Improved Governor Response at the Dinorwig Power Station

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Dinorwig Power Station, located in North Wales, UK is one of the largest Pumped Storage facilities in Europe and has the capacity to generate electricity with six (6) 300MW pump generator units. These units make a significant contribution to ensuring the day-to-day stability of the UK, which relies on the Dinorwig Powerhouse to deliver rapid, consistent response. Upgrading the digital governor controls on Unit #1 resulted in reliable, accurate and faster response to a range of frequency excursions. This paper provides an insight to this achievement, which has re-enforced Dinorwig as one of the leading Pumped Storage plants in the World.
A. Introduction

The First Hydro Company operates a large pumped storage hydroelectric power station located in Dinorwig, North Wales, UK. Six 330MW (300MW declared capacity) pump-turbines operate synchronous generators, that provide power to the UK National Grid. Commissioned in the early 1980’s, this power station can generate up to 1320MW of electricity in under 12 seconds while running in condense mode, or 1728MW from standstill in just 90 seconds. Water flows from the upper reservoir downhill through a single tunnel which then splits into six penstocks, and operates at an average head of 557 meters. At full water storage capacity, the plant can generate just over 10 GWhr of energy.

Dinorwig Power Station is one of the fastest responding power plants in the World, and in order to maintain this status, a reliable and accurately responsive Governor is essential.

The UK National Grid is an ‘islanded’ system with and the UK power demand typically varies between 30 to 60 GW at any moment. The UK grid operates at a nominal frequency of 50Hz and is a dynamic system, with the operational range of frequency being between 49.80Hz and 50.20Hz. This in turn requires fast, real-time frequency control and reserve services, which is the primary function of the Dinorwig hydro power plant. The Dinorwig plant is considered a key feature of the UK National Grid and is expected to operate reliably with an extremely high level of availability.
B. Why Upgrade The Governor?

During the original build of the station, an analogue Governor was installed and commissioned. This was upgraded in the mid-1990’s by its natural successor, a PLC based digital solution, specifically designed to control a pumped storage Hydroelectric power plant. Over the last 30 years, both of these systems have been reliable and have met the standards required to make Dinorwig unique as the expected primary frequency regulation power plant in the UK.

The industrial control systems at Dinorwig have recently been standardised using Rockwell Automation products. Continuous updating of the existing installed systems has resulted in a strong and reliable integrated system at Dinorwig, one that seamlessly integrates with the SCADA systems.

However, the Governor Control System was isolated and vulnerable, facing hardware obsolescence issues, reduced support, and difficult communications with the rest of plant. The programming software was only available on the DOS operating system, and the hardware was on average 16 years old.

In addition, the Speed Monitoring system that resided in the same cabinets as the Governor controller was a hardwired analogue/digital relay system that had been in use since the station was originally commissioned in the early 1980’s. This system faced similar obsolescence issues as the Governor.

The obvious solution would be to replace the Governor Controller and the Speed Monitoring control system with the Rockwell PLC, since the rest of the unit had already been upgraded with this PLC platform. The main objective was to produce software that was functionally identical to the original governor. However, with this upgrade, an opportunity to remedy issues in the existing Governor and a potential to make improvements with the new Governor and its related systems presented itself. Following a thorough competitive tendering process, American Governor Company (AGC) was selected to deliver the Governor and Speed Monitoring Control System Upgrade.

It must be noted that this upgrade does not include any hydraulic or mechanical aspects of the Governor, just the electronic control system.

C. Specifics of the Dinorwig Governors

The governor at Dinorwig is a Kvaerner / Boving system (Figure 1) consisting of a Pilot Actuator now driven by the upgraded PLC system, which controls the position of the main distribution valve, via the balancing lever. The distribution valve controls two servomotors in parallel that drive the regulating ring and the Guide Vanes (Wicket Gates). This pilot stage system hydraulically operates at just under 40 Bar.
Figure 1- Kvaerner / Boving

The technical specification for the project was generally based on providing a new digital governor as good as or better than the existing governor. However, it also presented a number of
challenges that many of which were more challenging compared to the usual grid conditions in the US:

I. System frequency target is 50.00Hz, and expected frequency excursions are 10X’s greater than usual disturbances found on the US grid.

