WOODWARD

Application Note 51557
(Revision NEW, 8/2016)
Original Instructions

Effect of Speed Control and Actuator Dynamics on Steam Turbine Response

WARNING

The engine, turbine, or other type of prime mover should be equipped with an overspeed shutdown device to protect against runaway or damage to the prime mover with possible personal injury, loss of life, or property damage.

The overspeed shutdown device must be totally independent of the prime mover control system. An overtemperature or overpressure shutdown device may also be needed for safety, as appropriate.

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Illustrations and Tables

Chapter 1.
General Information

Executive Summary

Many people are aware that the responsiveness of the speed control and actuation systems effects the dynamic performance of the steam turbine system as a whole. They do not know if the differences between different controls or actuation systems are significant in terms of the performance of the turbine. Limited documentation exists to help quantify the effects of the control and actuation system performance, on the performance of the turbine.

The analysis in this application note uses turbine overspeed during a load rejection event as an important and measurable performance parameter, to help compare and quantify the effects of different levels of control and actuation system dynamic performance.

The results in this paper demonstrate that as expected, slower speed control recursion rates and longer speed control dead times result in higher speeds for the steam turbine during a load rejection event. Slower actuation system response also results in higher turbine speeds. Higher turbine speeds are a concern as they result in stress on the steam turbine, which results in reduced life of the turbine. In addition, handling a full load rejection without an overspeed trip is typically a turbine performance goal. If a turbine can respond to a full load rejection without tripping on overspeed, it can stay on line and aid grid stability or provide power in island mode.

As shown in the simulation results in this application note, a control with minimal deadtime and synchronous I/O, such as a Woodward MicroNet or 505 provides the best system response. Similarly, a modern actuator such as the VariStroke 1, with a higher bandwidth and faster slew times, also provides the best system response. A control with a slow recursion rate, such as 40 mS, or with asynchronous I/O such as a PLC, or a system with a slow actuator such as a relay valve provide the worst system response.

The simulations in this analysis showed that even for a slow turbine, a Woodward control with a VariStroke actuation system resulted in the best turbine control, with an overspeed of 5% above rated speed on a 100% load rejection. A PLC type control with a Woodward CPC and third party relay valve, demonstrated an overspeed of 22% above rated speed. Faster turbines would experience more overspeed.

Introduction

The load rejection analysis for this Application Note used simulations in MatLab® and Simulink®. The models used in these simulations represented the dynamics of typical system components and are discussed further in the sections below. The detail in the turbine models was minimized where possible, as unnecessary detail can result in simulation results that are more difficult to interpret across a variety of turbine systems. A turbine model that is detailed and specific for a specific turbine does not necessarily represent a range or turbines.

The responses shown in Figures 3-1 through 3-6 were the result of general dynamic principals, and the relative responses for each system would be consistent for a wide variety of turbine systems.

In installations with turbines with faster acceleration than that used in these simulations, all of the maximum overspeed numbers for each control and actuation system would be higher. All of the graphs shown in this analysis would shift upward. Similarly, for a turbine with a steam chest with a long time constant, all of the maximum overspeed numbers would also shift upward. In general, turbines with longer delays or faster acceleration would require controls and actuation systems with higher bandwidth to prevent an overspeed trip during a load rejection.

These simulations demonstrated that the performance of any steam turbine would improve with a control that has a faster recursion rate and less deadtime, and will also improve with an actuator with higher bandwidth and faster slew times. As there are tradeoffs in system design, such as cost, complexity, and noise immunity, there are limits to the amount of performance gain that can be achieved in a given system. As with all technologies, actuator and control performance typically improve over time with innovations. Performance that was not available or was prohibitively expensive even 5 years ago is often available now.

Chapter 2.
Model Details

System Level Model

The control and actuation models used for these simulations were transfer function models, as shown in the Turbine Model section below. The scaling in all of the models as shown in Figures 2-1, 2-2, and 2-3 are normalized, with "1" corresponding to full load or 100% actuator, and "0" corresponding to turbine stopped or 0% actuator. The entire system in the simulation was composed of a control, an actuation system, and a turbine.

The six simulation combinations were as follows:

- A Woodward type of control with an EHPC (Electro Hydraulic Power Cylinder actuator)
- A Woodward type of control with a hydraulic amplifier (This is a hydraulic actuator)
- A Woodward type of control with a VS1 (VariStroke-I hydraulic actuator)
- A PLC or process type of control with a VS1 (VariStroke-I hydraulic actuator)
- A Woodward type of control with a CPC (Current to Pressure Converter) and relay valve
- A PLC or process type of control with a CPC (Current to Pressure Converter) and relay valve

Figure 2-1 below shows a drawing of the system models.

