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Initial Investigations into the Unsteady Operation of Hydroelectric Systems During Rapid Starting of Francis Turbines

D.R. Giosio, A.D. Henderson, J.E. Sargison, J.M. Andrewartha and G.J. Walker

School of Engineering
The University of Tasmania, Hobart, Tasmania, 7001, Australia

Abstract

In order to maintain a secure and reliable power supply within the stringent voltage and frequency limits required by the Australian Electricity Market Operator (AEMO), power utilities (market generators) must have the capability to provide reserve power generation to control system frequency in the event of a system contingency. In the Australian market this service is referred to as frequency control ancillary services (FCAS) and includes regulation and contingency reserves. In the Tasmanian context, a relatively isolated power network predominantly supplied by renewable energy sources, this reserve capability must be provided by hydro turbines and the HVDC link (if not operating at the limit) as Tasmania's thermal generation and increasing wind generation do not offer this capability.

This paper presents the initial investigations into the feasibility of increasing the availability of fast reserves through the rapid start-up of Francis turbines from synchronous condenser mode as a means to supply additional fast raise frequency control ancillary services to the Grid. The paper reviews the present knowledge and existing use of hydro turbines for the provision of fast frequency control while keeping in mind the unique nature of the Tasmanian system. The results of preliminary testing on a model Francis turbine unit are given along with a brief discussion of ongoing research efforts.

Introduction

In addition to meeting the current demands of the electricity market AEMO is required under the National Electricity Rules (NER) to maintain power system security by ensuring adequate reserve capacity within the system should any deviation or contingency event occur [1]. AEMO manages the power system through the procurement of three major categories of ancillary services: frequency control, network control and system restart, however the focus of this paper is on frequency control ancillary services only. The three major categories of frequency control ancillary services are defined as:

- Regulation services, Raise and Lower
- Contingency services, Raise and Lower including:
    - Fast service available within 6 seconds (R6 & L6)
    - Slow service available within 60 seconds (R60 & L60)
- Delayed service available within 5 minutes (R5 & L5)

Frequency Control Ancillary Services (FCAS)

AEMO procures FCAS from energy providers to ensure that in the event of minor frequency fluctuations, due to normal changes in demand and/or generation, or the occurrence of a contingency event, such as the loss of the single largest generating unit in a region, the system frequency is maintained within the standards set by the NER. As such, frequency control ancillary services can be divided into two categories: regulation frequency control and contingency frequency control. Regulation frequency control is the correction of the minor frequency fluctuations of the system due to changes in load and/or generation and is continually used by the automatic generation control (AGC) to maintain system frequency. Contingency frequency control is the correction of a major frequency deviation resulting from the loss of a generating unit or major load.

Since the commissioning of Basslink, a 500 MW high-voltage direct current (HVDC) transmission system, in 2006 and the subsequent inclusion of Tasmania into the national market the supply of adequate fast raise R6 FCAS has been problematic [2]. Fast raise FCAS is the most difficult service to supply for hydro schemes and this problem has only been worsened by the increasing contribution of wind generation and the addition of a combined cycle (CCGT) generation plant that are unable to provide adequate fast response [2].

It is noted that the required amount of fast raise reserve (R6) varies depending on the size of the largest generator contingency, system load and inertia. The most difficult conditions in which to meet the R6 demand are light load conditions and HVDC power reversal (under this condition all FCAS must be sourced locally in Tasmania), as hydro plant availability is significantly reduced with Basslink import and the increasing contribution of wind and CCGT generation. Additionally, very few hydro machines being operated overnight are sufficient providers of FCAS. Flexibility of the HVDC link makes it very attractive to operate in arbitrage mode with Tasmania importing cheap overnight power from the mainland and selling energy during high price periods. This mode of operation results in the Tasmanian system being very light and having problems with meeting R6 FCAS requirements. To meet these requirements Hydro Tasmania is often forced to operate more lightly loaded hydro units. This mode of operation results in low efficiency of water usage, increased maintenance requirements and accelerated plant damage. It is estimated that the availability of an additional 10-15 MW of R6 would eliminate most of the low load operation.

