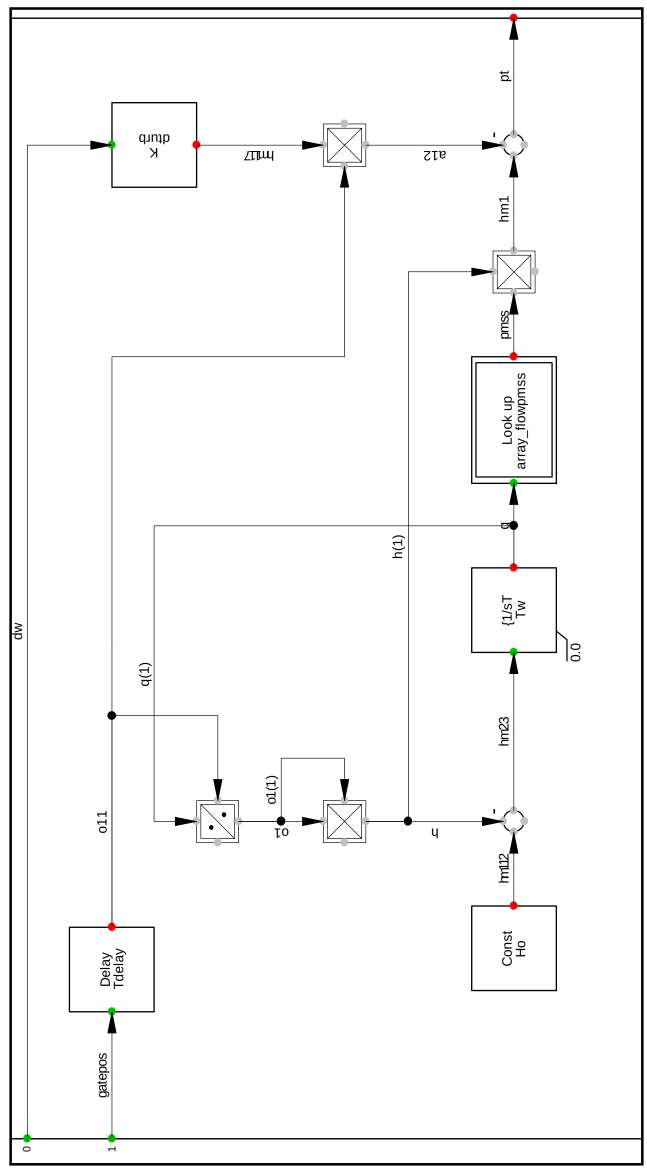

Figure 5. Turbine and Penstock Model – Single Penstock (G1A, G3 and G4)

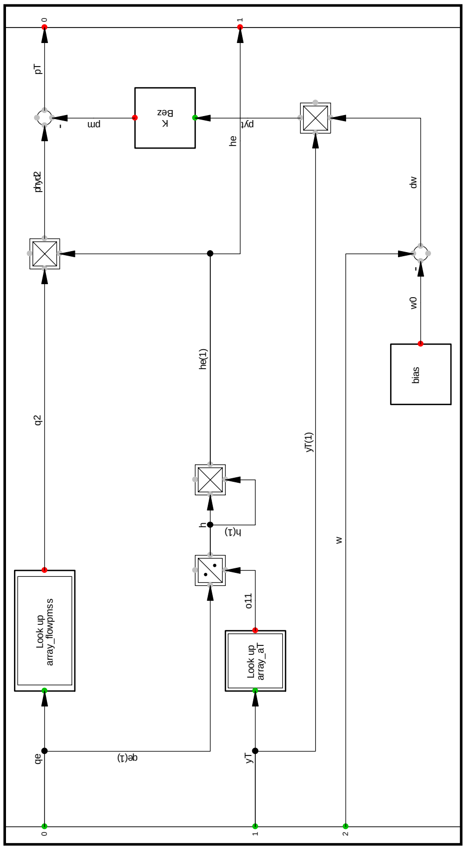

Figure 6. Turbine Model – Shared Penstock (G2A-1, G2A-2 and G2A-3)