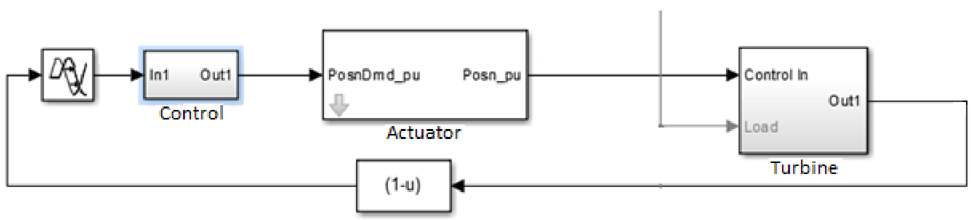

Figure 2-1. Example System Model

The far left block simulates the control sampling, it outputs the turbine speed to the next block to the right entitled "Control", which simulates the speed control. The speed control outputs the actuator demand to the next block entitled "Actuator", which simulates the actuator. The actuator outputs the amount of steam to the far right block entitled "Turbine", which simulates the turbine. The turbine speed is output from the turbine block on the right, back to the sampling block on the left, to close the loop. The block with (1-u) at the bottom of the diagram is scaling, for initial conditions. Again, the scaling of each of the signals is normalized between zero and one.

Turbine Model

The turbine model for all of the simulations was the same, and was comprised of an integrator with an acceleration rate of 25% per second for the first set of simulations, and 50% per second for the second set of simulations. This was a reasonable approximation, as gas turbines accelerate at around 20% per second, as do some of the slower steam turbines. A few accelerate as slowly as 10% per second, and the occasional steam turbine accelerates as quickly as 80%/second. A turbine with a slower acceleration would have a lower maximum overspeed on a load rejection, and a turbine with a faster acceleration would have a higher overspeed on a load rejection, if everything in the system scaled linearly.

The turbine model did not include a time constant for the steam chest, to account for turbines with an oversized steam chest or with a significant steam chest delay. With significant steam chest delay, all of the overspeed results would be higher, and the control and actuation performance would be more critical.

To reiterate, additional delays in the turbine model or a turbine with a faster acceleration would make ALL of the overspeed amounts higher in the simulation cases presented here, but the relative effects of the control and actuation system performance would remain consistent.

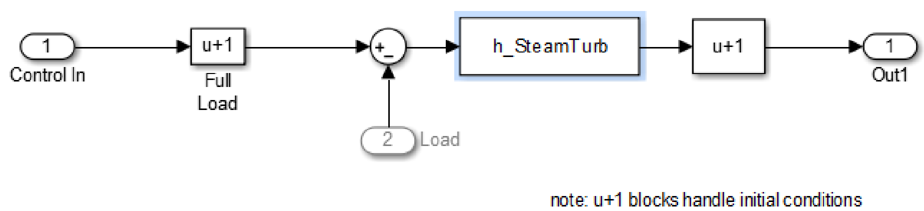

Figure 2-2. Turbine Model

For the simulation results in Chapter 3, the time constants for the steam turbine were:

- Acceleration = 0.25,0.5
- h_SteamTurb = Accel/s;

The u + 1 blocks are included in the model to manage the model initial conditions for each of the simulation cases. These blocks have no effect on the simulation dynamics.

Here are three turbine examples, to help put 25%/second and 50%/second acceleration into perspective. These examples are also referenced in various papers and literature for the ProTech overspeed devices.

- A 22MW turbine with a Rotor Inertia of 17882 lb-ft^2 (753 kg-m^2), would have an acceleration in the neighborhood of 20%/second.
- A 224MW turbine with a Rotor Inertia of 308000 lb-ft^2 (12979 kg-m^2), would have an acceleration in the neighborhood of 12%/second, neglecting the effects of reheat line delays.
- A 5.2 MW turbine with a Rotor Inertia of 1836 lb-ft^2 (77.4 kg-m^2), would have an acceleration in the neighborhood of 47.5%/second.

Control System Model

The control system algorithm used in these simulations was a simple PI control, modeled using a transfer function. A PI control is an old but very widely used control architecture, and represents the majority of the controls in the steam turbine industry.

For the first set of simulations, the recursion rate (or “rate group”) of the MicroNet and 505 type controls is nominally 5 mS and the recursion rate of the PLC type control is nominally 40 mS. For the second and third set of simulations, several recursion rates are simulated for each control architecture, including 5 mS, 10 mS, 20 mS, 40 mS, and 60 mS.

For consistency across the results, the PI control for each of these simulations was individually automatically tuned for 40 degrees of phase margin. This allowed for good response, while maintaining margin to allow for system variation due to wear, temperature, etc. Although a phase margin of 40 degrees is a typical design constraint, many controls in actual use are tuned for more than 40 degrees of phase margin, which would result in higher overspeeds for all of the simulation cases presented here.

The turbine control was comprised of three transfer functions, a dead time for the speed signal, the speed signal filtering, and a speed PI control.

- Speed signal dead time – The speed signal deadtime is due to the sampling of the speed signal, by the control. Two different controls were simulated, a synchronous low dead time control such as a Woodward MicroNet or 505 control, and a PLC or process type of control with asynchronous I/O.
    - The Woodward type control was simulated with Woodward control specifications, including synchronous I/O with low deadtime. This resulted in an average system deadtime of 1.5 times the recursion rate. This can be calculated as the sum of one recursion rate due to the execution time, and 0.5 recursion rates due to the average sampling deadtime.
    - The PLC or process control deadtime was simulated with a deadtime of 1.5 times the recursion rate plus 17.5 mS. 1.5 times the recursion rate is again the sum of 1 recursion rate for execution time, and half of the recursion rate due to the average sampling deadtime. The 17.5 mS is assumed to be deadtime due to asynchronous I/O handling. This time could be longer in some systems, making the simulation results worse for this control architecture than presented in this analysis.

