Balancing Intermittent Renewables with Europe’s Largest Pumped Storage Hydro

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Overview

Dinorwig Power Station in North Wales, UK, is one of Europe’s largest Pumped Storage Hydro facilities with six (6) 300MW pump-generator units and 1100GWh of energy storage. Since it was commissioned in 1984, Dinorwig has made significant contributions to the day-to-day stability of the UK grid by virtue of its ability to provide Primary Frequency Control during Low Frequency (LF) events and Fast Ramping response during major disruptions on the grid. With the influx of a large amount of intermittent renewable generation and fast-responding battery storage systems, Dinorwig has been called upon to do more. A software upgrade program beginning in 2013 addressed this need and enhanced the station’s ability to provide flexible, reliable response to more frequent frequency and voltage excursions on the grid. This paper will describe the new operational modes being used to accommodate the changing needs of the UK grid, reinforcing Dinorwig in particular and Pumped Storage Hydro in general as vital to the electricity grid of the future.

A. Introduction

First Hydro Company operates a large Pumped Storage Hydro power station called Dinorwig located in North Wales, UK. Six (6) 330MW (300MW declared capacity) pump-turbines connected to synchronous generators provide both real and reactive power to the UK National Grid. Commissioned in the early 1980s, this fast-ramping power station can generate 1,320MW of electricity in under 12 seconds when running in Synchronous Condense mode, and can go from Cold Start to 1,728MW in under 90 seconds. This compares favorably to nuclear and coal-fired steam power plants, which can take hours or days, respectively, to reach the necessary temperatures for energy generation. This is too slow to address unexpected, rapid power shortages. While Li-ion battery storage systems can respond nearly instantaneously and are achieving significant scale (100MW systems are becoming common), they are typically primarily used for short-term frequency support and can provide full output for between 15 minutes and four hours (400MWh). By contrast, the single Dinorwig pumped storage power station can provide over 1,100,000MWh of energy generation when needed.

Fig. 1. Dinorwig Upper Reservoir

The theory of operation is simple: during Generate mode water flows from the upper reservoir (average head of 557 meters) downhill through a single tunnel that splits into six penstocks, one for each unit. During pump mode, large amounts of electricity are taken from the grid to pump the same water uphill to refill the reservoir. With a full upper reservoir, the plant can generate just over 1,100MWh of electricity. This compares favorably to current battery storage systems that offer only 10-20MWh of electricity storage.

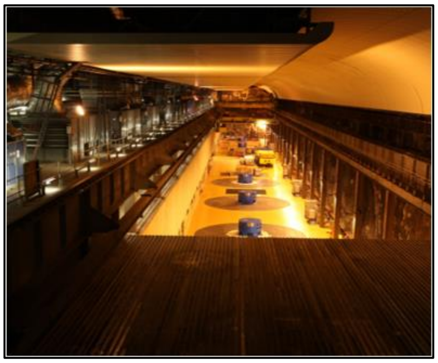

Fig. 2. Dinorwig Underground Powerhouse

The UK grid is a dynamic system, with total load demand typically varying between 30-60GW at any given moment. Frequency must be maintained between 49.80Hz and 50.20Hz. Achieving this requires real-time frequency control and fast-ramping reserve energy, which are the primary functions of the Dinorwig hydro power plant. The Dinorwig plant is considered a key feature of the UK National Grid and is expected to operate with an extremely high level of availability. In order to maintain the status of Dinorwig as one of the fastest responding power plants in the world, a reliable, responsive, sensitive, and accurate governor is essential.

Fig. 3. Dinorwig Outlet to Lower Reservoir

B. Evolution of the UK Electricity Grid

During the original build of the station, an analog governor was installed and commissioned. This was upgraded in the mid-1990s as part of a Unit and Plant Automation upgrade by a major original equipment manufacturer (OEM) using PLC-based digital controllers. Over the last 30 years, this system has been reliable and met the expectations of Dinorwig as the Primary Frequency Regulation power plant serving the UK.

In 2013, First Hydro embarked on a modernization program in which the first of the six units at Dinorwig was upgraded to the newer Control Logix™ PLC platform. First Hydro procured the equipment directly and implemented the software updates for the Unit and Plant controls. American Governor Company was selected to implement the governor software conversions over a three-year period. With the software and hardware conversion, Dinorwig produced even better results in terms of Primary Frequency Regulation and overall control flexibility, with several new control modes implemented. It is notable that, since the first installation in 2013, no governor programming changes have been required.