Operation in Tail Water Depression Mode

Many hydroelectric units have been originally designed to allow operation in a synchronous condenser (SC) mode, the feature allowing the supply of reactive power while motoring the generator/turbine with the tail water depressed [3]. In the SC mode air is forced into the runner cavity such that the runner is able to spin at synchronous speed in air rather than water thus decreasing the friction on the runner and reducing the amount of power input required from the system. It is also noted that in SC mode the hydro unit typically operates with the main inlet valve (MIV) closed (unless there is no MIV in the case of lower head Francis turbines with guide vane seals) and the governor solenoid de-energised. Historically this has been done in order to control reactive power and provide voltage support to the system [4]. In recent years there were many static var devices installed making SC mode rarely used.

Operation in SC mode has been tested to establish potential modifications to provide rapid machine start-up [3, 5] and capability to supply additional R6 FCAS. The following main modifications to SC mode are required in order to facilitate rapid machine start-up:

- The main inlet valve remains open, the water instead being held by the inlet guide vanes.
- The governor remains active, keeping the guide vanes in the closed position unless triggered to operate.

When required, due to a drop in the system frequency below a nominated level and/or high rate of change of frequency, the inlet guide vanes are rapidly opened, flooding the runner and expelling the air volume through the draft tube, and with some delay (typically 1-2 sec), delivering rapid reserve power to the system. This new mode is known as tail water depression (TWD) mode.

The proposed tail water depression (TWD) mode of operation for the purpose of providing fast FCAS is not new however; in fact one of the primary roles of the Dinorwig pumped-storage hydroelectric power plant is to regulate system frequency of the British national grid [6]. The Dinorwig plant consists of six 317 MW Francis type pump-turbines with the ability, when operating as spinning reserve, to be brought from zero to full power output in 10-15 seconds [6,7].

Tail water depression mode operation is extremely well suited to Tasmanian conditions as in this mode the machine does not need to generate power (it does however consume a small amount of power). The TWD mode allows the provision of additional fast raise FCAS but also increases system inertia, provides reactive power control, provides fault level injection and eliminates the need to operate at low load and low efficiency. However some regulatory changes may be required to allow generators to be dispatched in this mode as current NER rules do not cover such options.

Initial Testing

Initial field tests conducted at Hydro Tasmania's Reece Power Station on a 116 MW Generating unit revealed that with some modifications the supply of fast response FCAS is possible via the rapid transitioning of a unit from SC operation to generation. However while the results of the initial FCAS tests were positive, the response was relatively slow due to an undesirable 6 MW additional power draw and oscillations experienced in the first few seconds of draft tube flooding, significantly reducing the total fast raise FCAS contribution during the 6 second R6 FCAS window (Figure 1).

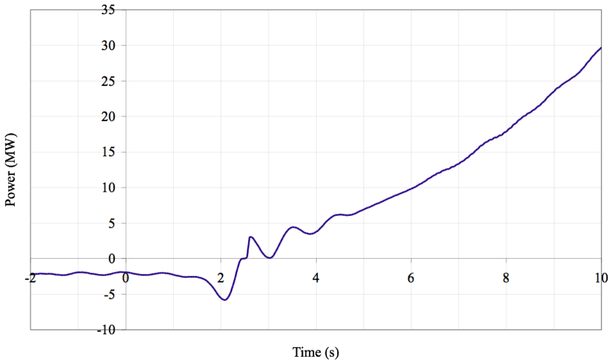

Figure 1. Power output from the Reece unit during transition from tail water depression mode to generation mode [8].

Communication with hydroelectric generators has confirmed that similar rapid transition from SC mode has been successfully implemented. These sites will be further investigated to identify any characteristic differences that may favour this mode of operation.

Reverse Power Flow

A study by Magsaysay et al. [3] on the rapid load response of the Dinorwig power plant reports the observation of a reverse power flow into the machine upon transition from synchronous condenser mode which lasted for 2.7 seconds with a maximum magnitude of approximately 40 MW. A similar power dip has also been reported on a 325 MW unit at the Ohkawachi Power Plant, Japan where the negative power flow was found to last for up to 60 seconds with a maximum magnitude of 60 MW [3]. Magsaysay et al. attribute the power reversal to a decelerating torque applied to the pump-turbine by the initial surge of water hitting the runner as the inlet guide vanes are opened. This deceleration results in a change in the electrical load angle causing the machine to momentarily be driven as a motor [3]. No mention is made of the precise time at which the tail water level actually impinges on the runner or whether this plays a role in the power reversal, it is mentioned however that water is only allowed to enter the runner chamber once the air is evacuated.
Mansoor et al. [6] and Munoz–Hernandez and Jones [7] both report similar behaviour following a step load increase and consider the negative power flow in this case a result of the requirement for part of the available mechanical power to be used to accelerate the water column as the inlet guide vanes are opened, causing a drop in pressure at the turbine inlet and a subsequent decrease in generated power [6,7].