- Speed Signal Filtering – The speed signal in both the Woodward control and the PLC or process control solutions was assumed to have a second order filter, with two 5 mS poles. This was optimistic for a PLC or process type control, as most controls, which are not dedicated turbine controls, will have more filtering than this to compensate for lower sampling speeds, resulting in a higher overspeed after a load rejection. Controls with less filtering typically have noise and aliasing issues, particularly for speed sensor inputs.

- Speed PI control – The speed control was modeled by the transfer function:

$$h_{PID} = P/(1 - \frac{1}{\frac{s}{I}+1})$$

  This is a standard parallel PI control.

Five speed control recursion rates were simulated, 5 mS, 10 mS, 20 mS, 40 mS, and 60 mS.

If further performance improvements were desired, the control could be configured with a different control architecture, as a PID or with a feed forward architecture. Another option for load rejections with a breaker opening would be to configure the control with logic that closes the control valve for a certain amount of time, with various permissives, upon detection of a breaker opening. The standard 505 series of controls contains logic like this. This could help overcome PI control and recursion rate limitations, at which point control dead times and actuation system delays would be the limiting factors for system performance.

Actuation System Model

The models used in these simulations were simple second order models, with time constants and slew rates based on Woodward test data.

- Woodward EHPC - The EHPC actuator is significantly slew rate limited, so even though the small signal bandwidth would support higher control gains, the control architecture of a PI control requires lower gains for stability with large transients. The model parameters for the EHPC were:
    - 2 Hz bandwidth
    - 615 mS slew time
- Woodward Hydraulic Amplifier – The model parameters for the hydraulic amplifier were:
    - 0.82 Hz bandwidth
    - 400 mS slew time
- VariStroke 1 – The VariStroke 1 is the latest steam turbine actuator. The model parameters were:
    - 4.5 Hz bandwidth
    - 300 mS slew time
- CPC driving a Relay valve – The dynamics of this configuration were dominated by the relay valve, not the CPC. The model parameters were:
    - 0.6 Hz bandwidth
    - 455 mS slew time.

Note: The relay valve dynamics can and typically do dominate the dynamics of the entire actuation system. As an example, a VariStroke 1 with a relay valve will perform worse, in many cases much worse, than a VariStroke 1 alone, or a VariStroke 2.

A diagram of the actuator model is shown below in Figure 2-3.

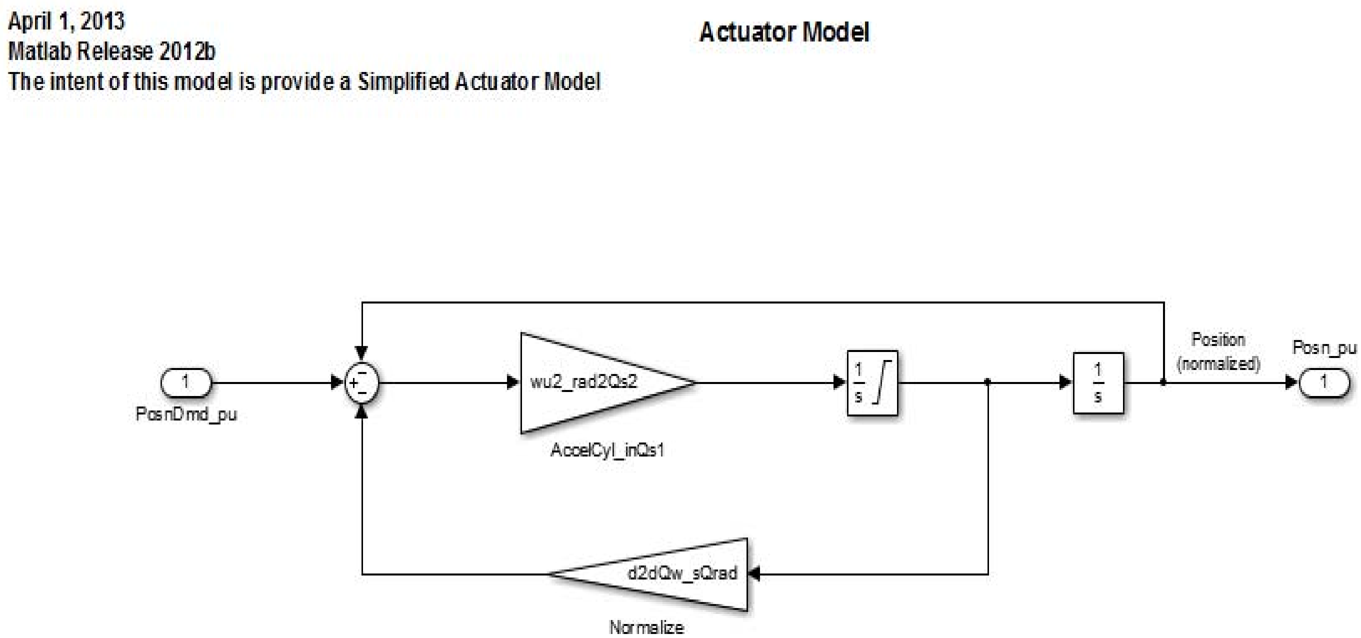

Figure 2-3. Actuation System Model

Note that the actuators are all modeled as second order models with slew rate limiting. The bandwidths and slew times for each actuator are given in the previous section.

