Operational and Performance Advances with Digital Governor Controllers on Multiple Needle Impulse Turbines

A Case Study of Governors at PG&E's Stanislaus Powerhouse

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Abstract

Multiple needle impulse turbines are among the most efficient designs of hydroelectric turbines, hoever are often restricted from reaching their full operating potential due to control limitations in their legacy governor systems. Mechanical, analog and early digital governors lack the ability to separate control of the deflector and the individual needles, which results in numerable operating obstacles: primarily poor needle control and the inability to realize the maximum efficiency of the turbine. Today, modern digital controllers and hydraulic controls allow for precise, independent positioning of the deflector and each needle, and therefore needle sequencing. With these key features, all of the aforementioned shortcomings can now be overcome.

This paper provides an overview of the gains achieved at the Pacific Gas & Electric Co. Stanislaus Powerhouse through the installation of a modern digital governor in late 2009. Testimony of the difficulties incurred operating a mechanical governor on an impulse turbine, the failed attempt at piggy-backing a digital controller onto the existing mechanical governor, and the ultimate success achieved through the conversion to a full digital governor are the central focus of this paper.

Stanislaus Powerhouse is capable of rapid loading and unloading, therefore the unit receives constant and significant load setpoint changes throughout the day. The mechanical governor was previously controlled via pulses which resulted in severe over/under shooting of the load setpoint. Now a setpoint is sent over a communications link to the digital governor, which can quickly change and hold load. Before and after trends of load requirements and actual load are presented in the paper. The implementation of needle sequencing has allowed PG&E to operate the turbine at higher efficiencies than previously possible. The paper will review these gains in efficiency as well as discuss how PG&E has taken advantage of other system improvements.

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Mechanical Governor Operation on Multiple Needle Impulse Turbines

Standard mechanical, analog and early digital governors control Pelton wheel impulse turbines using the same equipment as those used on Francis and Kaplan turbines. The governor will directly actuate the deflector servomotor in response to speed deviations from the speed setpoint. A needle/deflector cam provides the needle distributing valves (one per needle) with a setpoint which is dependent on the deflector servomotor position. The shape of this cam (see Figure 1) serves two purposes, to position the needles slightly open for synchronization and to keep the deflector positioned just out of the needle stream while at load.

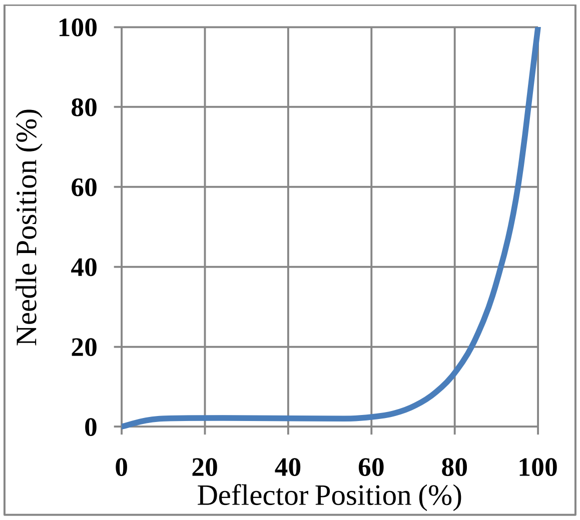

Figure 1 – Needle / Deflector Position Relationship

This method of control exhibits two critical limitations: needle control is indirect and there is no ability to individually position the deflector and each needle. The most apparent effects of indirect needle control are:

- **Poor needle control:** Lost motion in the cables, links and levers which connect the needle controllers to the deflector servomotor result in sluggish needle response and a large needle position deadband.

- **Poor load control**: Poor needle control invariably results in power hysteresis when controlling load. In the most favorable of operating modes, a modest deviation in actual load from the load setpoint is tolerated. When tight load control is required, operators and SCADA RTUs will often attempt to make frequent and small changes to the governor's speed adjuster. This constant modulation can result in the premature wear of governor control linkages and associated equipment.

- **Non-linear speed droop**: Governor droop is typically set to 5% when connected to the main grid. The governor primarily acts on the deflector position and deflector droop is therefore linear throughout its operating range; however the needle-to-deflector relationship results in a non-linear droop setting for the needles. When tested, a typical legacy governor can exhibit a droop response of the needles ranging from 50% (little to no response to speed changes) at low loads to less than 1% at high loads (excessive needle movement in response to speed changes). When operating at 1% droop, it is not uncommon to see ±10% needle movement and power generation due to very normal grid variations. Again this excessive movement can result in the premature wear of governor control linkages and associated equipment.

Some of the consequences of the fixed deflector/needle position relationship are:

- **The inability to realize the maximum efficiency of the turbine**: While impulse turbines are typically very efficient; their efficiency often drops off at lower load levels (see Figure 2). However, if operating multiple needle units with fewer needles some of the low end efficiency can be regained. On a unit operating evenly throughout its load range, total operating efficiency gains of up to 2% can be achieved. Unfortunately this is not easily accomplished with a legacy governor (refer to Stanislaus Powerhouse section below for more information).

