A Real-Time Regulator, Turbine and Alternator Test Bench for Ensuring Generators Under Test Contribute to Whole System Stability

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Abstract: A new Test Bench for speed governors has been developed and successfully tested in a simulation laboratory and in a Hydro-Québec hydroelectric powerhouse. Equipped with a Real-Time Simulator, the RT-LAB BERTA Test Bench makes it possible to cause the speed governor and turbine to react as though they are operating in an islanded power system, while remaining connected to the main grid. This ensures that the generating unit under test actually contributes to the stability of the whole power system. On-site testing has demonstrated that previous speed governor settings which were thought to be very stable were in fact generating undesirable power oscillations. Through the use of the proposed Test Bench, more accurate settings can be made on-site without the need to conduct laborious analyses.

Keywords: Speed Governor, Islanded Operation, Frequency Stability, Power System Stability, Speed Regulation, Frequency Regulation, Test Bench, Real-Time Simulation.

1. INTRODUCTION

Digital models of speed governors and turbines are necessary to carry out stability studies of an AC generator in an islanded power system, as well as general stability studies of a large power system. Such models were developed many years ago and have improved as knowledge, requirements and computer simulation technologies have evolved. These models are not individually validated on-site, since it is impossible to ensure that only one generating unit will react to a power system disturbance. Even a load trip or a generating unit trip in the proximity of a unit under test will lead to a general reaction of the power system. Identifying modeling parameters requires either highly accurate calculations, using data that manufacturers are reluctant to provide, or very costly and arduous on-site tests.

Speed control parameters must be set following the principles listed in Section 3. To do so, the engineer must conduct stability studies using available digital models. On-site settings are usually unusable since in practice it is impossible to perform tests representing the real stability of the speed setting.

By designing a Test Bench for speed governors and turbines with a Real-Time Simulator, it is possible to cause the governor and turbine react as though they were operating in an islanded power system. It is then possible to adjust the speed governor and validate the governor and turbine models in the same test session.

The proposed Test Bench, called RT-LAB BERTA, is equipped with such an islanded operation Real-Time Simulator, which enables high-fidelity simulation and testing to be conducted with physical Hardware-in-the-Loop (HIL). This capability enables the Real-Time Simulator to interface with a real synchronous generator in a real large power system. The Real-Time Simulator achieves this by generating simulated signals which are ready to be injected into the real speed governor of the generating unit under test.

2. BASIC CONCEPT OF SPEED REGULATION

The frequency of a large power system acts as the speed of a single AC generator supplying a load. When a large disturbance causes an observable variation in the power system load, (for example, when many loads or a significant load are tripped, or when generating units are tripped) the power system reacts as if it were a single large generator whose inertia equals the sum of all the inertias of the rotating masses in the system. When a load is tripped, the rotating masses accelerate and when a generator is tripped, they decelerate. To reset the frequency to its rated value, the speed governors of all the generators in the power system correct the operating point of the turbines. Their control settings must be such that this correction does not create any instability in the power system, while bringing back the frequency to its rated value as quickly as possible.

2.1 Operating in Islanded Mode

Figure 1 illustrates the frequency behavior of an AC hydro-generator operating in an islanded power system. The initial
load being 0.875 p.u. on the generator MVA base, an additional load of 0.05 p.u. is applied at time \( T = 5 \) seconds. The inertia constant \( H \) equals 3.2 MJ/MVA and the water starting time of the unit is 2.67 seconds at rated water head and full turbine power (0.95 p.u. on the MVA base).

The speed governor model is shown in Figure 2. Its parameters are listed in Table 1.

### Table 1: Speed governor settings

<table>
<thead>
<tr>
<th>Test no</th>
<th>( B_p )</th>
<th>( K_d )</th>
<th>( K_p )</th>
<th>( K_i )</th>
<th>( K_{sm} )</th>
<th>( T_{act} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>0.05</td>
<td>0</td>
<td>1.163</td>
<td>0.105</td>
<td>3.333</td>
<td>0.07</td>
</tr>
<tr>
<td>E2</td>
<td>0.05</td>
<td>0</td>
<td>1.163</td>
<td>0.25</td>
<td>3.333</td>
<td>0.07</td>
</tr>
</tbody>
</table>

In a multi-machine power system, the synchronous interconnection of an AC generator with other generators will only stabilize a generator to the extent that the other generators will stabilize the system owing to their inertia. However, the other generators may not contribute to the frequency regulation of the system. In such cases, the accuracy of the setting is affected and large frequency deviations can degrade the quality of the voltage wave and trip loads or generators, ultimately jeopardizing the stability of the power system.

There is a limit to the number of generating units that would be unstable in an islanded power system, beyond which the whole system would become unstable. Figure 3 shows clearly that increasing the proportion of badly tuned speed governors will eventually lead to the instability of the whole power system. A well-adjusted speed governor is therefore an absolute requirement, regardless of the operating mode of the generator.