Chapter 3.
Simulation Results

Results – Slow Turbine

Figures 3–1 through 3–3 show some load rejection simulation results for a turbine with a 25%/second acceleration rate. In each figure, the response lines are color-coded as follows:

- **Dark Blue** – Woodward speed Control, EHPC actuation system
- **Pink** – Woodward speed Control, Hydraulic amplifier actuation system
- **Red** – Woodward speed Control, VariStroke 1 actuation system
- **Green** – PLC or Process speed Control, VariStroke 1 actuation system
- **Light Blue** – Woodward speed Control, CPC with relay valve actuation system
- **Black** - PLC or Process speed Control, CPC with relay valve actuation system

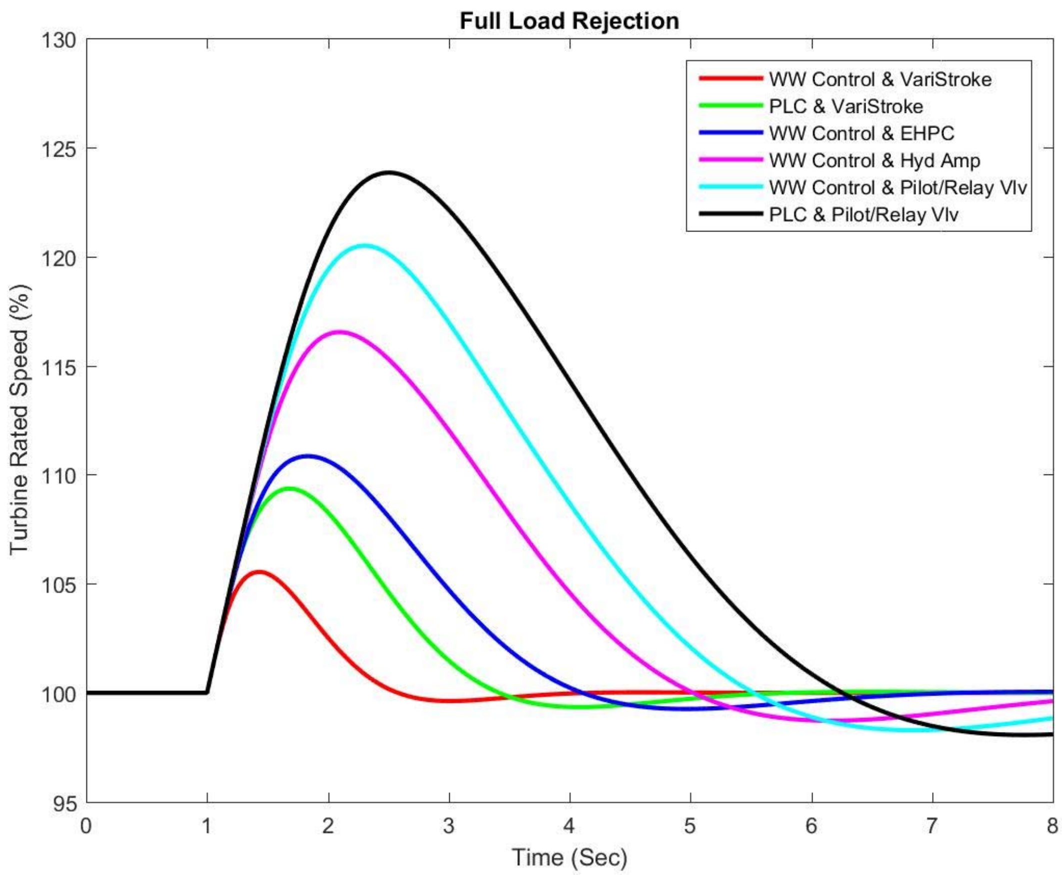

Figure 3-1. Slow Turbine - Full Load Rejection Summary

The responses in Figures 3-2 and 3-3 include multiple recursion rates, which result in multiple lines of the same color in each figure.

The line with the highest overspeed peak corresponds to the control system with the slowest recursion rate, the 60 mS recursion rate. Conversely, the line with the lowest overspeed peak corresponds to the control system with the fastest recursion rate, the 5 mS recursion rate.

