Testing & Modeling of Generator Controls

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INTRODUCTION

The testing and modeling of generators, and their associated controls, is a complex topic. This is in part because of the variety of different generators and controls found on a practical power system, and the manner in which they interact during normal and abnormal power system operating conditions. There is a consensus within the industry that the development of accurate models for generator control systems is a key step in establishing operating-security limits and in simulating and understanding the operation of the system during disturbances.

The most common objectives of utilities embarking on systematic test programs, to establish models of their facilities, include:

- Simulate system or local disturbances, to compare with measured data or reconstruction of actual events and derive remedial actions
- Simulate system disturbances in the planning or operating time frame to establish secure operating limits and assess alternative plans
- Coordinate existing or new protection and control systems
- Study the addition of new facilities

Regardless of the reason for testing, the first step should be to identify the model requirements and translate them into specific criteria: location of critical stations, list of critical units, list of critical components (e.g. generator, excitation system, governor…), type of models and data to be collected, and finally, types of tests to be performed.

GENERATING UNIT CONTROLS

Figure 1 provides an overview of the turbine-generator control loops for a typical fossil-fired unit. These controls allow the power system to meet the continually changing customer load requirements by adjusting the active and reactive outputs of the generators. Briefly, the major control loops are:

Power System Generation Dispatch includes automatic generation control systems (AGC) for the maintenance of overall system frequency and tie-line interchanges and manual operator controls such as economic dispatch.

Prime Mover Energy Supply System for fossil-fired units (shown) includes fuel supply and boiler control loops, while for hydroelectric machines, penstock and conduit systems will participate in the dynamic behaviour.

Turbine Controls include the governor (speed control loop) as well as supplementary controls that are active during full or partial load rejections.

Excitation System includes the amplification stage(s), automatic voltage regulator (AVR) function, excitation limiters and supplementary controls such as power system stabilizers (PSS), and outer control loops (e.g. power factor or reactive power regulators).

Included within these control loops are the turbine and synchronous generator. Clearly, the modeling of these components can have a significant impact on the accuracy of the representation of each of the major control loops.

While not explicitly shown in Figure 1, plant auxiliaries and large system loads may require detailed modeling, especially for conditions involving large variations in system frequency and voltage /2/.

The need to represent each of these components and control loops, and the type of model required, is established by determining the type of simulations which are to be performed, and the types of operating conditions to be represented.

MATCHING MODELS TO REQUIREMENTS

Define the Need

The first step is to define why the tests and models are required. Some questions that must be answered are:

- Is the sole purpose of performing the tests to develop simulation models?
- Are the tests intended to reproduce disturbance conditions in order to identify deficiencies and improper coordination of limiters and controls?
- Will the models be used to produce recommendations for changes to equipment settings?

Once these questions have been answered, the modeling requirements may be identified.