### 3. MAIN PRINCIPLES TO CONSIDER WHEN ADJUSTING A SPEED GOVERNOR

Following the basic concept discussed in the preceding section, basic principles can be derived that must be observed when optimizing speed governor parameters.

The **first principle** to follow when setting the speed governor of a synchronous generator is that the speed governor must be set to ensure operating stability in an islanded power system, regardless of its actual operating mode, as demonstrated in the preceding section.
A second important principle dictates that the speed governor must avoid contributing to natural electro-mechanical power oscillations. This typically occurs when the control gains of the speed governors, mainly the derivative gains, are too high or when the speed or electric power signals attacking the speed governor control unit are not properly filtered. The small oscillations of these two signals in the frequency range between 0.4 Hz and 3 Hz, characterizing synchronous operation in a multi-generator system, reverberate on the displacement of the turbine gates and generate destabilizing mechanical power oscillations.

Here are other principles to follow:

- Each generating unit must contribute to regulating the speed of the power system;
- PSS behavior must not interfere with the speed governor and conversely;
- Settings must be made as quickly as possible to minimize frequency deviations during a load variation, without compromising the operating stability in an islanded power system;
- Regulating action must not place excessive demand on power chain components of the gate or valve servomotors. For instance, a high gain in the mechanical amplification chain can cause intolerable vibrations in the servomotors’ oil piping and compromise the security of the facility.

4. HARDWARE-IN-THE-LOOP TEST BENCH DESCRIPTION

4.1 Test Bench Setup with Physical Hardware-in-the-Loop

The Real-Time Simulator incorporated into the RT-LAB BERTA Test Bench enables high-fidelity testing and simulation to be conducted with physical Hardware-in-the-Loop (HIL). Figure 4 illustrates how an actual RT-LAB BERTA Test Bench is deployed for onsite testing; including how it will interface with physical hardware including a physical Speed Governor under test, a physical Turbine under test, a physical generator synchronized to the real power grid, and physical Current & Voltage Transformers.

The electric power generated by the synchronous generator is controlled by the speed governor. This governor controls the opening of the wicket gate, while the turbine generates the mechanical power driving the generator which transforms mechanical power into electric power.

The proposed Test Bench receives signals from the generator and from the speed governor. It also injects signals into the speed governor to verify and optimize the speed governor parameters as if the synchronous machine were connected to an islanded power system.

The signal for the gate servomotor stroke (1) is usually available in the speed governor cabinet or can be captured with a suitable meter.

Figure 4: Illustration of how RT-LAB BERTA is setup for onsite testing; configured with Physical Hardware-in-the-Loop

The current (2) and voltage (3) signals are captured on the secondary windings of the voltage and current transformers of the generator.

Once captured, the signals are converted into voltage signals proportional to real values. These signals are within the ±15 Volt range and are therefore compatible with the AD converters.

The frequency error signal, synthesized by the islanded Real-Time Simulator or generated by a definite step or sinusoidal function, is converted into alternating voltage (4) oscillating at the simulated controlled frequency. It is then injected into the appropriate input port of the speed governor.

4.2 Test Bench Hardware Components

The proposed Test Bench’s equipment is designed to be compact and portable, and includes:

- Voltage and current sensors to adapt high-current and high-voltage signals to signals in the range of ±15V;
- AD and DA input/output boards;
- Standard PC computer with Intel Dual-Core processor for real-time computing;
- 3-way switch (2 for input, 1 for output) for connection between the generator output voltage, Test Bench output and the input port of speed governor;
- A laptop computer to control the Test Bench and signal monitoring;
- An additional flat screen;
- An emergency UPS power supply;
- Two robust carrying cases;
- Required cables and accessories.

4.3 Test Bench Software Components

The basic software consists of the following:

- RT-LAB Real-Time simulation platform;
- OPAL-RT TestDrive user interface (developed with LabVIEW) to control and monitor the Test Bench;
• BERTA Speed Regulator Test Software including the following modules:
  • Digital calculators for frequency and electric power;
  • Modules to estimate the speed and mechanical power;
  • Real-Time Simulator of islanded power system operation, including a power stabilizer simulation function;
  • Adjustable PID controller;
  • Signal generator for speed errors;
  • Signal converter for speed errors into AC modulated voltage;
  • Speed governor and turbine adjustable linear models for comparison with real values.
• “BERTA_Alert”: Continuous monitoring module, including an automatic signal recording launcher following a frequency variation in the power system;

Test Bench optional modules include:
• “BERTA_Training”: Training and test preparation module, including a simple power system model ready for real-time simulation;
• “BERTA_Ident”: Command (.m) and modeling (.mdl) MATLAB files to facilitate off-line estimation of the turbine and speed governor models.