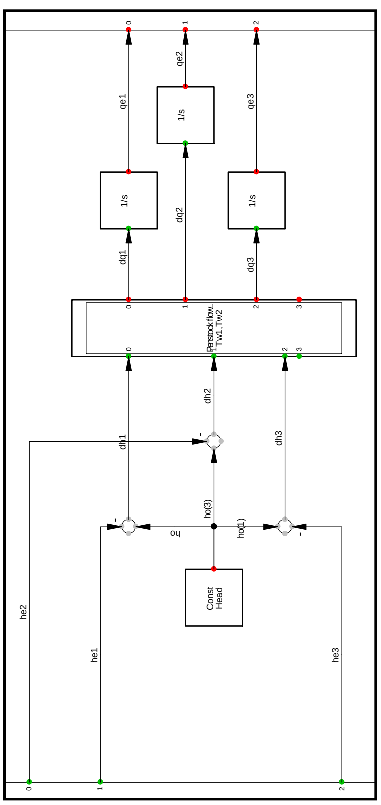

Figure 7. Turbine Model – Common Penstock Model (G2A-1, G2A-2 and G2A-3)

A. Penstock Time Constant Calculations

The penstock time constant (water starting time constant), "T_w", is the time required for the rated head to accelerate the water in the penstock from zero to rated velocity. The following equation can be used to calculate the water starting time constant "T_w":

$$T_w = \frac{Q \times L}{g \times H \times A} \tag{1}$$

where Q is the maximum flow rate (m^3/s), H is the head (m), L is length of penstock (m), A is penstock area (m^2), and g=9.8m/s^2 is the gravity constant.

For a varying diameter penstock, the sum of the ratios of the lengths and areas of the penstock segments was used as follows:

$$T_w = \frac{Q}{g \times H} \sum_{i=1}^{n} \frac{L_i}{A_i} \tag{2}$$

Station	Q (m^3/s)	H (m)	L (m)	A ($m^{2)}$)	T_w (s)
1A	42	27	173.7	10.18	2.71
2A (Common Section)	37	223.5	650	3.1	3.57
2A-1/2A-2 (Individual Section)	37	223.5	50	3.1	0.27
2A-3 (Individual Section)	37	223.5	125	1.86	1.13
3	19	50.57	88.5	4.1	0.83
4	19	57.3	108	4.1	0.9

It should be noted that according to the model [1] for shared penstock turbines, a single value should be entered to represent the time constant T_{W2} of the individual sections. In other words, the model assumes the time constants of all the individual sections, leading to a single unit, are the same for all the units sharing a penstock. We therefore used an average value of T_{W2} = 0.7 sec and we believe it provides enough accuracy for our studies.

VI. Governor Model

SKM developed a governor model based on the customised PLC governor system that is used widely on TrustPower's hydro stations.

Figure 8 illustrates the governor model which includes:

- A PID control system that is implemented in a PLC. This section also includes a frequency excursion detection section and instantaneous reserve logic, which is physically implemented inside the PLC.
- The mechanical/hydraulic components that physically open & close the flow of water to the turbine. This section includes representations of the distribution-valve/servo-system and the gate/scroll-cage.
- Logic to facilitate the injection of the System Operator's standard test signal into the governor model.