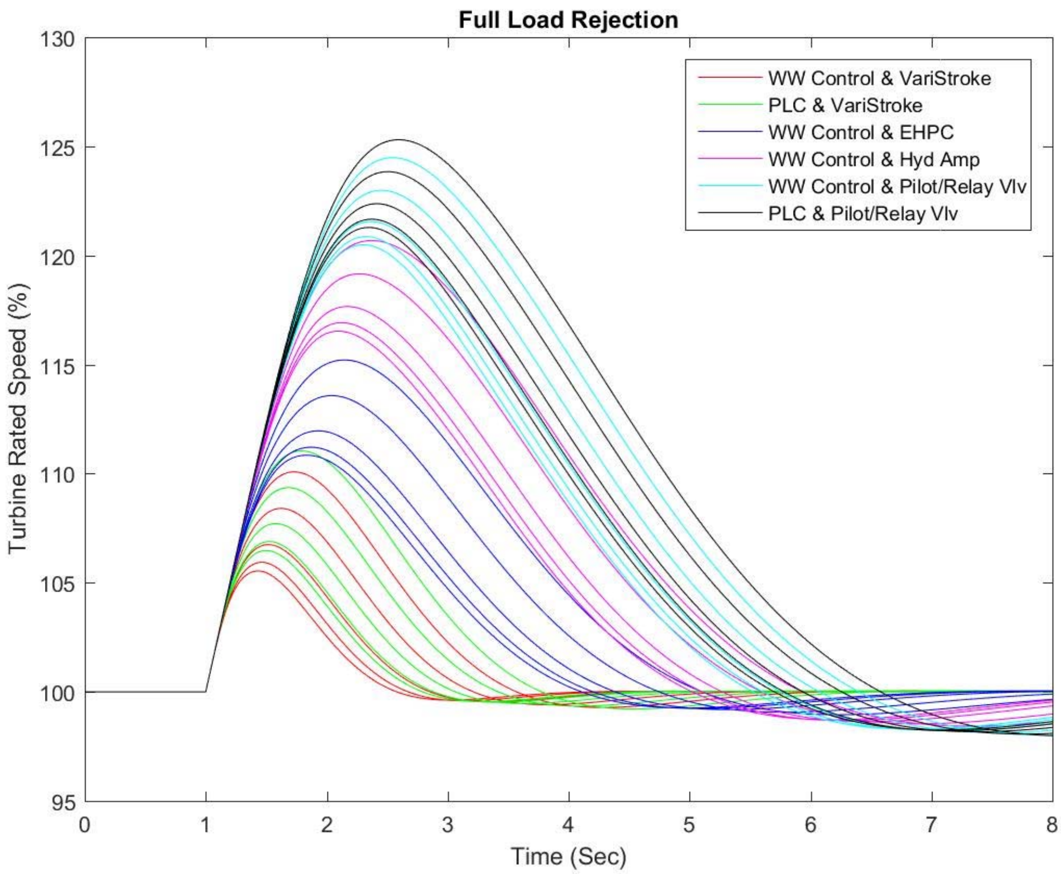

Figure 3-2. Slow Turbine - Full Load Rejection, Multiple Recursion Rates

The recursion rates included in this simulation were:

- 5 mS
- 10 mS
- 20 mS
- 40 mS
- 60 mS

The best response is denoted by the red traces in Figure 3-2, which correspond to the VariStroke with the Woodward control. The systems with the VariStroke actuator are the only systems with overspeeds of less than 110% of rated speed, which is typically the overspeed trip limit. The Woodward control with the EHPC and hydraulic amplifier, are the dark blue and pink lines, respectively. The worst responses are shown in light blue and black, and are the systems with the relay valves.

In addition to the 100% load rejection simulations, 75% load rejections were also simulated, as shown in Figure 3-3.

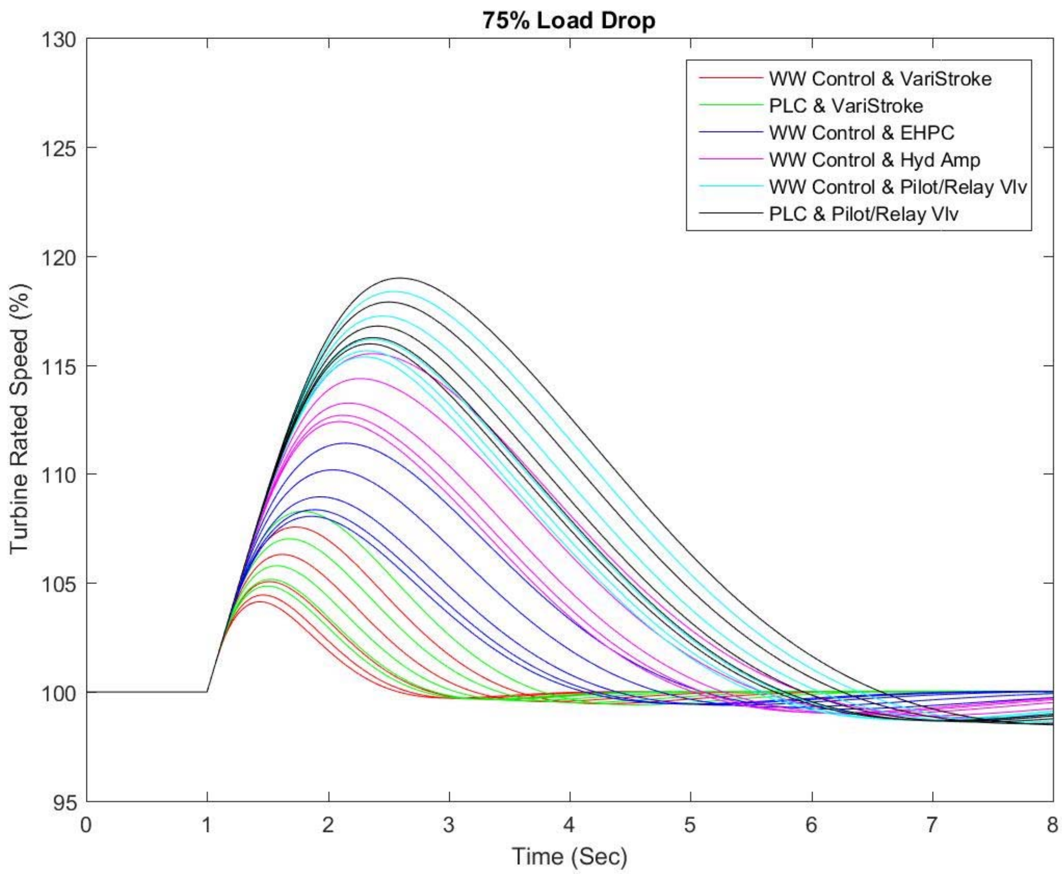

Figure 3-3. Slow Turbine - 75% Load Rejection, Multiple Recursion Rates

The results shown in Figures 3-1 through 3-3 demonstrate that for optimum dynamic turbine performance, both the turbine control, and the actuation system are critical.