The existence of such negative power flow behaviour following a step load increase is well documented. Indeed, Jones et al [9] have proposed a standard specification of responses for a hydroelectric power station operating in frequency-control mode in which following a step increase the negative power excursion (denoted P_6) and the time at which positive power generation begins (denoted t_{p7}) are assigned as critical test criterion. This non-minimum phase (NMP) behaviour of hydroelectric power plants is well known and understood to be a key physical limitation in the rapid response of hydropower systems [7].

It should be noted however that the studies by Mansoor et al. [6] and Munoz–Hernandez and Jones [7] are both concerned with the step response of a hydro turbine unit operating at part load for the purpose of continuous frequency regulation, not the supply of instantaneous reserve following a contingency event by the transition from synchronous condenser mode to generation.

To the best of the authors knowledge there has been no published work to date to focus on the minimisation of, or the influential factors involved in, the size and duration of the observed negative power flow.

The work by Magsaysay et al. [3] looks at the power dip observed by bringing a hydro unit online rapidly from TWD mode and considers the possible negative effects such a reverse power flow could have on a power system, particularly isolated or low inertia systems, in the form of large voltage and frequency drops [3]. If unmanaged, these frequency drops can have considerable consequences and could potentially lead to system blackout. A solution to these negative effects of the power reversal is offered by the use of a static frequency converter (SFC) providing an asynchronous link to the network [3]. The solution however only mitigates the frequency problems associated with the power reversal and does not actually eliminate the reversal. Due to the energy required to power the

SFC the use of the SFC actually extends the time required to compensate for the power reversal and thus reducing the ability of the unit to provide fast FCAS.

For the low inertia Tasmanian system in the Australian energy market where the contribution to fast R6 FCAS is based on average energy delivered during the first 6 seconds from the time of the frequency trip, it is critical to develop a deeper understanding of the parameters involved with the observed power reversal in order to reduce its severity and maximise the potential for fast raise FCAS contribution.

Initial Model Testing

Preliminary studies have been undertaken at the University of Tasmania where a simple small-scale Francis turbine model test rig was used to investigate the hydraulic transient and the associated reverse power flow resulting from the rapid transitioning of a hydro turbine from TWD mode to generation mode.

A power reversal similar in appearance to that reported in the literature and experienced at the Reece power station was also observed on the generic small-scale model shown in Figure 2.
The ability to reproduce this response on such a simple model suggests similarity in the nature of the hydraulic transient and provides strong evidence that the power dip is the result of a physical phenomenon associated with the process rather than being a peculiarity of the power station.

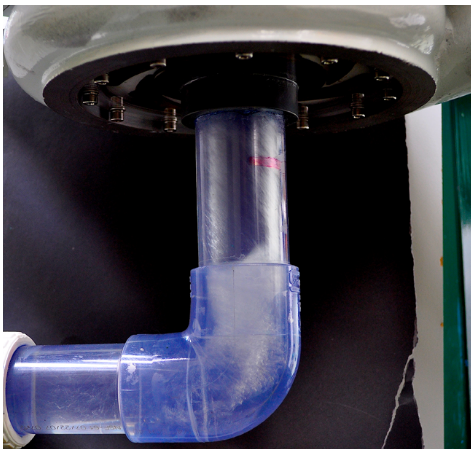

Figure 2. Air expulsion through the draft tube during the transition from TWD mode to generation mode of a model Francis turbine following the rapid opening of the main inlet valve.

Conducted as a feasibility study before more a stringent model testing program was planned the simple model was used to investigate the influence of two possible key parameters: the rate of inlet guide vane opening and the initial level of tail water depression. In each case tests were performed for three basic settings in order to gauge the relative influence of each parameter.