Even with the upgraded PLC, however, First Hydro continued to operate the six units using the same methodology that had been utilized in the 1980s. During the day, the units were operated in Generate mode to provide LF response. Overnight, the units would operate in Pump mode, utilizing low-cost power from the grid to replenish the upper reservoir. For over 30 years this consistent cyclic operation has helped maintain UK grid stability.

Since 2013, however, renewable energy generation (wind and solar, primarily) has been increasing its share of the energy mix in the UK, while traditional baseload power plants (coal and nuclear, primarily) have been on the decline due to increasing public and political pressure to reduce greenhouse gas emissions. While retiring large, baseload coal and nuclear power plants is considered beneficial to mitigating climate change, there are significant ramifications for grid stability, since wind and solar generation cannot be considered baseload generation due to their known variability.

When wind and solar began replacing coal and nuclear in terms of MW generation, new problems arose, including greater and more frequent frequency deviations on the UK grid. Who would pick up the slack? The answer, as we will see, was Dinorwig. The commonly held belief was that battery storage systems would be the answer to balancing variable wind and solar generation, and in just the last few years many such systems have been installed in the UK. Battery systems have the ability to provide full power output nearly instantaneously (milliseconds) in response to a dip in Grid Frequency. Conversely, when there is an excess of generation during a sunny, windy day, they can absorb some of the excess generation by charging their batteries. Indeed, this "instant" source of real power has added to the Primary Frequency Response capability of the UK grid. However, there are drawbacks to battery systems: unless designed for this duty, battery systems usually offer a shorter-duration response of 15 minutes to a few hours at most (Zablocki). They also have a shorter lifespan of 7 to 10 years compared to Pumped Storage Hydro (Smith). Finally, lithium-ion batteries are not recyclable, and environmental questions are emerging about what to do with Li-ion batteries once they have reached the end of their useful life.

In the next section we will present empirical data to demonstrate how Dinorwig has risen to the occasion and is now more critical than ever to the stability of the UK grid.

C. Traditional Dinorwig Operational Modes

Before coal-fired plants in the UK were retired, these plants provided more than just consistent (baseload) power. They provided physical inertia to the grid using the "flywheel effect." The stored rotational inertia in these units enabled the grid to withstand instantaneous, short-term disturbances with no operator or control intervention required. If the disturbance lasted longer than a second, Dinorwig's LF Droop function backed up this inertial response by quickly producing a significant amount of power to help maintain a consistent grid frequency. Figure 4 below shows a typical LF Droop response from several Dinorwig units. Normally, one or more Dinorwig units are run in what is known as Spin Generate (also known as Spinning Reserve). The units are synchronized and online, but their Guide Vanes are open just enough to overcome friction and windage. The chart below shows a traditional Day in the Life of a Dinorwig unit. When the Grid Frequency (red trend line on bottom) fell below operational frequency limits, the unit responded nearly instantaneously, opening the Guide Vanes (purple trend line in the middle) according to the pre-programmed Droop curve, thus increasing the Power output of the unit (blue trend line at top). This action corrected the Grid Frequency quickly, and the unit continued to maintain nominal Grid Frequency in the minutes that followed.