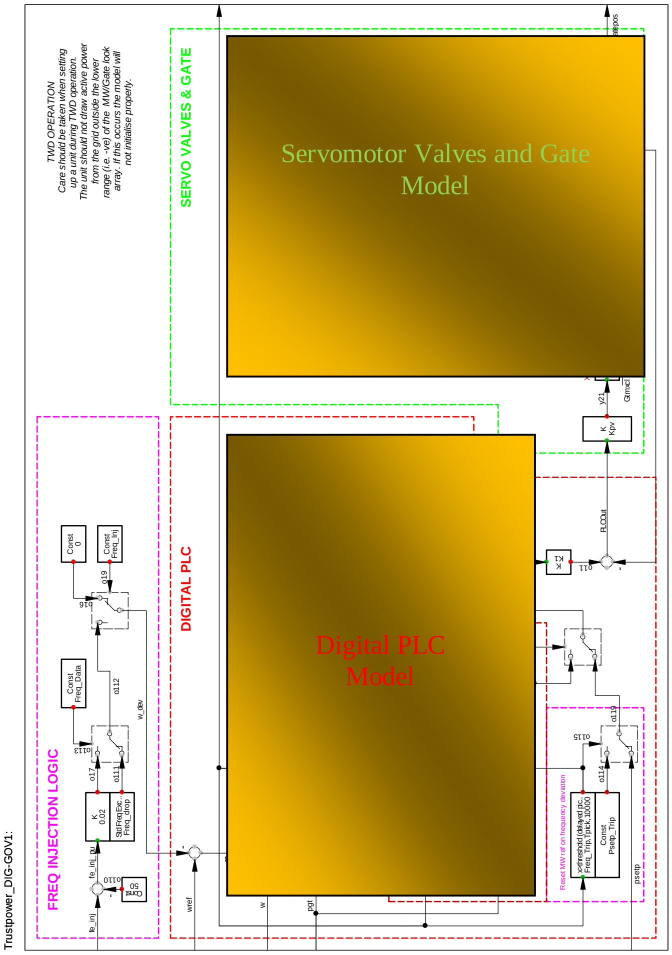

Figure 8. Trustpower Governor Model

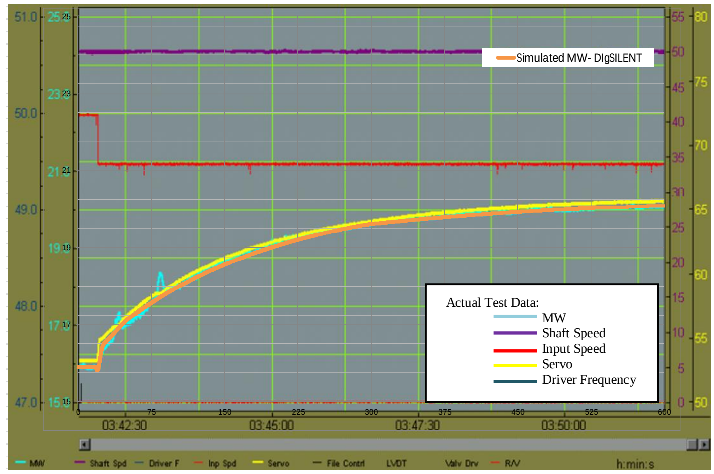

Figure 9. G2A-1: On-line under frequency injection: Simulated vs Test

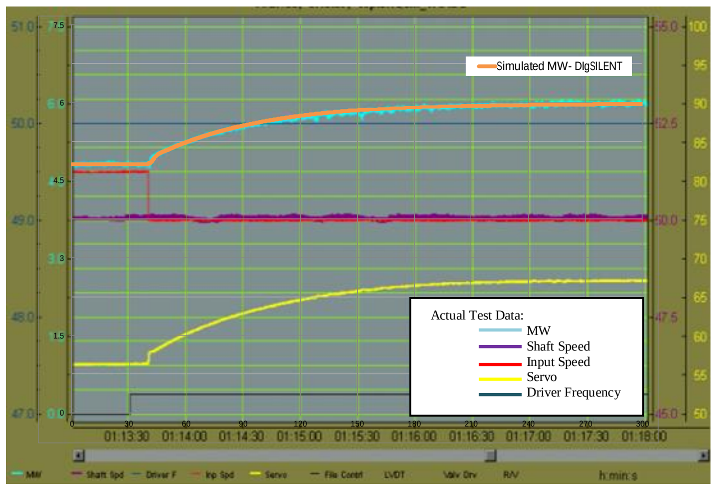

Figure 10. G3: On-line under frequency injection: Simulated vs Test

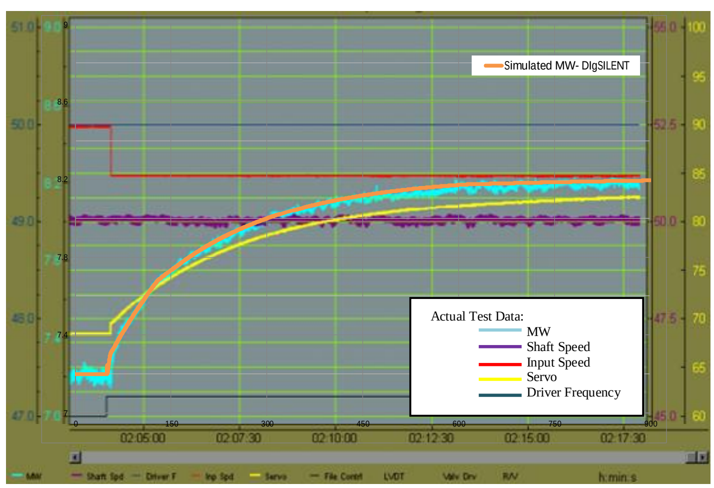

Figure 11. G4: On-line under frequency injection: Simulated vs Test

VII. Governor/Turbine Tests

One set of physical test results (on-line frequency step test) was available to SKM for validation of each unit (G2A-1, G3 and G4) at the Waipori power station. We have then proceeded to examine stability of each unit whilst operating isolated from the grid.

A. On-line Frequency Step Test

To undertake the frequency step test, the governor frequency reference input was replaced with a synthesised speed signal while the unit was connected to the grid. The speed reference signal was stepped by -1% and the response captured for each unit at Waipori station. Note that SKM didn't have access to the numerical values for the test results. Therefore, to compare the test result with the simulation results for verification purposes, in each case SKM has placed the simulation results (colored orange) from the DIgSILENT model on top of the available test plots. In each case the simulated results that are placed on top of test results are coloured orange. Simulation vs. test comparisons for units G2A-1, G3 and G4 are shown in Figure 9, Figure 10 and Figure 11 respectively.

B. *Governor Stability*