Inlet Guide Vane Opening Rate	**Opening time**
Fast	5 seconds
Medium	25 seconds
Slow	40 seconds
Tail Water Depression Level	**Distance below runner**
High	$0.375D_{runner}$
Medium	$0.750\ D_{runner}$
Low	$1.125\ D_{runner}$

Table 1. Classification of test conditions for both opening rate and tail water depression level tests.

Figure 3 illustrates a clear trend that indicates the presence of a shorter, more pronounced power dip for high initial tail water levels that gradually reduces in severity but increases in duration as the initial level of tail water depression is decreased. At the lowest possible TWD level able to be tested the power dip is almost eliminated, however the time taken for the system to show any decrease in its power demand is approximately 2 seconds longer than with the higher TWD levels. In relation to the provision of fast 6 second FCAS this may mean that it is actually advantageous to incur a power dip if the recovery is rapid enough, rather than reducing the power dip at the expense of lost FCAS generation time.

It can be seen in Figure 4 that the influence, on both the magnitude and the duration of reverse power flow, of the guide vane opening rate is much more significant than that of the initial level of tail water depression as shown in Figure 3. The results indicate that while the magnitude of the power dip is slightly increased, the time before positive power is produced can be dramatically reduced with the use of increased opening rates. Practically however the safe rate of guide vane opening will be limited by the upstream pressure transients produced by the opening of the gates.

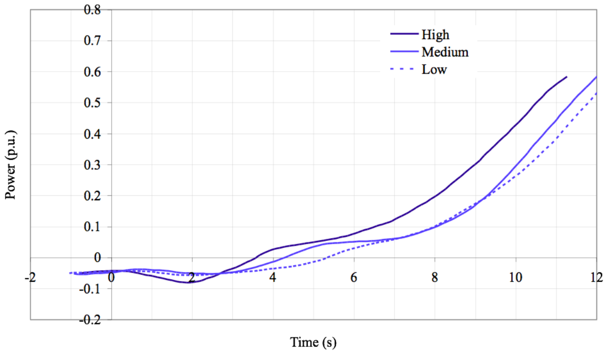

Figure 3. Influence of the initial tail water level on the observed power reversal during transition of a model Francis turbine from tail water depression mode.

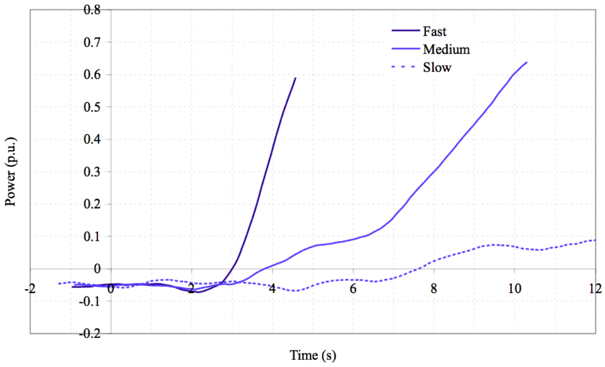

Figure 4. Influence of inlet guide vane opening rates on the observed power reversal during transition of a model Francis turbine from tail water depression mode.

Ongoing Research

Through a combination of computer simulation, model testing and a full-scale test program, the current research project aims to further investigate the flow physics associated with the rapid start-up of hydro turbines from spinning in air to normal generation mode.

The anticipated outcome of the project will be to develop a deeper understanding of the performance of turbines operating under transient two-phase conditions occurring within the runner cavity and draft tube during transition, which will ultimately be used to develop an improved set of operational guidelines conducive to greater fast FCAS provision. In particular, the project will focus on the hydraulic effects limiting the inlet guide vane opening rates such as the propagation of pressure transients in both upstream and downstream waterways, cavitation effects, the machine stresses involved with faster guide vane opening and low-load operation, the identification of factors that influence the general dynamic response of hydro turbines and the development of appropriate power plant selection criteria and optimal operational guidelines for hydro machines operating in TWD mode.

Future Model Testing

Following the encouraging results of the preliminary study, work is currently been done on the design of a more suitable test rig for a detailed investigation into the cause and effects of the hydraulic transient observed upon rapid start-up of Francis turbine units.