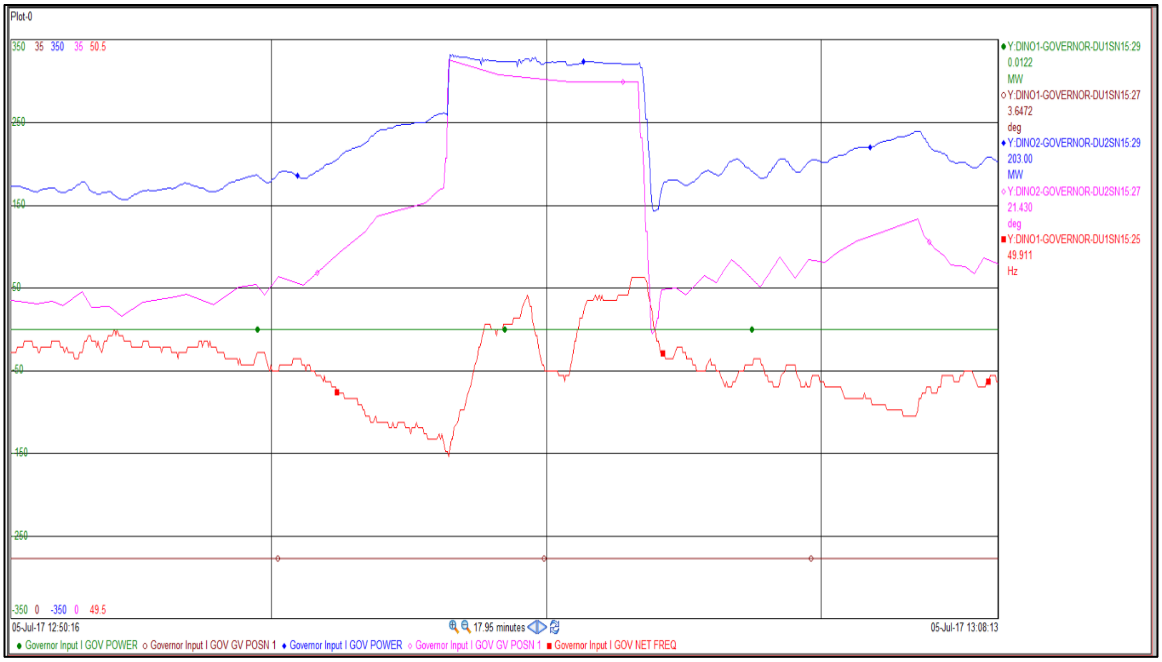

Fig. 4. Typical LF response during Generate mode. Governor software modifications in 2013 enabled Primary Frequency Response also when operating in Pump mode.

Dinorwig operators can now select from a wide variety of Generate and Pump modes of operation. Among some of these control schemes are:

a) Generate Mode
b) Generate Spin Mode (also known as Synchronous Condense mode)
c) Pump Mode (allows frequency control during pumping)
d) Pump Spin Mode
e) Part Load Response Mode (PLR)
f) Black Start
g) Manual Mode

D. New Dinorwig Operational Modes

Until recently, Dinorwig was the first line of defense for LF Response. Now, battery storage has become the primary source of instantaneous LF Response. So, what does Dinorwig do now? Everything else. As mentioned before, coal and nuclear have largely been silenced. Consequently, the “flywheel effect” of these baseload sources of generation has been significantly reduced, and generation flexibility has become of paramount importance. When Dinorwig is operated in Generate Spin mode (connected to the grid and spinning but not passing any water), this massive generator acts like a giant flywheel, providing needed rotational inertia. Within 10 seconds, a unit in Generate Spin mode can go from -5MW (motoring; providing Synchronous Condensing capability to help maintain grid voltage) to generating 300MW when needed. This rapid transition is shown in Figure 5.

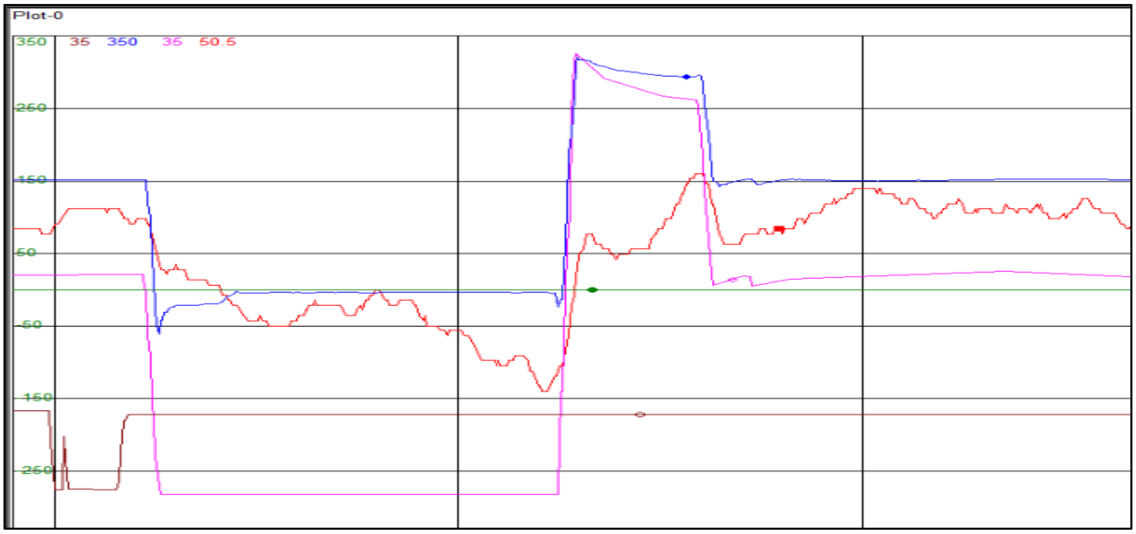

Fig. 5. Operational Transition from Generate Spin to Generate (reaching 300MW in less than 10 seconds) triggered by significant LF event. Notice the correction of grid frequency thanks to this large pumped storage unit.