In accordance with *The Code* [2] SKM has investigated the stability of the DIgSILENT plant model for each of the stations within the Waipori scheme. This has initially been undertaken, by loading each of the stations to 80% (resistive load) whilst isolated from the grid, and subjecting each station and/or generator unit to a 10% increase in resistive load. This has been undertaken using the model/parameters outlined in the previous sections.

1) Station 2A: Stability of station 2A is investigated in this section whilst all the three units G2A-1, G2A-2 and G2A-3 are online and isolated from the external grid.

Figure 12 illustrates the responses of the units to a small step increase of 0.15MW (gross step of 0.1 MW imposed to both units G2A-1 and G2A-2 at 110kV bus; and 0.05MW imposed to unit G2A-3 at bus 33kV bus) in the initial resistive load of 50 MW/80% (G2A1=17MW, G2A2=18MW and G2A3=14.4MW). This figure shows that all the unit responses are oscillatory using the as-left PID parameters after a small step change in resistive load. It is worth noting that the oscillations do not appear to be growing (not unstable).

SKM's further investigations indicate that by modifying the governor PID parameters (as shown in Figure 13, *Kp* changed from 2 to 0.5 and *Ki* changed from 0.14 to 0.01) the DIgSILENT model predicts stable station behaviour even after larger step changes in the resistive load. Figure 13 illustrates the station subjected to a 5.8 MW/10% increase (gross step of 4 MW imposed to both units G2A-1 and G2A-2 at 110kV bus; and 1.8MW imposed to unit G2A-3 at bus 33kV bus) in resistive load from 50 MW/80% (G2A1=17MW, G2A2=18MW and G2A3=14.4MW) which shows the responses of all three units to be stable and reasonably well damped.