II. Time to synchronise and generate power from Standstill to be as good as or better than existing.

III. Time to generate power from Spin Generate (Condense mode) to be as good as or better than existing.

IV. Option to operate the unit in Power-Control (dead-band mode) or Frequency Control.

V. Unit to be capable of meeting UK Grid Code requirements (and therefore contracted positions) with respect to Primary and Secondary Response. This translates to achieving declared power output within a defined time.

VI. Respond to Low Frequency events, by achieving maximum power output in 10 seconds.

VII. Continuous Frequency Response mode at various Droop.

VIII. Use of minimum and maximum Power Output limits

IX. Dynamic Pumping Control where guide vanes are driven to a set-point determined by System Frequency and Water Column Head.

Another considerable challenge at Dinorwig was the limited time to commission the system to have it available for commercial use. Testing control functionality during a commissioning is both time-consuming and high risk. It was widely accepted that a time period would be allocated for on-line commissioning activities, however; the commercial impact of an extended or difficult commissioning period could cost in upwards of ten’s of thousands of £’s (pounds), per day. To mitigate the potentially costly commissioning period, a laboratory Simulator and unit Model based on unit site conditions has offered clear advantages. Critical plant operations could be tested off-line with no risk to the plant; faults could be detected and remedied at an early stage, and on-line commissioning time would be significantly reduced. This led to a Governor Model and Simulator being developed by a 3rd party in Wales, with the intention to pre-commission the Governor Control System before it was installed in the plant.

A Plant Model can be presented in many formats. The type best suited to this type of generation scheme is the ‘Hardware-in-the-Loop’ or HIL Simulator and Model. This type of Model allows for external hardware components to interact with the Model, and to perform their duties and control, as if they were connected to the real plant. This is particularly well-suited to PLC based systems.

The function of the hardware-in-the-loop (HIL) Simulator is to act as a substitute for a single Unit of the real Plant and its primary application is to replace the Plant during commissioning of new Governor hardware and software. Ideally, from the point of view of the Governor, the Simulator will appear indistinguishable from the real Plant by:

I. Accepting the same control signals from the Governor PLC as the real Plant;

II. Sending the same measurement signals to the Governor PLC as the real Plant;

III. Communicating the same logic signals to and from the Governor as the real Sequencer;

IV. Producing simulated responses which reproduce the steady-state and dynamic characteristics of a single Motor/Generator and turbine in different modes of operation.
In order to achieve a true representation of the Dinorwig Plant responses, a number of key characteristics were modelled:

I. Simplified unit sequence and controls
II. The Guide Vane model
III. Hydraulic characteristics including Water Start time, water column oscillations and water hydrostatic pressure.
IV. National Grid characteristics including load and stiffness.
V. Auxiliary plant such as Auto-synchroniser, VFSE, Blowdown, Dynamic Braking.

The resulting Model was implemented on dSpace hardware controlled by Matlab/Simulink modelling. A suitable user interface was provided to allow online monitoring, parameter adjustment and test initiation. Further trends and graphs were also made available as well as a feature to export test results into suitable Excel format for further analysis. The Model was compared against true plant responses and it was tuned to provide a ‘typical’ response under various conditions and power contracts such as high/low water head, Low Frequency on the national grid, spinning reserve, pumping, and run-up to synchronous speed.

Figure 2 – HIL HMI user interface.
D. Solutions to the Issues Facing First Hydro Company

A. The new governor code was specified to be written so as to emulate the existing governor code, with the flexibility to make improvements. Some of the major challenges encountered during the writing of the new governor software were due to the new software having to abide by the following:

i). The operational controls of the unit had to be seamless for the operators, whereas the HMI screens had to operate and function exactly like the original governor software. This was a rather difficult procedure due to the fact that improvements to the unit were requested but the operational interfaces could not change. This was a high priority that the HMI screens and control room hardware interfaces remain intact so that the operators did not have to learn a new system. As referenced before, Dinorwig plays a critical role in supporting the UK grid and not having to re-train the operators in learning new screen functionality greatly reduced this potential risk for error.