Figure 5 depicts the moment-by-moment response: when Frequency (red trend line on bottom) fell below a defined setpoint, the unit responded nearly instantaneously, transitioning smoothly from Generate Spin mode to Generate mode, rapidly opening the Guide Vanes (purple trend line in the middle) to put megawatts (blue trend line at top) onto the grid. When this restored grid frequency just seconds later, the unit then proceeded to keep grid frequency from declining again.

While battery systems are good at providing Frequency Response and can source or sink hundreds of megawatts, they provide only limited voltage support. This so-called "synthetic inertia" is a temporary phenomenon provided by the inverter power electronics and last only a few seconds (exact duration is a tightly-guard secret; proprietary information). Solar farms and large windfarms with AC inverters provide a similar feature, with similar limitations. Thus, unlike a hydro pumped storage, these other renewable energy sources cannot provide grid inertia support nor contribute to provide sustained reactive power unless a huge capacitor bank is installed at additional expense. Wind farms will only produce power when wind is blowing. Solar will only produce power during daylight hours. Pumped storage systems are available and dispatchable 24/7.

The next several graphs will highlight how the many changes to the UK generation mix have changed the way Dinorwig operates. Figure 6 shows three units online and performing daytime LF responses during Summer 2019.

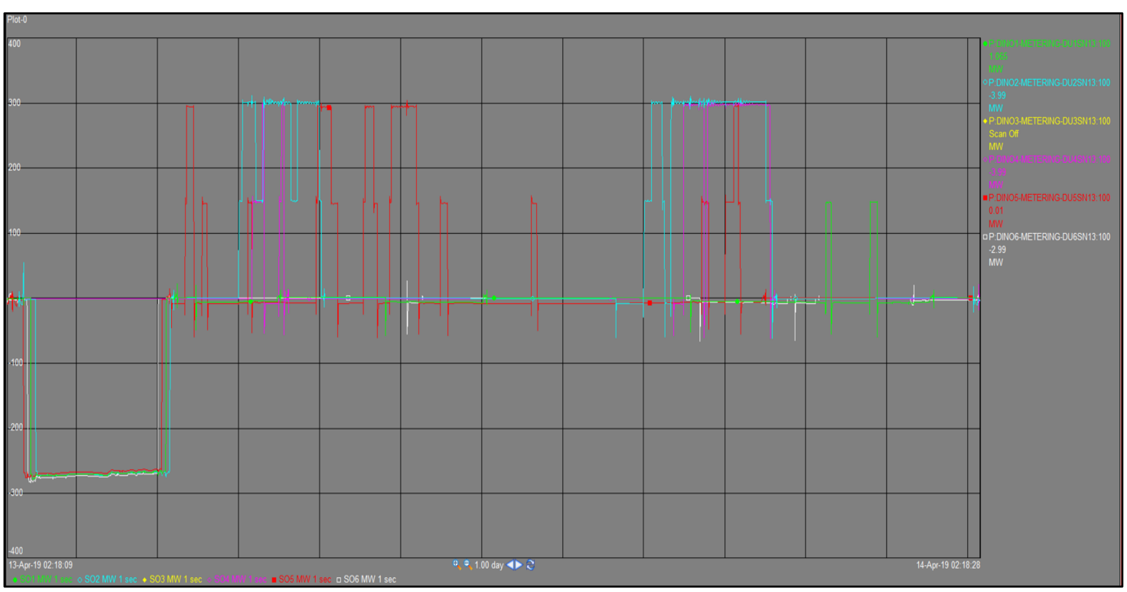

Fig. 6. Today's Operation: 13 LF Events in a Single Day, Covered by Three Dinorwig Units

Before major battery storage became operational and several fossil plants were shut down, Dinorwig on average was performing typically only one to three LF responses per day. On the day shown in Figure 6 above, Dinorwig performed a total of 13 LF responses, utilizing three different units, during a 24-hour period. In the authors' experience, based on numerous training classes given to large utility customers, operators widely believe that this phenomenon is occurring due to the lack of flywheel effect resulting from the retirement of the fossil plants provided and the volatility of wind and solar generation.