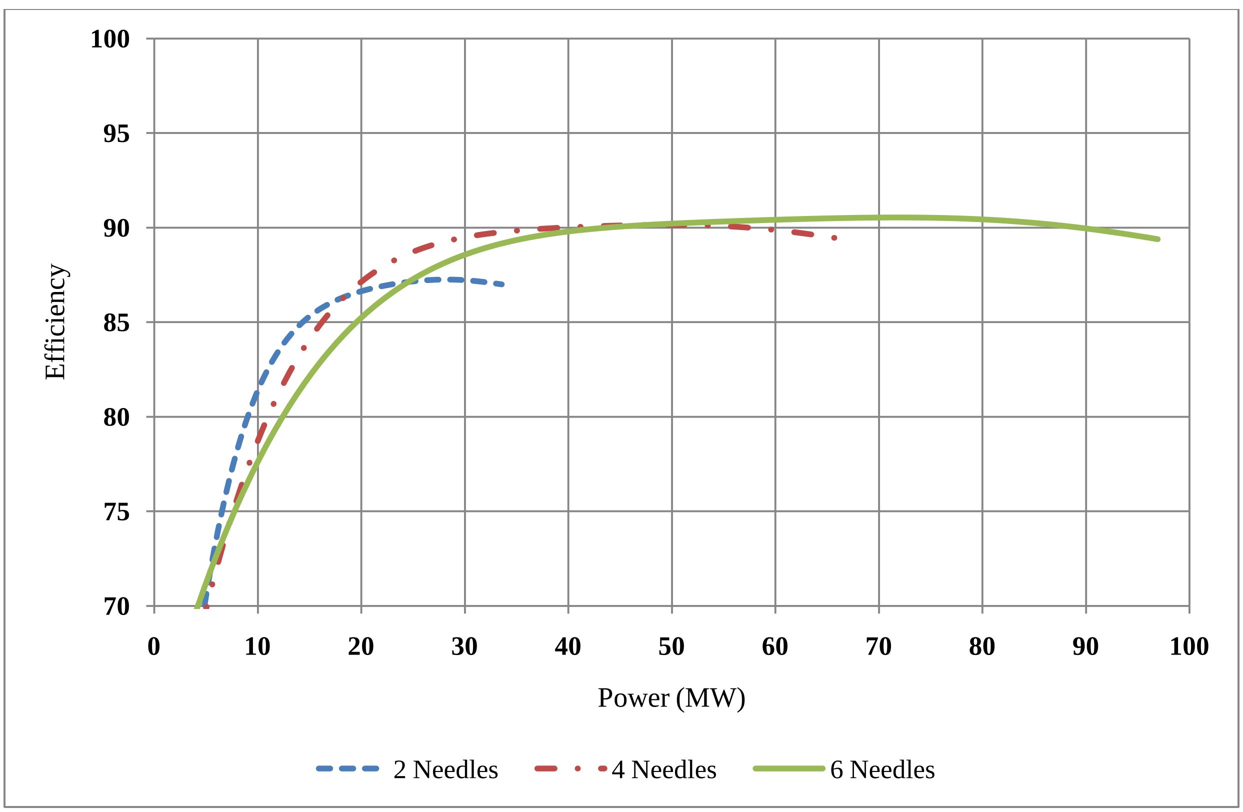

Figure 2 – Turbine Efficiency for 2, 4 and 6 Needle Operation at Stanislaus Powerhouse

- **The inability to hold an isolated load**: The needle/deflector cam will position the deflector in the water stream only while at zero load. Once loaded, the deflector moves out of the stream and governing action is primarily accomplished via needle movement (while the deflector may be able to divert water from the runner on a sudden frequency rise, there is no ability to pick up more load on a frequency drop). Because of the slow response time of needles, it is usually not possible to hold a local load of any significant size with an impulse turbine.

Stanislaus Powerhouse

The Stanislaus Powerhouse is a one unit facility on the Stanislaus River near Angels Camp, CA, owned and operated by Pacific Gas & Electric Company (PG&E). The station was commissioned on March 11, 1963 with an Allis-Chalmers six-needle Pelton wheel type impulse turbine and a General Electric generator. The turbine nameplate rating is 113,000 HP at 1,525 ft head and the generator nameplate rating is 91 MW, 91 MVA, 0.9 pf, at 13.8 KV. The governor controller originally installed was a Woodward Mechanical Cabinet Actuator for Multiple Nozzle Impulse Turbines, which would operate the single deflector servomotor and each of the six needle servomotors.

Figure 3 – Woodward Mechanical Governor - 6 Needle Impulse Turbine

Operating with a Mechanical Governor

Stanislaus Powerhouse is controlled via the California ISO, and is used for load following. For that reason, the generation setpoint for the unit is in constant flux. With the Woodward mechanical governor, the ISO would send a megawatt setpoint to PG&E's master station at their remote switching center. The master station would then send raise or lower pulses to the Stanislaus Powerhouse Remote Terminal Unit (RTU). The RTU output relays would subsequently energize to raise or lower the speed adjuster on the governor. The inherent sluggishness of the mechanical actuator system provided slow response to this constantly changing megawatt setpoint and in most cases would not reach the desired load before the setpoint would again change. This resulted in the governor almost constantly being in a state of change. Figure 4 shows the typical output variations seen at Stanislaus, which occur up to 100 times per day and often span the full operating range of the unit.