5. USING THE PROPOSED TEST BENCH FOR REAL-TIME SIMULATION OF GENERATORS OPERATING IN AN ISLANDED POWER SYSTEM

5.1 Operating Principle of the Islanded System Simulator
The proposed Test Bench is equipped with a Real-Time Simulator, which simulates an islanded power system. This enables the generator under test, which is part of a larger physical power system, to behave as if it were operating as part of an islanded power system.

The Real-Time Simulator enables the operator to quickly and accurately set speed governor parameters, thereby ensuring the frequency stability of the unit when operated in an islanded power system, and improving its contribution to power system stability when it is synchronized with a large power system.

The Real-Time Simulator generates a speed error signal corresponding to the behavior of the generator in an islanded power system. Injecting this signal into the speed governor while the unit is generating power in the system sets up a closed loop simulating the operation of an islanded system, even though the AC generator is actually synchronized to a multi-machine power grid.

The speed error signal is added to the actual frequency signal so that the governor will still react to an actual system frequency variation. An AC generator outputs a 10 V AC signal corresponding to the simulated frequency that will replace the original voltage signal.

5.2 PID Controller
The proposed Test Bench is also equipped with a PID controller that can be used instead of the speed governor’s actual PID controller. The output signal of this controller replaces the output signal of the actual controller and directly drives the servomotor chain.

5.3 Power System Stabilizer Simulation Function
The proposed Test Bench also permits monitoring of Power System Stabilizer (PSS) behavior during a power system frequency disturbance, enabling the engineer to determine whether the PSS and the speed governor contribute together to the system stability or react against each other.

This topic has been emphasized by P. Kundur as a factor influencing inter-area modes of oscillations: “Speed-governing systems normally do not have a very significant effect on inter-area oscillations. However, if they are not properly tuned, they may decrease damping of the oscillations significantly” (“Power System Stability and Control”, P. Kundur, page 822).

But the opposite is also true. Figure 5 illustrates interesting cases where the PSS badly interferes with the speed governor. The simulated disturbance is a sudden load increase that will decelerate all synchronous machines. Test E11b, where the stabilizers are switched off, illustrates the increasing instability of a multi-machine power system at natural power frequency of around 1 Hz. However, the frequency signal envelope perfectly follows the islanded system frequency curve. As shown by Test E61, the islanded system behavior is stable, which means that the speed governor is correctly set. But simulating the PSS in cases E11, E41 and E51 shows a deteriorated stability in islanded mode of operation. This means that the low frequency behavior of the PSS reacts against the speed governor. The proposed Test Bench therefore allows for on-site validation of PSS settings in case of generation or load rejection.

6. ON-SITE TESTS & RESULTS
Conducting on-site tests at a powerhouse has traditionally been a very costly endeavor since it requires the generator
under test to be taken offline. Extensive advanced planning and coordination with the utility's operations centre is required to schedule testing and typically all testing must be completed in just a few hours. The result has been that only a limited number of tests could be performed, producing results that were not always accurate.

Using the proposed Test Bench, more extensive testing of a greater number of speed governor settings can be performed in a shorter period of time without compromising the stability of the whole power system.

This is demonstrated through on-site tests performed in a Hydro-Québec hydroelectric powerhouse in November 2008. The set-up is as shown in Figure 4.

The simulated disturbance is a sudden 5% load increase. The islanded frequency signal is used to modulate the generated 60Hz voltage signal that is injected into the speed governor voltage input port.

The following figures clearly show that settings from Test20 (actual settings) are acceptable, but do not provide a very good system damping. Settings from Test60 show a better damping, though a greater initial speed decrease. Many other tests were performed using different settings and load variation steps. Hydro-Québec experts will eventually select the best settings according to their operating philosophy.

More than 60 tests were performed within only a few hours. This was achieved due to the very easy operation of the RT-LAB BERTA Test Bench.
7. CONCLUSIONS AND BENEFITS

Until now, it has been impossible to assess with a high degree of accuracy the behavior of a synchronous generator in an islanded power system. Characterizing such behavior is indispensable to properly setting a speed governor.

To date, model and parameter identification tests have proven to be very expensive and do not provide an accurate and robust model of a turbine. The process is time-consuming and arduous as described by the following steps that must be performed for each machine:

- Preliminary settings based on specifications provided by the constructor of the dam and manufacturers of the turbine and generator;
- Model and parameter identification tests in the power station;
- Off-line stability studies to recommend the appropriate settings, based on the models and parameters as determined by tests carried out in the power station;
- Return to the power station to implement new appropriate settings on the speed governor.

The proposed Test Bench allows these operations to be carried out in a single test run in the power station.

The return on investment translates into the following benefits:

- Accuracy of speed governor control settings ensuring that each machine has a stabilizing effect on the power system;
- Validation of PSS low frequency settings ensuring that the PSS and the speed governor do not react against each other;
- Accuracy of speed governor and turbine models;
- Stability and reduction of demand on servomotors by applying appropriate settings;
- Productivity gain for model identification and control setting;
- Shorter tests in the power station due to ease of use of Test Bench.

REFERENCES