Figure 7 below depicts data that was captured in June/July 2019. This graph shows how Dinorwig was able to quickly adjust the "typical" operations it performed since the 1980s. On the left of the trend, we see the units operating traditionally. Both units are in Pump mode to help stabilize the grid by absorbing power during an over-frequency event. Then, in a matter of minutes, Unit #1 goes from Pump mode to Spin Pump mode, then back to Pump mode again. The ability of this one unit to seamlessly switch between Pump and Spin Pump mode helps offset the effects of the variable renewable generation, helping to stabilize the grid frequency.

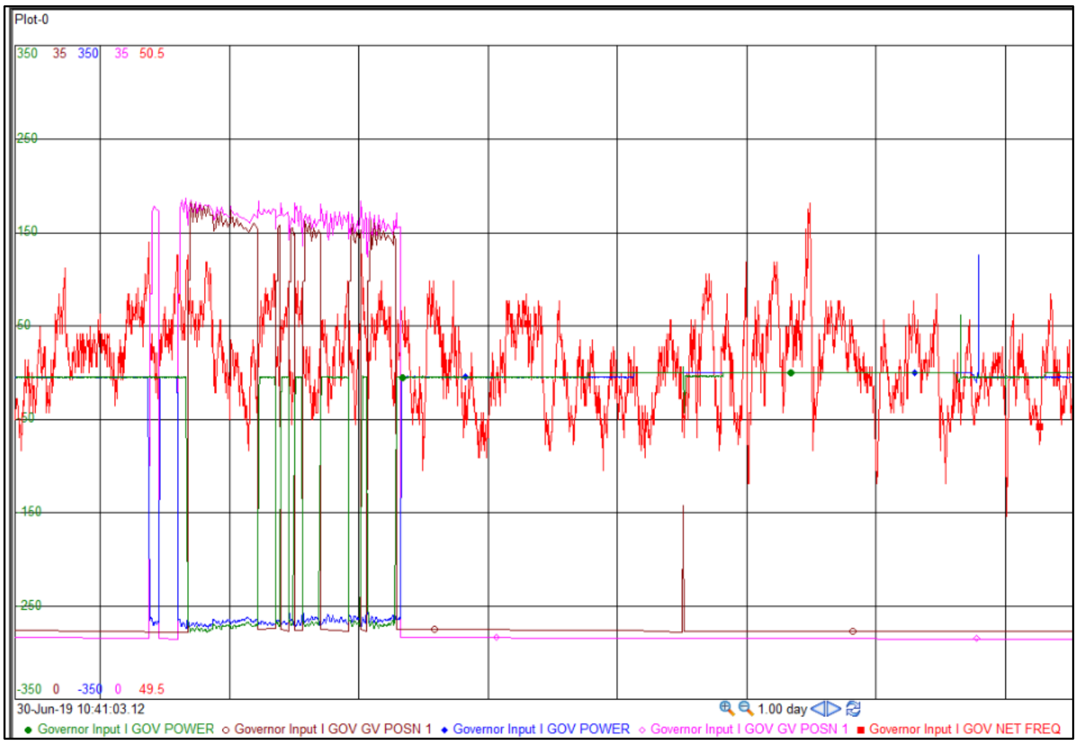

Fig. 7. Frequent Daytime Switching between Pump mode and Spin Pump mode

In this last example, if not for Dinorwig's flexibility, there could easily have been major issue (brownout or blackout) on the UK grid. During this event depicted below in Figure 8, all six units were called upon to help support the grid within a three-hour window. In the beginning of the trend, Unit #5 is online and in Generate mode with LF Droop support, helping maintain grid frequency. Forty-five minutes from the start of the trend, there was a major loss of generation on the UK grid. The call went out to Dinorwig to start three more units (Units #1, #2 and #3) immediately. Units #2 and #3 went online within seconds and were given a specific MW setpoint. Unit #1 also went on-line within seconds but was commanded into Spin Generate, providing sustained voltage support and additional rotational inertia to the grid. Thirty minutes later, Unit #1 was commanded to maximum MW output and Unit #6 was commanded to start. Soon after, Unit #6 was also commanded to maximum MW output. Even so, frequency continued to struggle to recover, so the last of Dinorwig's six units (Unit #4) was started and commanded to go to its minimum MW setpoint of 150 MW.