Again, the multiple lines for each color represent the recursion rates, slower recursion rates result in more speed overshoot on a load rejection. The recursion rates shown in Figure 3-3 are 5 mS, 10 mS, 20 mS, 40 mS, and 60 mS. The amount of overspeed increased as the recursion rate increased. As an example, the red trace with the lowest maximum speed is the 5 mS system, the next highest is the 10 mS system, and so forth. The red trace with the highest maximum speed is the 60 mS system.

Results – Fast Turbine

Figures 3–4 through 3–6 show the load rejection simulation results for a turbine with a 50%/second acceleration rate. In each figure, the response lines have the same color legends as the previous results in Figures 3-1 through 3-3.:

- **Dark Blue** – Woodward speed Control, EHPC actuation system
- **Pink** – Woodward speed Control, Hydraulic amplifier actuation system
- **Red** – Woodward speed Control, VariStroke 1 actuation system
- **Green** – PLC or Process speed Control, VariStroke 1 actuation system
- **Light Blue** – Woodward speed Control, CPC with relay valve actuation system
- **Black** - PLC or Process speed Control, CPC with relay valve actuation system

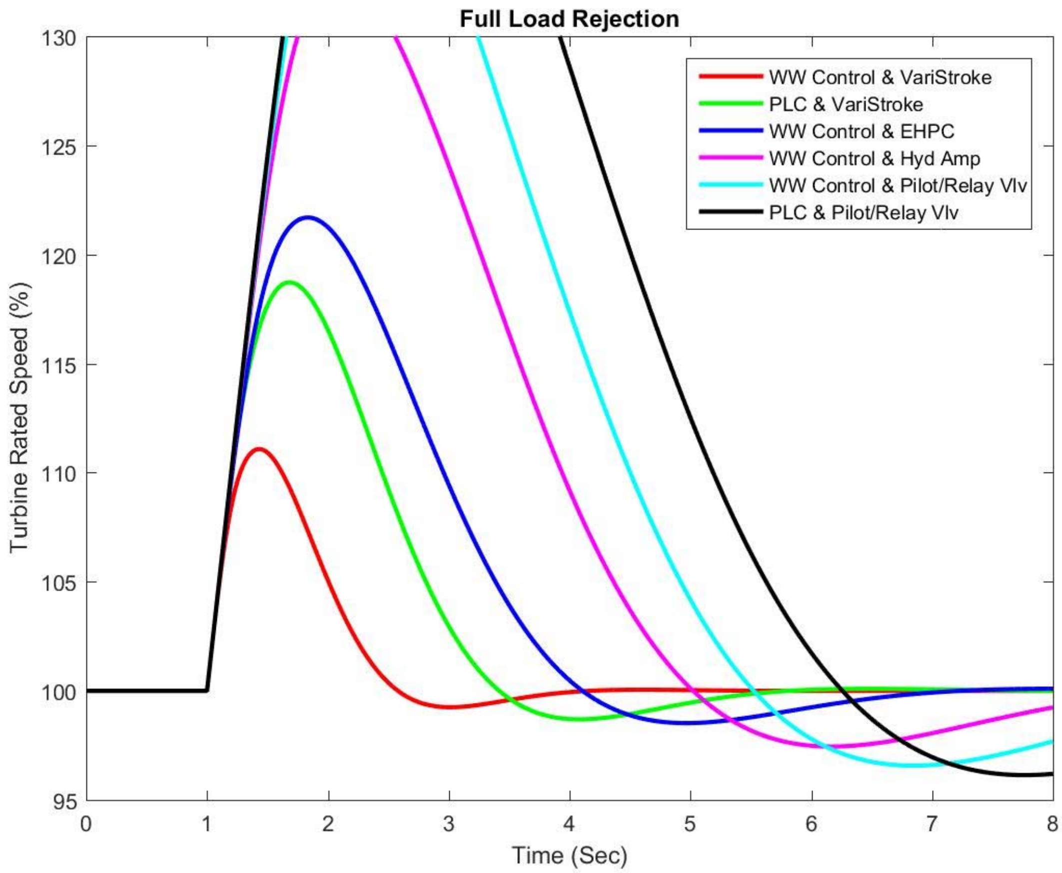

Figure 3-4. Fast Turbine - Full Load Rejection Summary

As with Figures 3-2 and 3-3, the responses in Figures 3-5 and 3-6 include multiple recursion rates, which result in multiple lines of the same color in each figure.