During the commissioning stage of the project, despite several control room distractions such as phones ringing, alarms and requests for permits, etc, the operator continued to operate the new governor and navigate the HMI screens, without delay or difficulty. This was important and proved that the operator was able to take control of the unit in the same manner as before the upgrade. This resulted in the operators gaining trust and familiarity with the new system from the outset.

ii). It was desirable not to have a separate Governor PLC, but to make it a subroutine of the existing main unit control PLC – i.e. the Governor PLC rack was simply remote I/O to the main Sequence PLC.

Why is this unusual? Typically, due to the stringent requirements demanded by the governor, the core governor PLC code (unless dictated by the project requirements, minor auxiliary equipment may also be coded within it) is usually done by a standalone PLC processor, with its own direct, hard-wired I/O signals that may or may not be interfaced with another PLC that controls most if not all of the units auxiliary equipment. If the governor is to perform its duty of controlling the unit in response to grid disturbances, then the speed of the PLC processor and accuracy of the speed sensing systems must have deterministic scan times and fast I/O update rates in order to abide by speed regulations set forth by the industry.

To verify and prove that the new governor PLC code would not be hampered by integrating it into the existing code (which controlled all of the units’ auxiliary’s and sequencing); extensive tests were performed to prove that the system architecture was robust and that the governor’s performance was time stamped as if the governor code was operating in a standalone PLC. The system architecture was developed using the Allen-Bradley Contrologix PLC platform. The governor I/O was mounted in a remote rack that communicated over an Allen-Bradley ControlNet communications backbone that offered...
consistent and deterministic update rates of 5ms for the entire governor I/O. (See Figure 1). The remote governor I/O chassis consisted of critical hard wired signals like Generator speed, Grid or Bus speed, Unit Megawatts, Generator Current, actual Guide Vane position and the Guide Vane commanded position just to name a few. Not only was care taken to make sure that the I/O was updated appropriately, but that the core governor program was tasked at specific intervals as to not to debilitate its performance.
With specific requirements demanded of the Dinorwig power station, these unique system functions needed to be integrated into American Governor’s core standard governor software.

**Droop:** Typically droop is set at 5% in the United States; however, at Dinorwig there is a mandatory requirement of 4% droop (with an optional droop setting below this) based on system frequency of 50Hz. This is predominantly due to greater frequency excursions in the UK than in the US. It is not uncommon that the frequency range fluctuates from 50.2 Hz to 48.8 Hz in the course of hours. The UK is basically an Islanded grid, which is why the Dinorwig Pump Storage Plant is so very critical to the stability of the UK grid.

**Part Load Response (PLR):** This is a mode in which the unit is set to respond to frequency at an optional droop setting producing a greater range of output. If the unit is set in PLR mode, the governor will respond to the grid frequencies normally, but if the grid frequency falls outside of operational limits the unit will achieve maximum Megawatt rating in less than 10 seconds. With this rapid loading of a unit, the frequency quickly stabilizes and or recovers within a short period of time. The demands of the Dinorwig plant are critical and this is why the modeling tests were important to perform.

**Manual Mode:** If a fault in the system were to occur, the unit will be placed in Manual mode in which the guide vanes will be directly controlled by open/close direct-acting hydraulic solenoid valves that are energized by the operator through an open/close selector switch located at the main room control panel. The governor PLC is no longer in control of the guide vanes at this point. Once in Manual mode the governor will follow the guide vane position and once the fault is cleared the unit can be placed back in auto control and the governor will perform a bumpless transfer from the current manual guide vane position into an equivalent MW setpoint with droop.

B. After the software was developed, testing was implemented by using the FHC unit modeling software. This sophisticated software models the complete water-hydraulics, mechanical and electrical characteristics of a unit.

A functional description was written by American Governor to First Hydro Company, in essence to prove that the concepts of how the Dinorwig Power plant operates with its unique functionalities were fully understood. With the approval of the functional description, project detail engineering was started. Many drawings were modified to show the demolition of the existing governor equipment and the installation of the new equipment. At the same time, the governor PLC programming was started.