At this point, with all Dinorwig units online, grid frequency turned the corner and started to recover. Remote operators then commanded Units #4 and #6 into Spin Generate mode while Unit #5 continued in Generate mode with Droop support to help with grid frequency regulation. If not for the powerful, flexible Dinorwig units, it is quite possible the UK grid would have suffered outages as loads were shed to compensate for the imbalance in generation versus load. The speed, power, and frequency control accuracy of these units demonstrate the tremendous amount of flexibility Pumped Storage Hydro plants offer. Even if coal or nuclear stations had not been retired, it would have taken hours or days to perform a Cold Start on one of those gigawatt-scale facilities. It is highly unlikely that there would have been sufficient (or any) reserve wind, solar, or battery capacity available to respond to this grid emergency. When the chips are down, the UK grid continues to rely on Dinorwig more than ever.

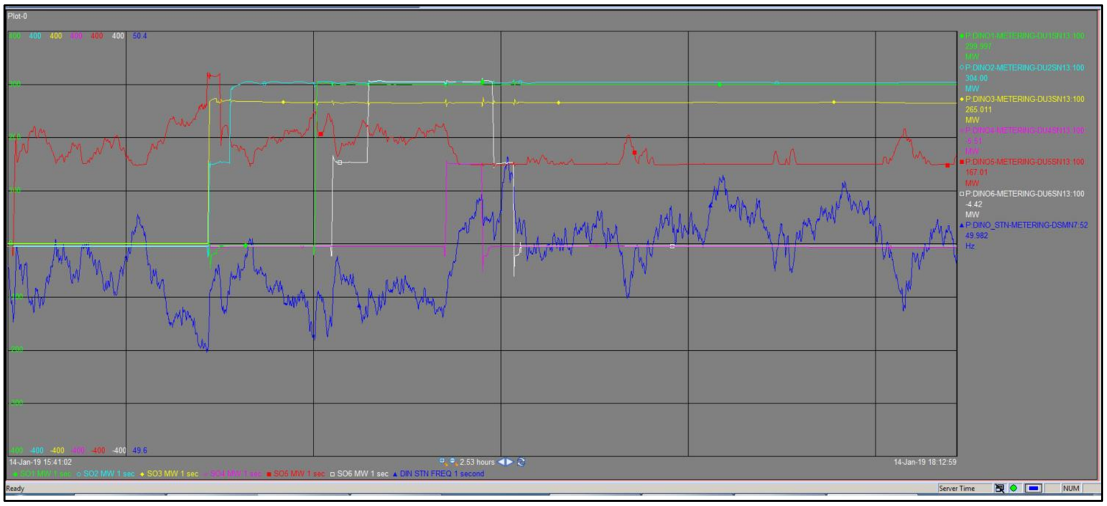

Fig. 8. All Six Dinorwig Units Respond to a Grid Emergency, adding 1,466 MW in minutes

Conclusion

With the increase in renewable energy in the UK, Dinorwig plays a critical role by proving over and over the flexibility of this pumped storage plant. With the recent modifications to the governor software at the Dinorwig plant, these six 300MW pump-generators now offer ever-greater flexibility and responsiveness. By providing the necessary flexibility to balance an increasing percentage of variable, intermittent renewable generation, one could say that Dinorwig has gone from "critical" to "super-critical" renewable energy. Dinorwig "remains an essential part of the UK's electricity pool due to its impressive response times. Nuclear can take days and coal power plants take hours to reach the necessary temperatures for energy generation, which is too slow to address unexpected or rapid power shortages… Pump storage generation offers a critical back-up facility during periods of unexpected peak demand or sudden shortfalls in supply on the National Grid system," ("Dinorwig: A unique power plant in the north of Wales"). By supporting the ever-increasing amount of wind, solar, and battery generation being added to the UK grid, now and in the future, the flexibility afforded by Dinorwig Power will reinforce its position as one of the fastest and most innovative responding Pumped Storage Hydro power stations in the world.

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Greg has many years of experience with hydro governors and controls. His hydro experience includes several 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.

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Roger has over 32 years of experience with hydro governor systems and technology, ranging from mechanical to analog to digital governors and control systems. He is regularly involved in national and international hydro conventions and serves on the Hydrovision International O&M Roundtable and PowerGen Steering Committees. For over three decades, he has contributed numerous technical papers and magazine articles and regularly participates as a speaker or moderator at hydro conferences nationally and internationally. Roger's hydro controls experience began in 1987 at Digitek, a company he eventually led. He became a Controls Sales Manager for both Woodward and General Electric before joining American Governor as Western

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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.