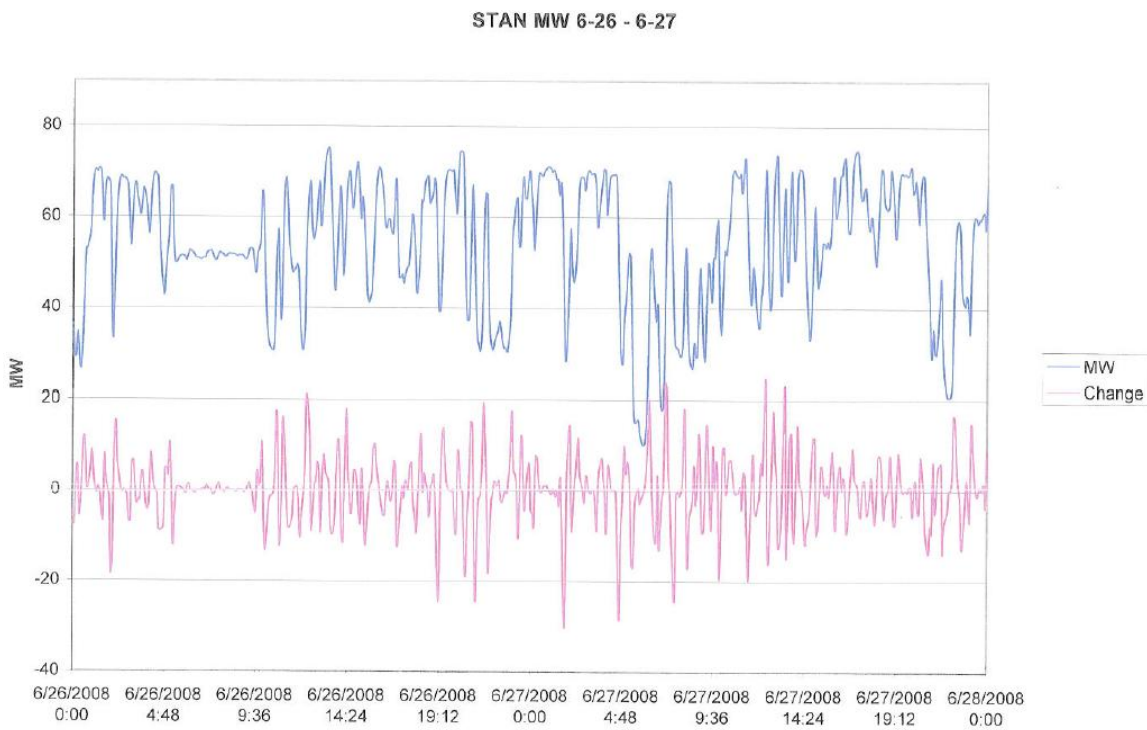

Figure 4 – Typical Output of Stanislaus Powerhouse - Two Day Period

Attempt at Needle Sequencing

The frequent operation of Stanislaus at low load levels makes it an ideal candidate for needle sequencing. Needle sequencing allows impulse turbines to be operated with a selection of their needles to maximize efficiency. Six needle turbines are typically operated with two, four or six needles in use, depending on load. The turbine efficiency would then follow the highest of the three curves seen in Figure 2. Because the efficiency gains are greatest at low loads and Stanislaus frequently operates in this range, the gains are estimated to be upwards of 2%.

Figure 5 – Needle Sequencing Controller

Around 1990 an attempt was made to add a piggy-back digital controller which would allow Stanislaus to operate with 2-4-6 needle sequencing. A Woodward 517 Digital Controller was installed. The system operated by manually forcing two or four of the needle controllers closed when required. To maintain constant load on the unit with fewer needles, the speed adjustment was moved to compensate for the addition or subtraction of the extra needles. In order for the California ISO to control load, pulses were sent to the controller which would then control the governor's speed adjuster.

Unfortunately the attempt was unsuccessful and the governor was ultimately restored to the original, mechanical state. The nature of the purely mechanical and hydraulic control made operating with needle sequencing unacceptable. With only the ability to turn needles on or off, transitions were harsh and resulted in significant output disruptions. The inherent slack still present in the mechanical linkages, levers, and restoring cables caused hysteresis in the speed adjustment versus megawatt relationship. As this difference increased the governor would begin to hunt between what the programmed curves in the controller indicated the speed adjustment should be and what was actually required to achieve the megawatt setpoint. The megawatt setpoint was conveyed to the digital controller via raise and lower pulses from the RTU. The controller would ramp the load up or down and only transition between needle pairs when the setpoint crossed the defined threshold. This resulted in excessively long load on and load off times when the load change requests were large. These three shortcomings led to the decision to abandon the piggy-back control system and restore the governor to its original configuration.

Decision to Replace the Mechanical Governor

The original mechanical governor configuration continued to operate satisfactorily and PG&E was able to maintain the equipment in good operating condition. However, the mechanical equipment has some inherent drawbacks (which were outlined earlier). The following list of common complaints by PG&E operations and maintenance personnel illustrate the type of difficulties they were having:

- Annual disassembly, cleaning, replacement of worn mechanical parts, and frequent readjustment of the governor resulted in high maintenance costs.
- The governor would quickly slip back out of calibration after being overhauled.

- While both paralleling and trying to achieve megawatt setpoint the governor would exhibit constant hunting. This hunting resulted in excessive time to parallel, which was often critical during a black start.
- RTU control relay and speed adjustment motor failures were frequent (often lasting just 12-18 months) due to the excessive adjustments. These failures resulted in a total loss of control by the ISO.

The lack of performance, frequent failures and high costs of maintaining the mechanical governor, in conjunction with the inability to operate the needles sequentially led PG&E to procure a PLC based Digital Governor in 2008/2009. The digital governor would replace all elements of the mechanical governor which were causing the previously listed flaws in the legacy equipment. Needle sequencing would be done directly, not through cams, cables and linkages. Modernization of the controls would also improve unit serviceability and reliability. The improved governor would enhance the ability of the Stanislaus Powerhouse to participate in grid restoration after local or large area grid power outage.

Solution provided by American Governor Company

In 2008 PG&E released a procurement specification for a Governor Digital Upgrade for biding by vendors. In early 2009 the project was awarded to American Governor Company. By November of 2009 the new equipment was installed, commissioned, recertified by the California ISO and released for service.

Governor Equipment

The scope of the project was to remove the control elements of the Woodward mechanical governor and replace these with modern components. The items removed included the flyballs, control column, needle/deflector cam, all links, levers and cables connecting the deflector to the needle control valves, as well as each pilot valve. Because the deflector and needle distributing valves were in good working order and modern components would not offer any performance improvements, they were retained.

Figure 6 – Digital Governor Controller

The Digital Governor Controller utilizes two Allen-Bradley Controllogix PLCs in a custom redundant configuration. Allen-Bradley's standard approach to redundancy allows for power supply and CPU duplication, but does not provide any backup for a failure of an I/O module. The approach taken by American Governor Company allows for full redundancy of the PLC, such that no single PLC component could cause failure of the entire governor system. This is made possible by use of an Ethernet/IP communication link between the processors, which transfers critical process information. A fault in the active PLC will result in a fully bump-less transfer to the backup controller.