After completion of the preliminary governor software, extensive testing was performed. This was probably the most critical path to prove the governor software functionality and robustness. The modeling software in conjunction with the PLC hardware was utilized to test the governor software in which many tests were performed. Thanks to ever evolving technology, the interfacing between the United States and Wales was completed remotely via a secure VPN connection. This allowed American Governor to connect to the test governor PLC and run
simulated events with the modeling software. This greatly reduced the costs of travel and engineering time. With the five hour time difference, First Hydro would run simulated tests, evaluate the tests and then forward the results to American Governor before they arrived for work. Any changes that were required were completed over the VPN network. After two weeks of remote testing support, the final factory acceptance test was conducted at the Dinorwig power plant with an American Governor field engineer on site.

The 124 page final acceptance test was completed with results documented and signed. The testing incorporated the following functionalities with each test performed (when applicable) at a simulated range of High, Medium and Low Net Head levels:

I. Human Machine Interface Testing (HMI)
II. Normal Starts / Stops
III. PID tuning
IV. Pump Starts / Stops
V. Spin Gen Mode (Spinning Reserve or Condensing mode)
VI. Spin Pump Mode
VII. Black Start
VIII. Part Load Reserve Mode (PLR)
IX. Megawatt Control with frequency control
X. Droop testing in Megawatt control
XI. Megawatt setpoint changes to verify the advanced feed-forward logic
XII. Load Rejections
XIII. Generator Current Limiting Logic
XIV. Governor Alarms, Trips and Faults
XV. Manual Mode
XVI. Speed Monitoring Logic
XVII. Extensive National Grid Tests.

These tests carried out with the new American Governor / Rockwell Governor on the Model proved to be invaluable. A two week testing program with well over 200 start-ups, pumping runs, frequency response, droop tests, fault/negative tests and many more operations pre-tested resulted in a system that was ‘pre-commissioned’ and ready to be installed and deployed at the actual Dinorwig plant.
Figure 4 – Trend of a simulated HIL test
E. Effects and Results of the New Governor Software

Preliminary software testing was completed using the FHC modeling to prove that the new software abided by the stringent National Grid requirements. Improvements were made in the software to further increase the functionality and response of the governor. For example: a Megawatt feed-forward routine was developed to very accurately achieve the desired Megawatt setpoint with little or no overshoot or undershoot while in the Power Control Mode. Power Control Mode is a mode in which the governor regulates Generator Megawatts based on a Megawatt Setpoint while still drooping according to grid frequency deviations.

Along with the updated governor PLC, new and less complicated speed sensing was incorporated. An existing compound voltage and current transformer configuration was originally utilized to sense the generator and bus voltage along with the current of the generator. This configuration was very complicated due to the wiring between the transformers. With the upgrade, all of the interconnecting wiring of the existing circuit was removed and replaced by separating each circuit individually and re-wiring them to new VT sensing modules supplied by American Governor. In addition, the generator VT and CT signals were wired to a new power transducer.

This simplified the speed sensing circuit, plus with the direct VT sensing, standard PLC cards could be utilized without compromising the sensitivity and accuracy of the speed signals. Upgrading the speed sensing also eliminated the existing speed monitoring system. This had been a very complicated wiring design, which utilized 3 separate proximity probes that provided pulses by sensing a toothed disk. That speed monitoring system had been used to sense the speed of the generator and energize outputs at pre-programmed speed setpoints (speed switches) See Figure 5 below.

![Figure 5](image-url)
All of the relays and control boards of the existing speed monitoring system seen in Figure 5 were replaced; by utilizing the same American Governor Speed sensing modules and adding a PLC output and input card we were able to recreate the speed monitoring system with less hardware, wiring and software. The proximity probes were re-used but were now directly wired into a new PLC input card. Figure 6 shows the upgraded governor remote I/O rack with the new Voltage Transformer (VT) speed sensing modules (silver rectangular boxes located on the right side of the panel).

![Figure 6](image)

A. Effects of Megawatt Feedforward

With the improved Megawatt feed-forward PLC code, overshoot and undershoot upon any MW setpoint change was greatly reduced. The phenomenon that occurs from the transients of the water column with rapid movement of the guide vanes can cause a governor to overreact. In the new governor, the advanced algorithm prevents the governor from reacting to these transients, which results in little or no megawatt swings around the new setpoint.
As depicted below in Figure 7 of an actual plant data trend, the setpoint was changed from 150 megawatts to 300 megawatts. The guide vanes are ramped at a constant rate until 300 megawatts was achieved. Notice in the graph that the megawatts reached this new setpoint and the governor maintained the 300 megawatt generator load without any oscillations brought on by the change in the head level and the water-hydraulic transients associated with the physical movement of the guide vanes.