The new scaled model is to be based on the existing Reece power station Francis type turbine with specific speed of $n_{sp} = 1.22$ ($n_q = 71$). Froude similitude will be observed for testing according to IEC 60193 standards [10]. Apart from the matching of important dimensionless parameters a critical aspect of the model will be the control of the inlet guide vanes and the ability of the vanes to seal and hold the rated head. Water shall be supplied from pressurised supply tank via a penstock so that hydraulic transients caused by the rapid guide vane opening may be studied. Pressure transducers are to be located at numerous positions in the draft tube, spiral casing and along the penstock while provision will be made for flow visualisation in both the runner chamber and conical draft tube section.

Modelling and Simulation

The development of an accurate dynamic model will be an integral part of the current project. Owing to the possible dangers and potential damage caused to the plant by induced hydraulic transients, as well as the costs and scheduling demands, the optimisation of the transition procedure will initially be conducted using numerical models. There have been a number of numerical models produced in recent years [6,7,11] for the purpose of studying the transient response of hydroelectric power plants, each building on the framework set down by the 1992 IEEE Working Group [12]. None however have dealt directly with the power dip associated with rapid machine start-up. For this purpose a MATLAB/Simulink based model will be developed, building on the work by Ng [11] on the unsteady operation of a Francis turbine to include the influence of the air cavity and the expulsion process on the power output during transition. The results of the numerical simulation will be verified by the improved scale model results and assist in the transfer of data from model testing to full scale.

Conclusions

While only in its initial stages the current project has demonstrated the existence of a certain hydraulic transient associated with the transition of a Francis type turbine from tail water depression mode and the resulting reverse power flow associated with this process. A number of potential key parameters including guide vane opening rate, tail water depression level, water acceleration time constant and draft tube geometry have been identified, however the actual degree of influence of each will be later confirmed with additional model testing and simulation.

Acknowledgments

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References

[1] Australian Energy Market Commission 2009, National Electricity Rules: Current Rules [online], AEMC, Available from: http://www.aemc.gov.au/Electricity/National-Electricity-Rules/Current-Rules.html [Accessed: (13.07.2010)].

[2] Hydro Tasmania FCAS Strategy - Additional Supply Options, Hydro Tasmania, Hobart.

[3] Magsaysay, G., Schuette, T., Fostiak, R.J. 1995, Use of a Static Frequency Converter for Rapid Load Response in Pumped-Storage Plants, *IEEE Transactions on Energy Conversion*, Vol 10., No. 4, pp. 694-699.

[4] G. Grigsby, L.L. 2000, *Electric Power Engineering Handbook*, CRC Press, Alabama.

[5] Ceravola, O.; Fanelli, M.; Lazzaro, B. 1980, "The Behaviour of the Free Level Below the Runner of Francis Turbines and Pump-Turbines in Opertion as Synchronous Condenser", *Hydraulic Machinery and Equipment Associated with Energy Systems in the New Decade of the 1980's: 10th Symposium*, September 28 - October 2, 1980, IAHR, Tokyo, pp. 765-775.

[6] Mansoor, S. P. et al., Reproducing oscillatory behaviour of a hydroelectric power station by computer simulation, *Control Eng. Pract.*, 8, 2000, pp. 1261-1272.

[7] Munoz-Hernandez, G. A., Jones, D., MIMO Generalized Predictive Control for a Hydroelectric Power Station, *IEEE Trans. Of Energy Conversion*, vol. 21, no. 4, 2006, pp. 921-929.

[8] Hydro Tasmania FCAS Strategy – Progress Report, Hydro Tasmania, Hobart.

[9] Jones, D. I. et al., A Standard Method for Specifying the Response of Hydroelectric Plant in Frequency-Control Mode, *Electric Power Systems Research*, 68, 2003, pp. 19-32.

[10] IEC 60193 Standard, 1999, "Hydraulic Turbines, Pumps and Pump-Turbines – Model Acceptance Tests", International Electrotechnical Commission, Geneve, Switzerland.

[11] Ng, TB., Walker, G. J., Sargison J. E., 2004, Modelling of Transient Behaviour in a Francis Turbine Power Plant, 15th Australian Fluid Mechanics Conference, University of Sydney, Sydney.

[12] IEEE Working Group, Hydraulic turbine control models for system dynamic studies, *IEEE Trans. Power Systems*, 1 (1992), 167-179.