To communicate with PG&E's master station each PLC is equipped with a ProSoft Technology DNP 3.0 Master/Slave Communications Interface Module. This allows for direct communication between the governor and PG&E's master station. The link is used both to transmit a load setpoint to the governor as well as to provide unit indication and governor status information (such as modes and alarms) back to the remote dispatching center.

In addition to redundant PLCs, redundant HMIs, power supplies and position feedback transducers on the deflector servomotors were utilized. No redundancy of the needle control equipment was included because the needles themselves are redundant (the unit can continue operating at a curtailed load level in the event of a failure of a single needle). The only single point of failure is in the deflector hydraulic controls. This was an accepted risk and could be mitigated through the addition of a redundant hydraulic control manifold stack.

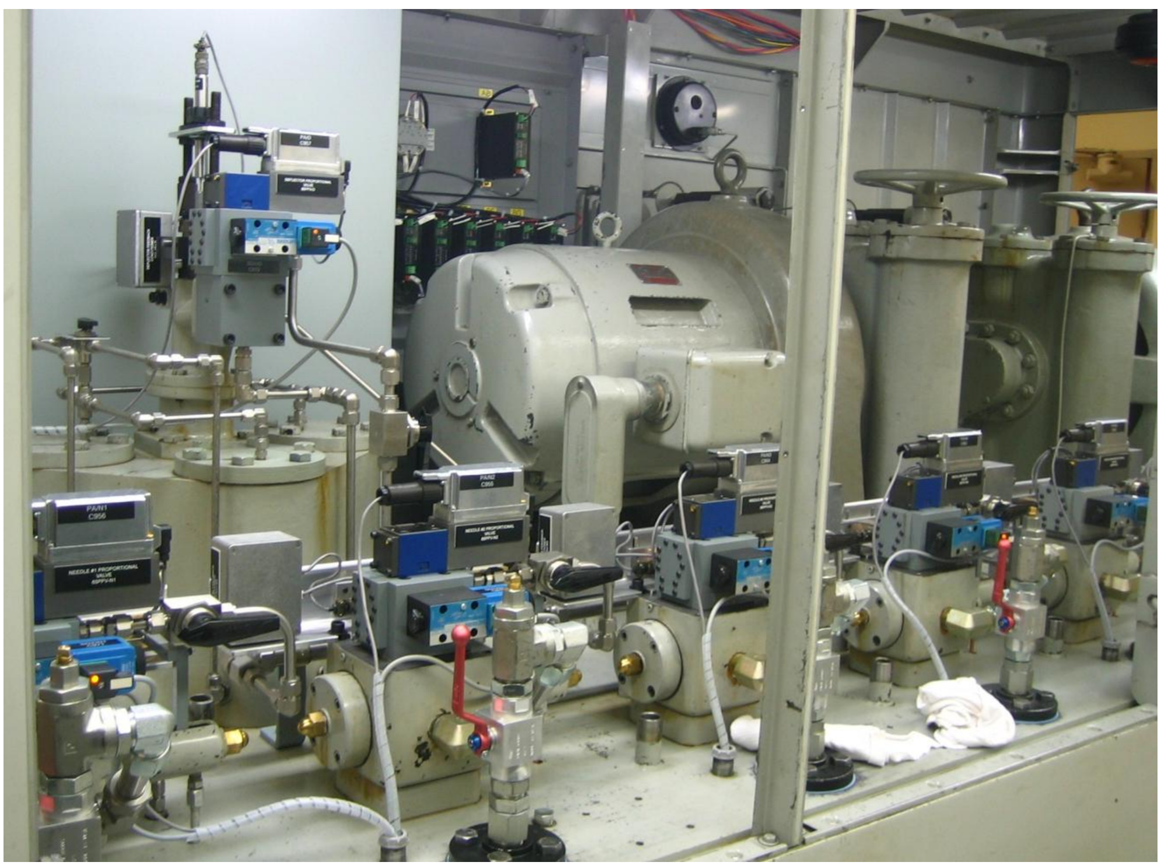

Figure 7 – New Deflector and (6) Needle Hydraulic Control Manifolds

The seven hydraulic control manifolds, also referred to as Electro-Hydraulic Interface (EHI) manifolds, seen in Figure 7, are designed to have redundant failsafe operation. Each manifold includes a highly precise Bosch proportional valve (which acts as a pilot valve to the existing distributing valves) and a standard directional spool valve (which acts as a shutdown solenoid). To position a servomotor the shutdown valve must be energized, which allows the proportional valve to control. The proportional valve itself is configured with a "fourth position" which acts to position the servomotor in the safe position (closed) in the event of a power loss. Therefore a loss of power or failure in either component will ensure a safe closure of the deflector or needle.

New Capabilities

While there is much to be gained through the installation of an advanced PLC based governor, it is the precise control achieved by the separate proportional valves which provides the most noticeable benefits of a digital governor conversion on multiple needle units. The ability to accurately position each servomotor (often to within 0.001") remedies all issues previously associated with poor needle control. Additionally, with the capability of controlling the deflector and each needle independently, new features and control schemes can be achieved.

Precise Load Control

To implement load following with the mechanical governor, PG&E utilized a PID control algorithm in their SCADA system. This control loop would compare actual megawatts to a setpoint received from the California ISO and send raise and lower pulses to the governor's speed adjustment motor as required. As seen in Figure 8, this control method can be classified as a cascade control system, because the outer loop (SCADA PID) controls power output while the inner loops consists of the unmodified speed governor. While cascaded control loops are common, this system tends to be overly sluggish to respond and prone to overshoots and hunting.