Again, the line with the highest overspeed peak corresponds to the control system with the slowest recursion rate; conversely, the line with the lowest overspeed peak corresponds to the control system with the fastest recursion rate

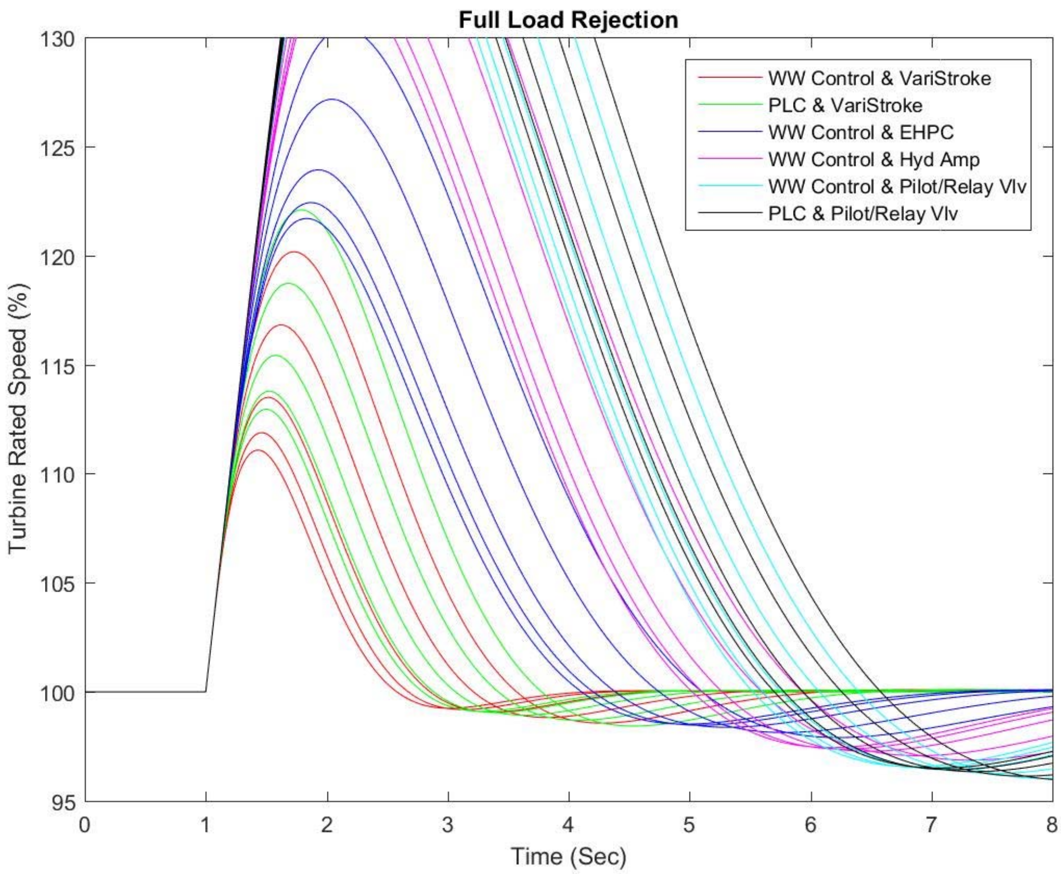

Figure 3-5. Fast Turbine - Full Load Rejection, Multiple Recursion Rates

The recursion rates included in this simulation were the same in both the 25%/second and 50%/second acceleration cases:

- 5 mS
- 10 mS
- 20 mS
- 40 mS
- 60 mS

As shown in Figure 3-5, the only response, which results in an overspeed near 110% of rated speed, is the system with a Woodward control running in 5 mS, and a VariStroke actuator, which is the pink trace with the lowest peak. To achieve a peak speed of less than 110%, a PID control or a feedforward control should be considered. The worse response is shown in black, and is the system with the PLC with the relay valves.

In addition to 100% load rejection simulations, 75% load rejections were simulated, as shown in Figure 3-6.