In this example the Net Head started out at 518.44 meters. After the new Megawatt setpoint was achieved, the Net Head descended to 507.53 meters before recovering to near its original value. With the fast movement of the guide vanes, the head level varied by 10.91 meters or 36 feet of head and the megawatt feedback signal had a lag of approximately 1.1 seconds associated with it. The guide vanes were still in control via the PID, but the guide vanes were not overcompensating for the extreme head deviation or the lag in the megawatt signal. Especially in the case of rapid movements of the guide vanes, a typical governor will try to compensate for these deviations while in the Megawatt control mode, which causes oscillations in the guide vanes. The 150 MW increase in load took approximately 12 seconds, with amazing stability and predictability.

Key:
- White = Net Head
- Purple = MW Setpoint
- Green = Actual Guide Vane Position
- Yellow = Actual MW

Figure 7
B. Effects of Improved Frequency Response

At the start of the actual trend data below, the left side, the start time is 09:55 AM:

I. Units 2, 3, and 5 are shutdown and Unit 4 is in Spin Generate (Condense mode).
II. Unit 1 and 6 are in Frequency control mode, with minimum Power Output set to 150MW, Setpoint Power at 150MW, Droop at 1% and maximum Power Setpoint at 320MW.
III. Unit 1 has the new Governor Control System, all other units are on the original Governor.
IV. As the frequency varies from the start of the chart to B, Units 1 and 6 respond to Frequency, and the difference in response between Unit 1 and 6 can be clearly seen at A and F, where the Unit is responding quicker and accurately to frequency variations.
V. At B, the System Frequency drops below 49.80Hz, and Units 1 and 6 react without causing significant disturbance to the grid (i.e. oscillations in power).
VI. At C, both units 1 and 6 have achieved response correctly, and deliberately overshoot the target, but where unit 6 remains at a level above the setpoint, unit 1 recovers to 320MW in under 30 seconds.
VII. Then a minute later unit 4 is set to 300MW and the hydraulic disturbance can be observed on units 1 and 6, and the recovery is good without any further grid disturbance.
VIII. As units 1 and 6 are brought back to lower loads, frequency control is resumed, with little undershoot from Unit 1. Notice that in Section D, Unit 1 recovers to the setpoint of 150 MW’s. In section E, Unit 6 goes to 150 MW’s but “bounces” up to approximately 160 MW’s and then recovers to 150 MW’s in over 2 minutes.
Figure 8 on the previous page, clearly demonstrates that the new governor is fully capable of responding to the stringent requirements of the National Grid. While maintaining the functionality of the original governor, the new governor has improved the response in frequency control, plus greatly reduced the over/undershooting of the targeted power setpoints without causing stability issues or excessive disturbance to the transmission system.

In Conclusion:
With the successful upgrade of Unit 1 Governor at the Dinorwig plant, First Hydro Company, along with American Governor Company, will in full faith move forward to integrate the new governor system on the remaining five units. The continuation of these governor upgrades will re-enforce Dinorwig Power Stations position as one of the most innovative and fastest responding Pumped Storage hydro power stations in the World.

**Toni Jones – Lead Control & Instrumentation Engineer**
Toni has worked at Dinorwig and Ffestiniog Power Stations in the UK for the past 6 years and has led the modernisation of the control systems at this high status power plant. His strengths are PLC & SCADA systems with particular emphasis on Pumped Storage unit control systems, including digital governors. Toni has worked in many industries including Aluminium Smelter (Rio Tinto), Steelworks (British Steel), The Royal Mint and many food & drink and medical facilities. This wealth of experience has led to strong Project Management skills to complement his technical skills. Toni is a Chartered Engineer, and gained his engineering education at Cardiff University, Wales.

**Greg Yohe – Project Engineer, Field Service / Commissioning Engineer**
Greg has many years of experience with hydro governors and controls. His hydro experience includes five years at Voith Hydro, where he was responsible for testing and commissioning digital governors and plant control systems. Greg engineers new governor control platforms and HMI systems, and has years of experience designing and supplying hydraulic power units for hydro plants. He is also an accomplished governor trainer.