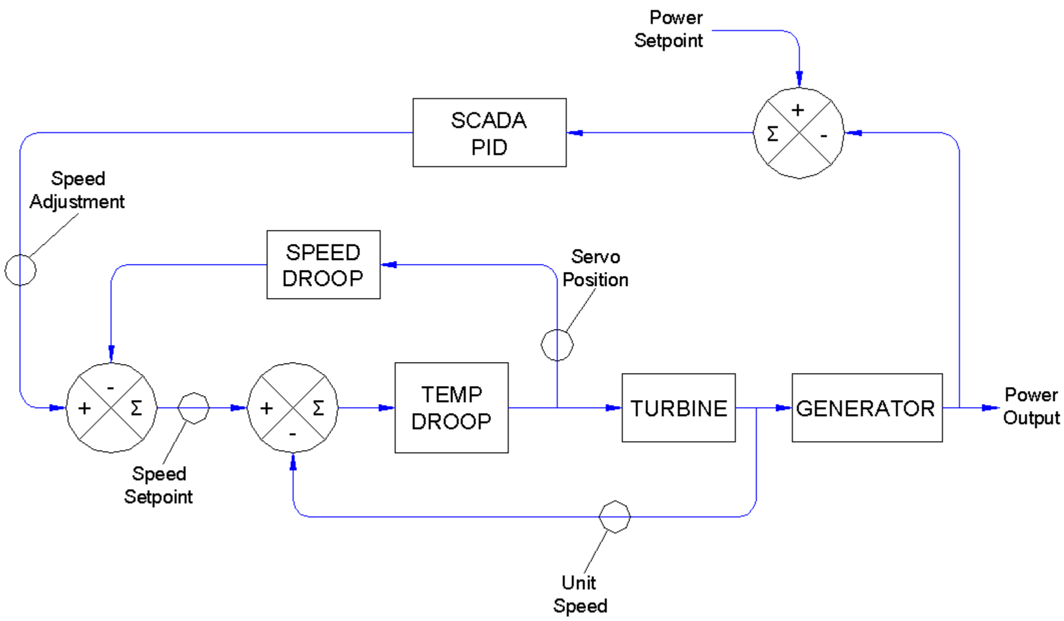

Figure 8 - Simplified Block Diagram of Load Control with SCADA PID Controller of a Mechanical Governor

This can be seen in Figure 9, which is a SCADA log of Generation Megawatts (green) vs ISO Setpoint (red) over a one hour period. The average delay to achieve setpoint can be measured at approximately 2 minutes, as can be seen at 17:15 and 17:55. Overshooting of the setpoint is witnessed at 17:27 and appears to be most significant after frequent setpoint changes. This is most likely due to incomplete reset of the dashpot at the time of setpoint change. Additionally, noticeable hunting of several megawatts can be witnessed between 17:40 and 17:50 during a period of no setpoint change.

The cause of this poor performance lies in three areas. First, mechanical governors do not have the ability to both load quickly and provide stable servomotor control. This is due to the nature of the dashpot which is either stable in the normal state or quick to respond when in the bypass state. Secondly, the significant physical backlash present in the mechanical actuator system as well as the aggressive needle/deflector relationship results in sluggish and inconsistent needle control. Finally, the outer loop controller (SCADA PID) is subject to all inherent delays of the needle servomotor timing and water starting time. With long lags invariably comes either slow response or instability.