2) Station 3: Figure 14 illustrates the response of unit G3 to a step (0.6MW/10%) increase in the resistive load of 5MW/80% whilst isolated from the grid. This figure shows that the unit's response is stable and reasonably well damped using the as-left PID parameters.

We note that the unit has also been tested using the Nyquist Criteria [3] and been found to be stable which confirms the outcome of this section.

3) Station 4: Figure 15 illustrates the response of unit G4 to a step (0.7MW/10%) increase in the resistive load of 5.7MW/80% whilst isolated from the grid. This figure shows that the unit's response is stable and reasonably well damped using the as-left PID parameters.

We note that the unit has also been tested using the Nyquist Criteria [4] and been found to be stable which confirms the outcome of this section.

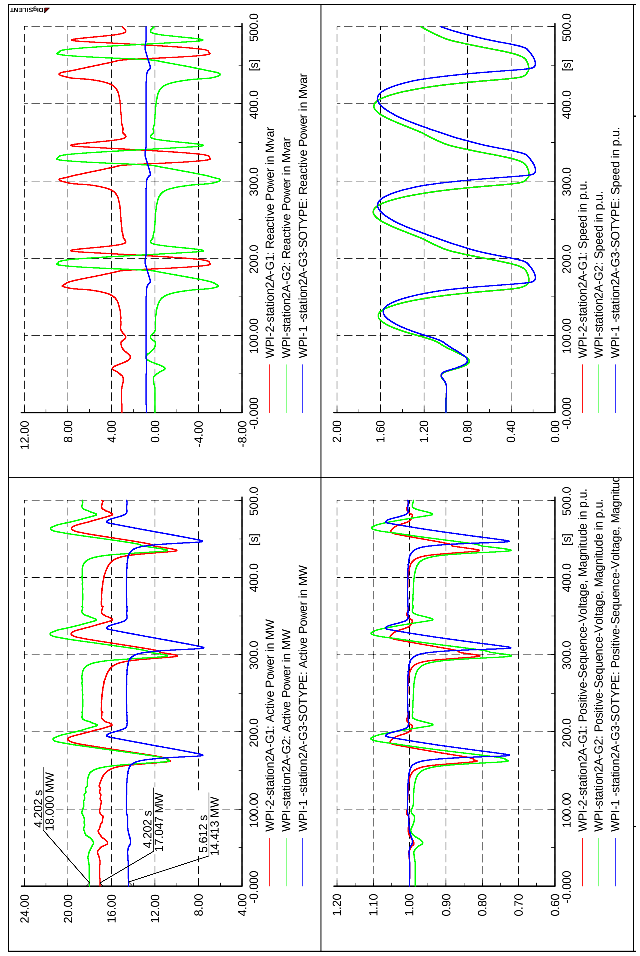

Figure 12. G2A: Stability Test: initial load of 50MW (G2A1=17MW, G2A2= 18MW and G2A3=14.4MW) followed by a small step of 0.15 MW (as-left PID parameters: Kp=2 and Ki=0.14)