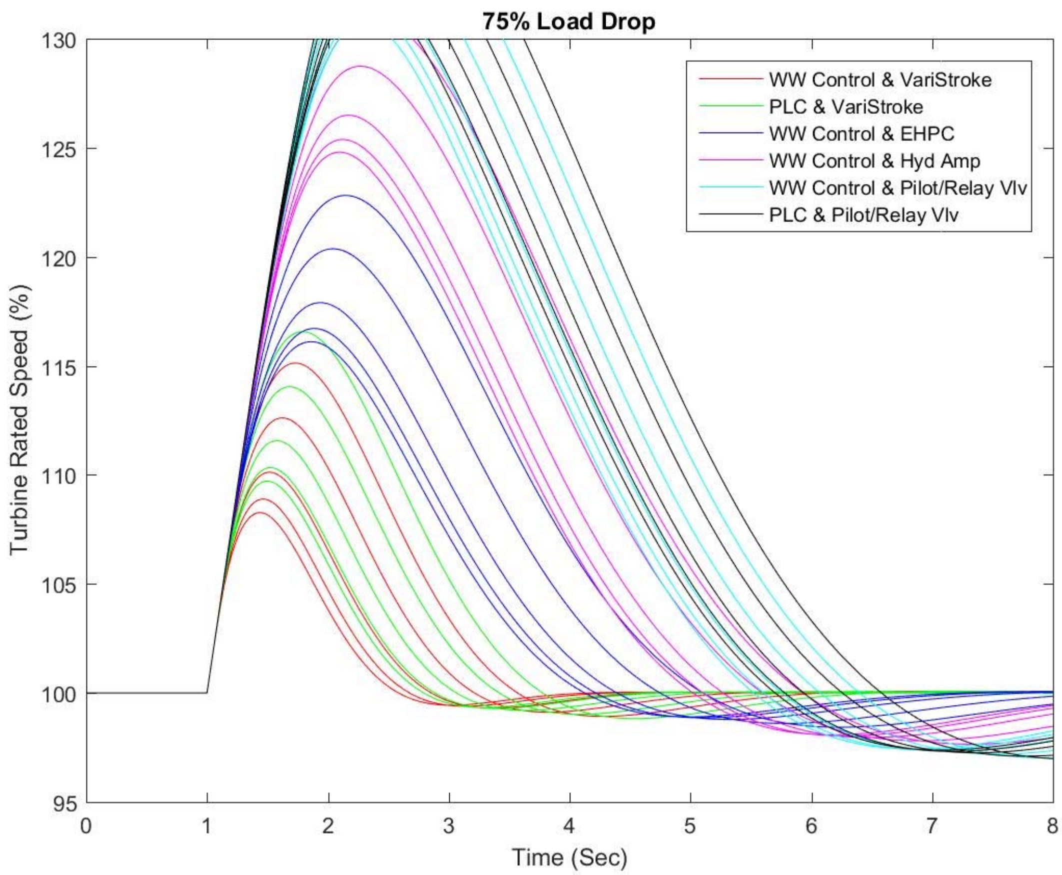

Figure 3-6. Fast Turbine - 75% Load Rejection, Multiple Recursion Rates

The results shown in Figures 3-4 through 3-6 demonstrate again that for optimum dynamic turbine performance, both the turbine control, and the actuation system are critical.

Again, the multiple lines for each color represent the recursion rates, slower recursion rates result in higher peak speeds after a load rejection

Summary of Results

High performance turbine speed control is more demanding than most other control applications in industry. Recursion rates are measured in milliseconds, dead times are measured in microseconds, and actuator slew rates are measured in hundreds of milliseconds.

The simulations in this application note showed that after a load rejection, turbine overspeed amounts were higher for systems with slower recursion rates, more deadtime, and slower actuation systems.

Below in Table 3-1 are the results of the 100% load rejection simulations for the 5 mS and 60 mS recursion rate systems. The values shown in the table are the peak Turbine Rated Speed (%) reached during the event.

Table 3-1. Summary of Maximum Turbine Overspeeds

Maximum Turbine Overspeed for 100% Load Rejection Event				
	5 mS Recursion Rate		**60 mS Recursion Rate**	
	Slow Turbine	**Fast Turbine**	**Slow Turbine**	**Fast Turbine**
WW Control & VariStroke	105.53881%	111.07761%	110.08335%	120.16671%
PLC & VariStroke	106.47546%	112.95093%	111.04294%	122.08587%
WW Control & EHPC	110.84529%	121.69058%	115.20759%	130.41517%
WW Control & Hydraulic Amp	116.52958%	133.05917%	120.68198%	141.36396%
WW Control & Pilot/Relay Valve	120.49088%	140.98175%	124.48097%	148.96193%
PLC & Pilot/Relay Valve	121.28073%	142.56147%	125.30274%	150.60548%

Note that as linear models were used for these simulations, the results scale linearly with turbine acceleration and recursion rate. This makes it possible to interpolate and extrapolate the results to turbines with other acceleration rates and recursion rates, for a general prediction of response.

In general, the simulations shown here were optimistic, and produced maximum turbine speeds during a load rejection, which were lower than the actual system, would be likely to exhibit. For a more precise prediction of response, more sophisticated models should be used which model things like steam chest constants, reheat line delays, the effect of any intercept valves, the effect of hydraulic and steam pressure changes, actual controller gains, etc.

Chapter 4.
Conclusions

Turbine overspeed during a load rejection event is an important parameter to understand and analyze during system design and analysis. Overspeed events degrade the turbine and an overspeed trip will adversely affect the turbine's ability to stay on line during an upset, which hinders grid stability. In island mode operation, it could mean a total loss of power to the facility.

Two system components, which are relatively inexpensive, can have a dramatic effect on the turbine system performance during a load rejection. These components are the speed control system, and the actuation system.

A control such as a Woodward 505 or MicroNet control, with synchronous I/O, low deadtime, and a fast recursion rate, and an actuator such as the VariStroke with a high bandwidth and fast slew rate provide optimum system response. As shown in the simulation results, high performance speed control and actuation system components resulted in a steam turbine system, which controlled the turbine speed to within 5% of rated speed, after a full load rejection event, for a nominal turbine. The simulations also demonstrated that for a faster turbine, a high performance speed control and actuation system would be necessary to avoid an overspeed during a full load rejection.

Lower turbine offspeeds result in less stress on the turbine itself, and turbines that do not trip after a load rejection event can help stabilize the plant or the local grid. If the speed control and actuation system performance is slow, or limited by long deadtimes or slow slew rates, it may not be possible for the turbine to avoid tripping after a full load rejection. This is more challenging for turbines with higher acceleration rates or longer steam chest delays. In order to achieve acceptable load rejection performance, both the turbine control and the actuation system should be designed with high performance turbine control in mind.

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PO Box 1519, Fort Collins CO 80522-1519, USA
1041 Woodward Way, Fort Collins CO 80524, USA
Phone +1 (970) 482-5811

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