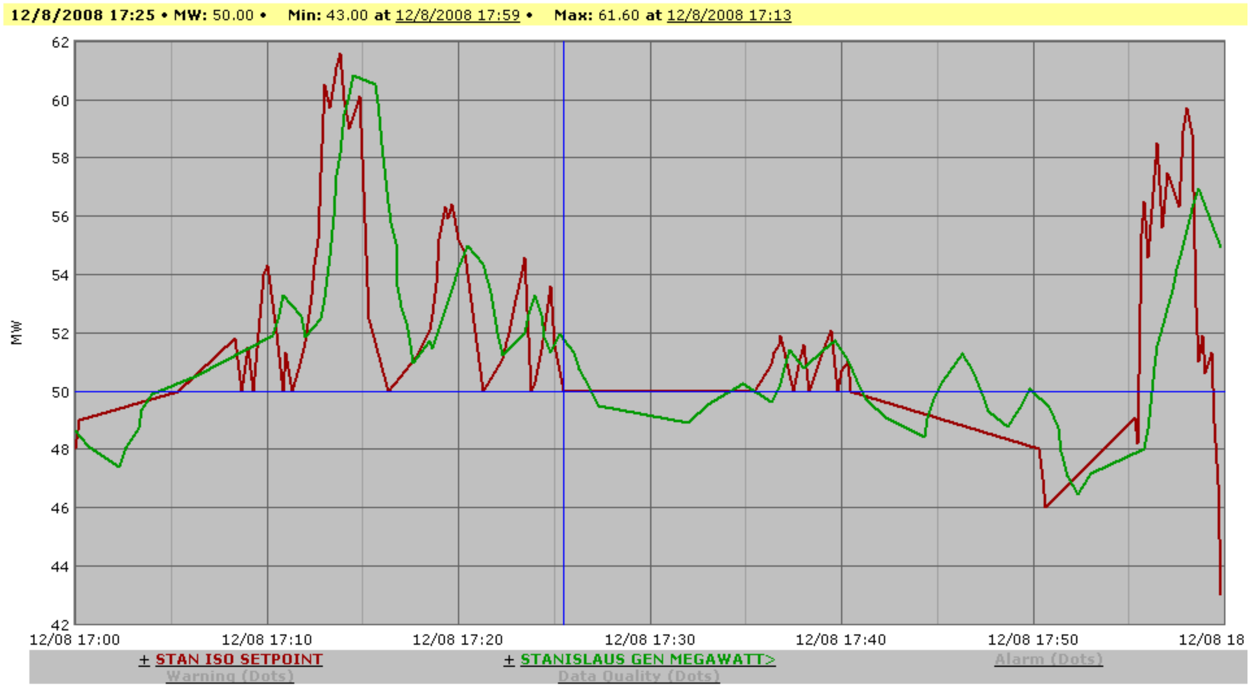

Figure 9 - Load Control at Stanislaus - Mechanical Governor - 1 Hour Window

At the heart of the new digital governor is a standard PID controller. The control algorithm employed is speed regulation (also referred to as speed droop with megawatt feedback) and is consistent with loops seen in IEEE Std 1207. Megawatt Feed Forward is included and is the critical feature which allows for smooth and rapid loading without any overshoot or hunting. In contrast to a dashpot bypass, which is essentially just a change in controller gains, feed forward allows quick, manual movements to be made without compromising unit stability. Figure 10 depicts a simplified block diagram of the control algorithm used.

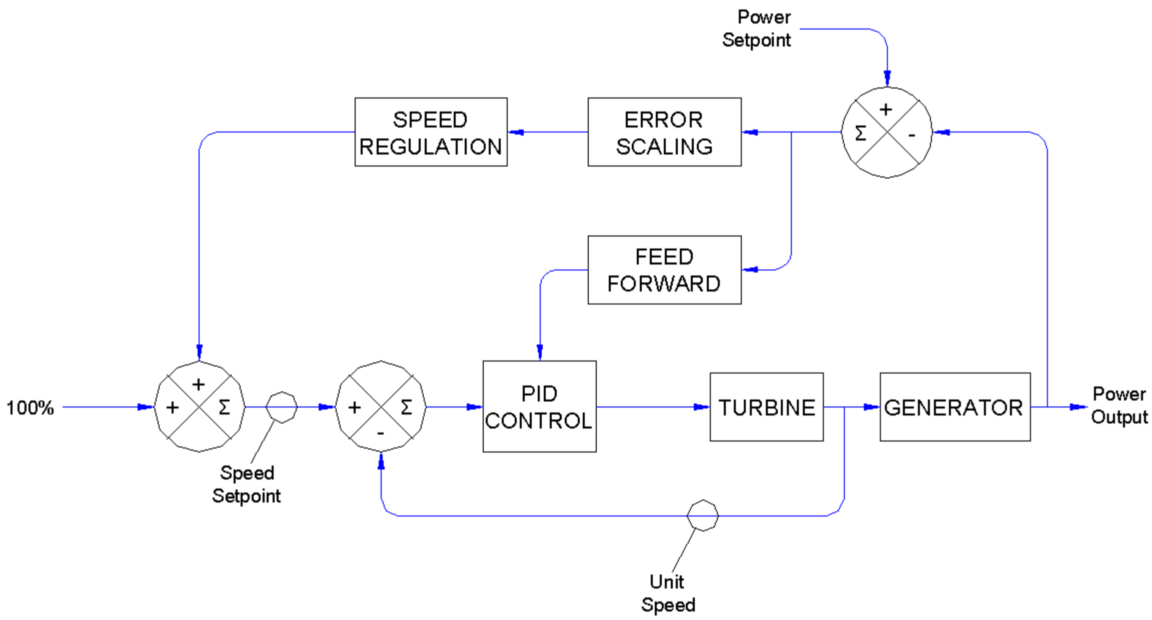

Figure 10 - Simplified Block Diagram of Load Control with Speed Regulation and PID Digital Governor

Figure 11 shows another SCADA log after the digital governor had been commissioned. The delay to reach the megawatt setpoint has been greatly reduced and is now consistent with the programmed ramp rates: 28 mw/min to pick up load and 16.5 mw/min to shed load. (It should be noted that while it appears that there remains an offset between the setpoint and actual megawatts, the setpoint is changing quicker than the unit can physically react. The megawatts are in fact tracking setpoint changes as they occur.) It is also apparent that there is little overshoot