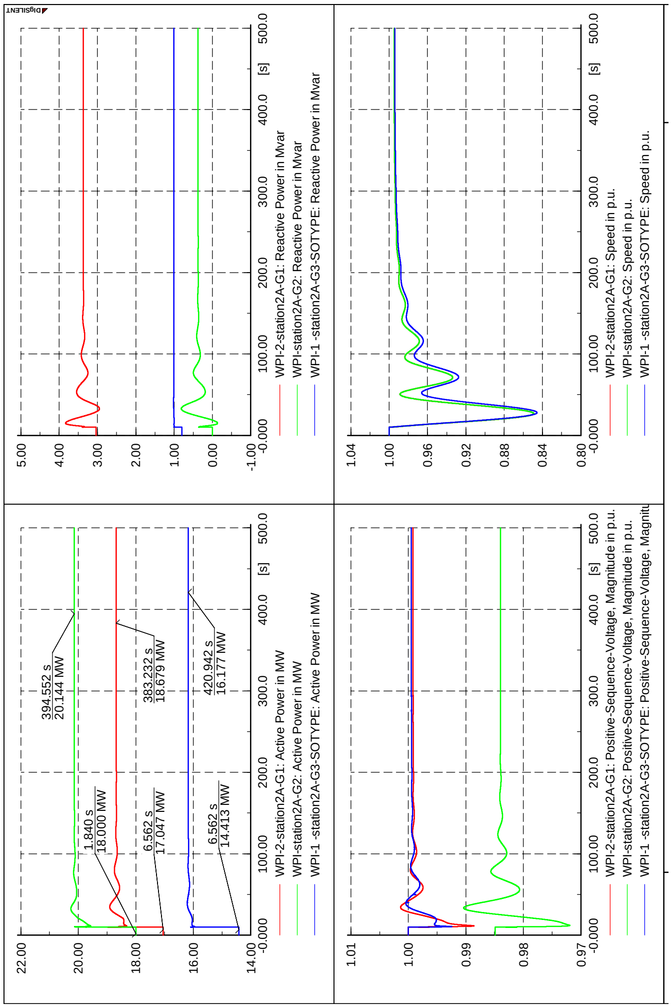

Figure 13. G2A: Stability Test: initial load of 50MW(≈80%) (G2A1=17MW, G2A2= 18MW and G2A3=14.4MW) followed by a step of 5.8MW (≈10%) MW (modified PID parameters: Kp=0.5 and Ki=0.01)

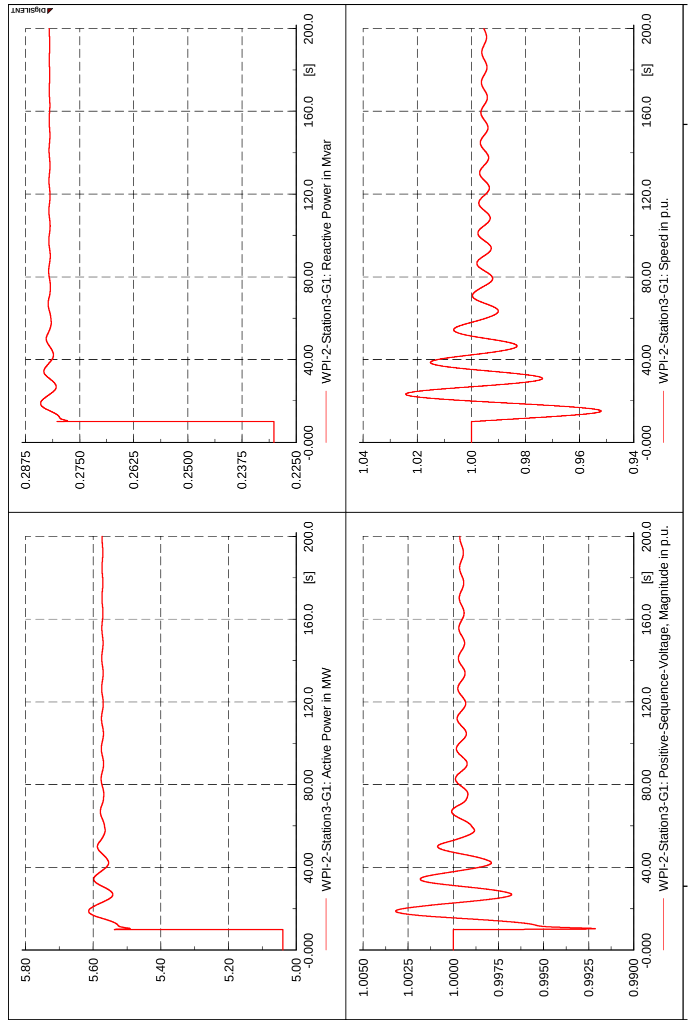

Figure 14. G3: Stability Test: initial load of 5MW/80% followed by a step of +0.6MW/10% in resistive load (as-left PID parameters: Ki=0.3):Stable

VIII. Conclusion

SKM has implemented two different plant models for the units at the Waipori hydro station. One plant/frame model was built for the units with single/individual penstocks (G1A, G3 and G4), and another plant/frame model was built for the units with a shared penstock (G2A-1, G2A-2 and G2A-3).