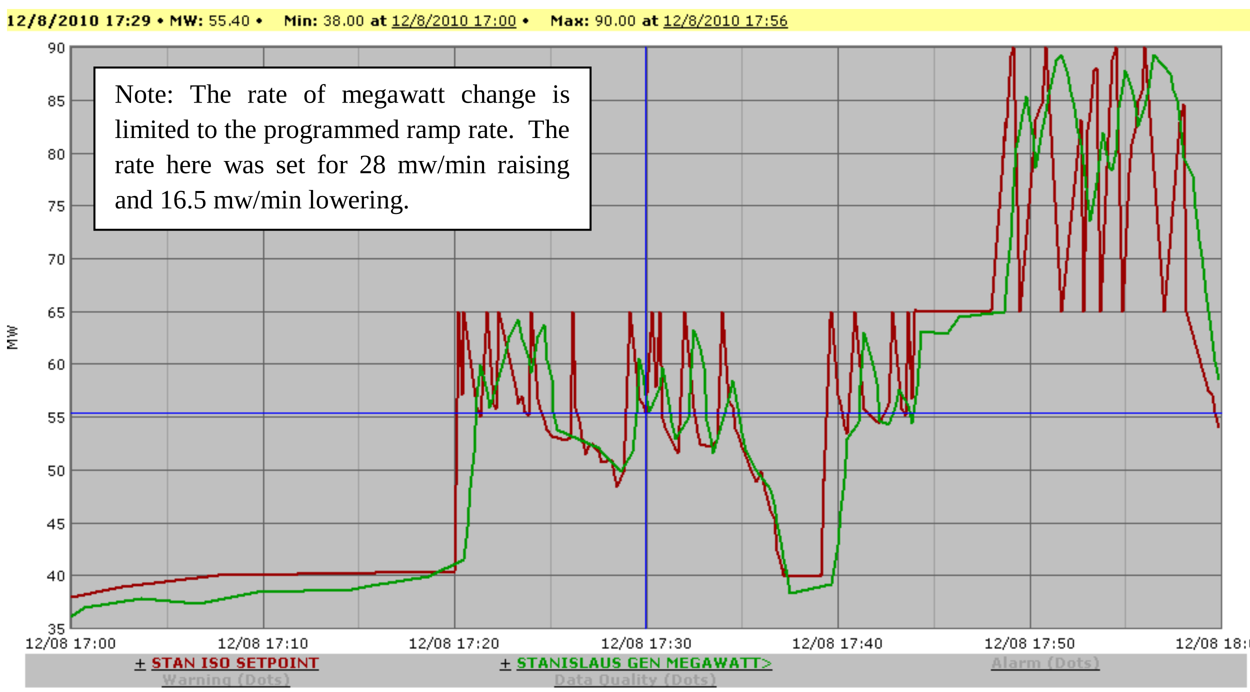

Figure 11 - Load Control at Stanislaus - Digital Governor - 1 Hour Window

and no hunting present during periods of stable demand. This can be attributed to the direct communication of Cal ISO's load demand between the PG&E master station and the governor as well as the use of the feed forward circuit.

Needle Sequencing

Successful needle sequencing depends on a seamless transition between needle pairs which is transparent to both operations and maintenance personnel. This means that power output should not be disturbed during a transition and that undue wear should not be put onto the needles or the needle distributing valves.

The sequencing algorithm developed by American Governor meets both of these requirements. The key to achieving this is through fully independent control of each needle. The governor PID control output is a single needle setpoint. This setpoint is then handled by the needle sequencing algorithm which controls which needles are used and at what rate needle pairs open or close to transition on or off. By transitioning needles at the proper rate, total flow through the needles matches what is required by the PID, regardless of what state of transition the needles are in.

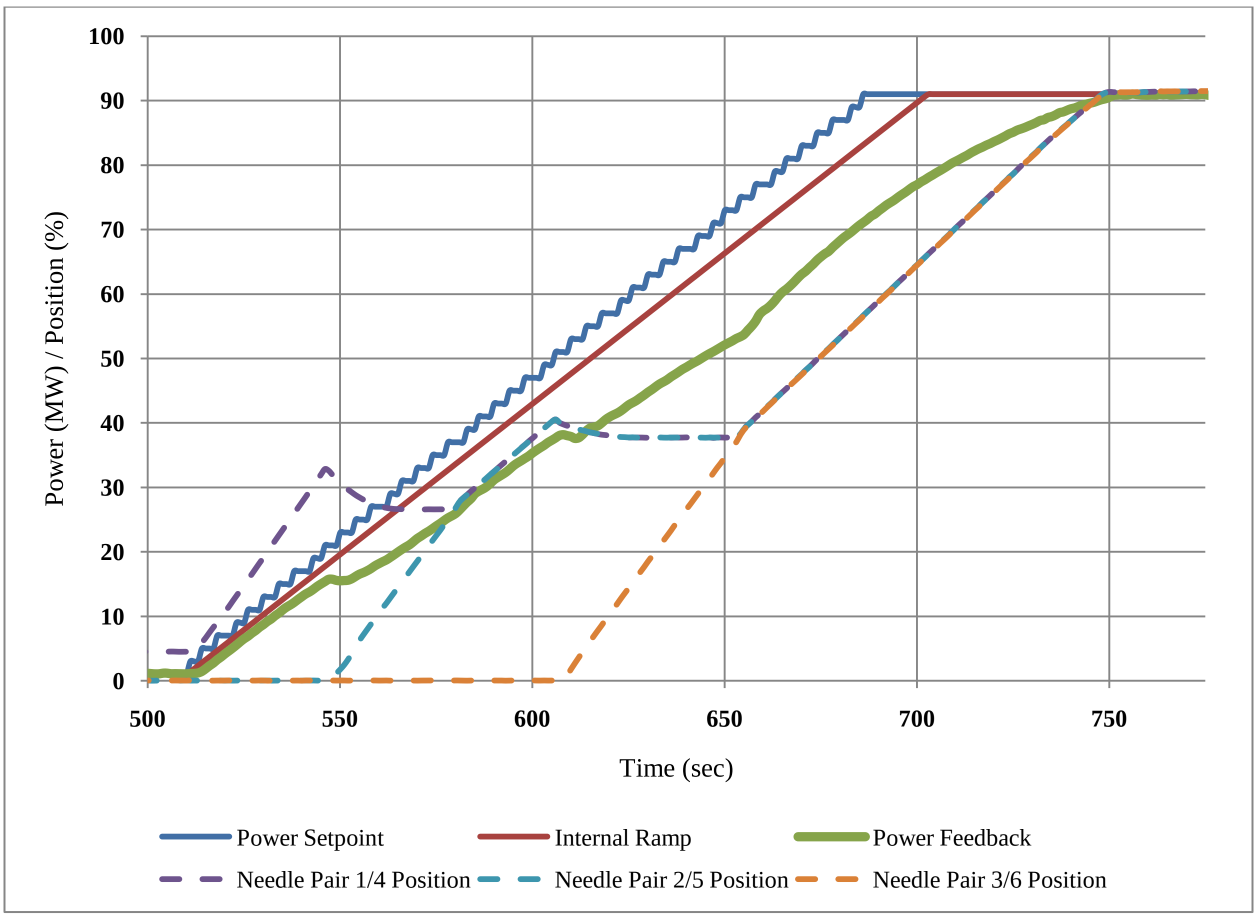

Figure 12 - Needle Sequencing at Stanislaus - Load On Ramp

The trend in Figure 12 was recorded during a California ISO recertification load on test. The power setpoint (blue solid line) was ramped up from no load to full load in just less than three minutes. An internal ramp (red solid line) ensures that load changes happen at the defined and certified ramp rates. The actual power output (green solid line) follows the ramp and cleanly trims into the setpoint. Each of the three needle pairs (dashed lines) can be seen to ramp open until a transition is required, at which point the next pair opens and the needle pairs match. During a transition the open pair(s) of needles either closes or holds in place, as required, to maintain a smooth ramp in power output.