The Governor/Turbine model is capable of predicting the plants' behaviour during frequency excursions (for all the stations 2A, 3 and 4).

The DIgSILENT model implemented (using the as-left parameters) for station 2A predicts sustained oscillatory behavior (not unstable) after a small step change in resistive load (all units operating at 80% load whilst isolated from the grid). It can be rectified by adjusting the PID parameters.

The plant model implemented (using the as-left PID parameters) for stations 3 and 4 predicts stable and damped behaviour at entire range of active output power (whilst isolated from the grid)

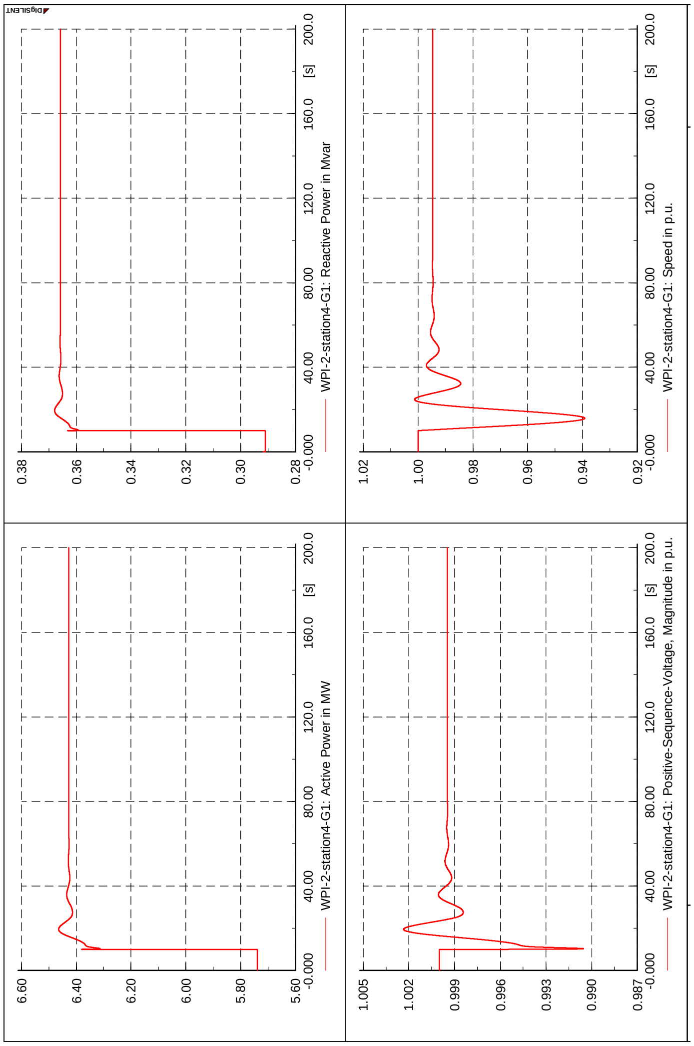

Figure 15. G4: Stability Test: initial load of 5.7MW/80% followed by a step of 0.7MW/10% in resistive load (as-left PID parameters: Kp=1.4 and Ki=0.15): stable

REFERENCES

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[2] "Electricity Industry Participation Code", Electricity Authority, New Zealand: http://www.ea.govt.nz/act-code-regs/code-regs/the-code/

[3] "Waipori 3 Power Station, Unit No. 1 - Governor Replacement Commissioning ", Contech Services Ltd report dated November 2008.

[4] "Waipori 4 Power Station, Unit No. 1 - Governor Replacement Commissioning ", Contech Services Ltd report dated February 2009.