By implementing this control scheme the overall operating efficiency has been increased by up to 2% with gains greater than 3% in the lower power ranges. This can be seen in Figure 13.

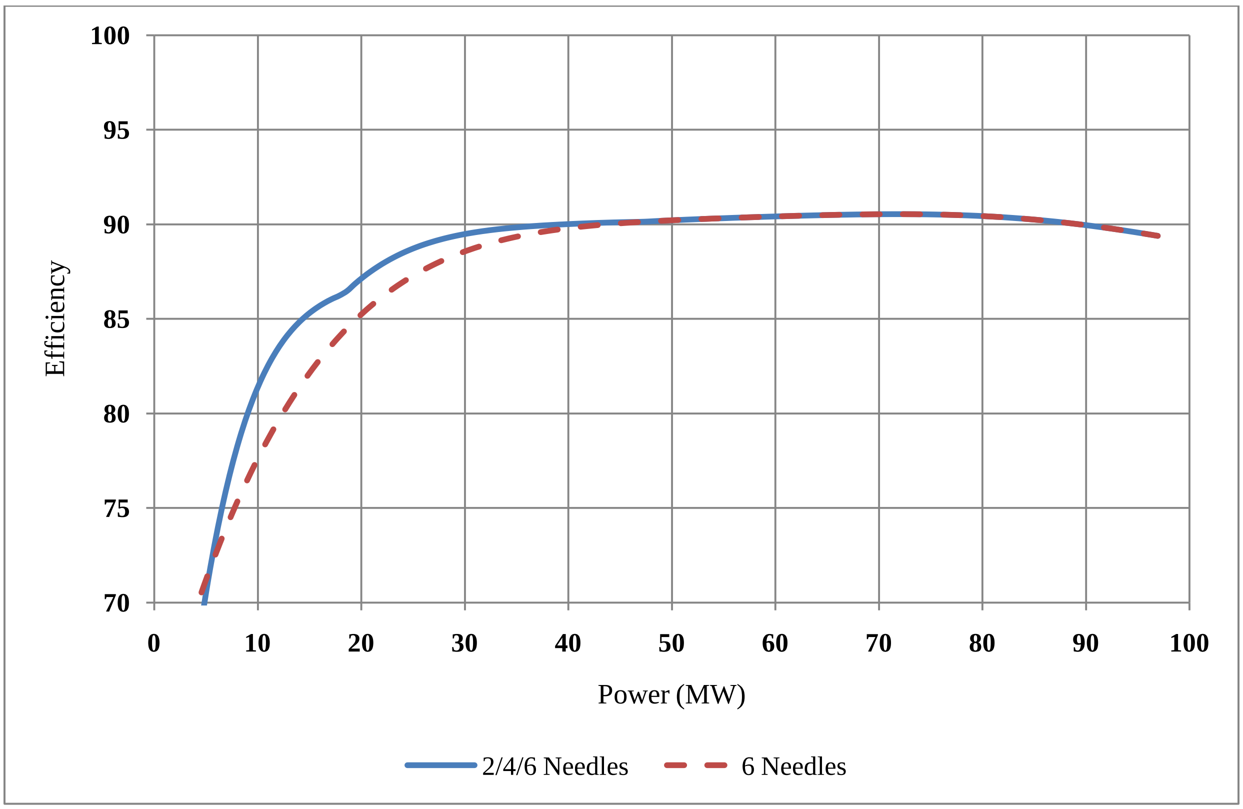

Figure 13 - Turbine Efficiency at Stanislaus - Needle Sequencing On vs. Off

Isolated Loads (Water Wasting Mode)

An additional benefit offered by the digital governor is the ability to hold isolated loads in a Water Wasting Mode. Under normal operating conditions, the deflector is out of the water stream and all governing action is achieved with the needles. This is adequate for power control on a stable grid, but would not work for speed control of an isolated load. The needles are simply not fast enough to respond to sudden load changes.

With the digital governor, the needles can be biased open further than required to hold line frequency at 60Hz. The deflectors would then enter the streams and modulate water flow onto the turbine to control frequency. This is where the term water wasting comes from, more water than is required to hold frequency is passed through the needles in order for the deflectors to both remove and add power to the turbine.

At Stanislaus this is used to hold 12 MW of local load in the event that all three high voltage lines are lost. It would be possible to hold any load up the generator rating with this control scheme.

Other Benefits

As with most digital conversions, other benefits were realized. Maintenance costs have dropped significantly due to the removal of the numerous mechanical control elements and the governor no longer requiring annual recalibration. As an added bonus, with the removal of mechanical pilot valves oil leaks have been virtually eliminated. If future expansion of the governor's capabilities or operating modes is required, the customizable nature of the PLC makes this a low cost addition. Further reading of the benefits (and consequences) of digital governor conversions can be found in the paper: *Overhaul or Upgrade: Governor Decision Factors* by Roger Clark-Johnson and Scott Ginesin at www.americangovernor.com.

Author Biographies

Matthew Roberts

Graduated BSME, George Washington University in 2006. He started with American Governor first in 2004 as an intern then full time after graduation. He is currently a Project Manager and Engineering Manager for their Pennsylvania office.

Mark Nunnelley

Graduated BSEE, CSU Sacramento in 1984. He started with PG&E after graduation as a Hydro Engineer and spent 6 years engineering Governor Systems, Voltage Regulators, and other generator protective and control schemes. Received his PE in 1987. In 1990 he accepted a position as a Maintenance Supervisor responsible for four hydro generators with a combined output of 100MW and the Supervisory Control and water data collection system over three watersheds.