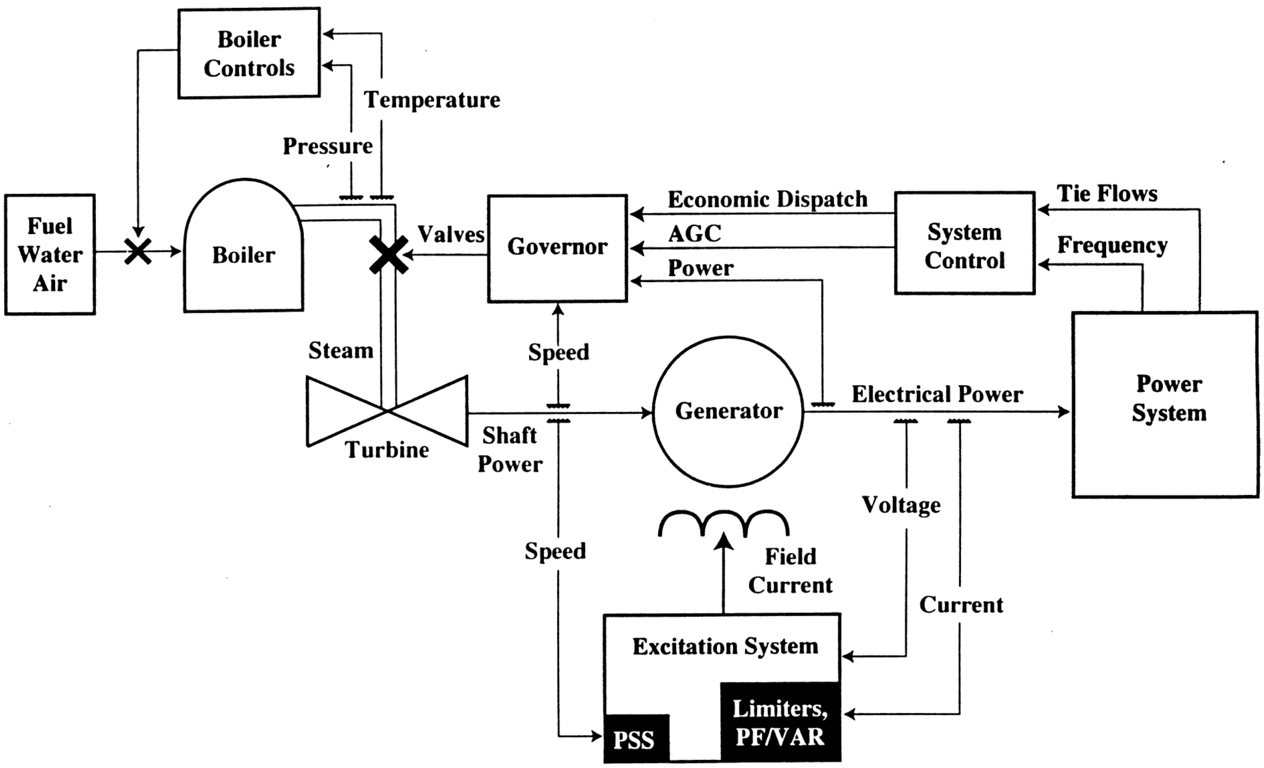


Figure 1: Turbine-Generator Control Loops

Select Location(s)

This is often the simplest stage, and involves considering the following factors:

- Was a station or specific unit a critical participant in a system event?
- Did the station, or specific equipment, exhibit unexpected behaviour during the system event?
- Is existing dynamic data available at a station?
- Is the available data supported by previous tests and measurements or well-documented manufacturer's data sheets?

A prioritized list of stations and units can usually be compiled from a quick review of a past system event or a forecast operating condition.

Define the Equipment Modelling Requirements

In order to determine which pieces of equipment must be modelled in detail, the type of simulations that will be performed must be defined. This involves establishing the time frame and the system conditions that are to be simulated (e.g. interconnected and/or islanded operation). The latter is often specified as a range of voltages and frequencies for which the models must be valid.

Table 1 provides example guidelines for equipment to be modeled for different purposes. These are only guidelines; location-specific details should be combined with the study objectives to arrive at a final decision. The entries can be interpreted as follows: "Y" indicates dynamic model

Table 1: Equipment Modelling Requirements

	STUDY TYPE					
EQUIPMENT	SSR	Transient	Small-Signal	Islanded Operation	Long-Term Dynamics	Voltage
Generator	Y	Y	Y	Y	Y	Y
Shaft System	Y	N	?	N	N	N
Excitation Systems						
AVR	?	Y	Y	Y	Y	Y
Stabilizer	?	Y	Y	?	?	Y
Limiters	N	?	N	?	Y	Y
PF/VAR	N	N	N	?	Y	Y
Turbine Controls						
Speed Governor	N	N	?	Y	Y	N
Overspeed Controls	N	N	N	Y	Y	N
AGC	N	N	N	N	?	N
Prime Mover	N	N	N	?	Y	N
Loads	N	N	?	Y	Y	Y

normally included, "N" normally not included, "?" may be included depending on the specific conditions and simulation goals.

The following are definitions of the study types used in Table 1 (typical bounds on study time scales for each phenomenon are indicated in parentheses):

SSR subsynchronous resonant interaction between synchronous machines and transmission system elements and controls. (< 1s)

Transient large disturbance, first-swing rotor-angle stability(< 10 s)

Small-Signal linearized analysis of oscillatory modes associated with rotor electromechanical oscillations and control system modes(<20 s or eigenvalue)

Islanded Operation operation of isolated portions of the system; large frequency and voltage excursions (10 s to a few minutes)

Long-Term Dynamics slow dynamics associated with operation following widespread disturbances (minutes) /3/

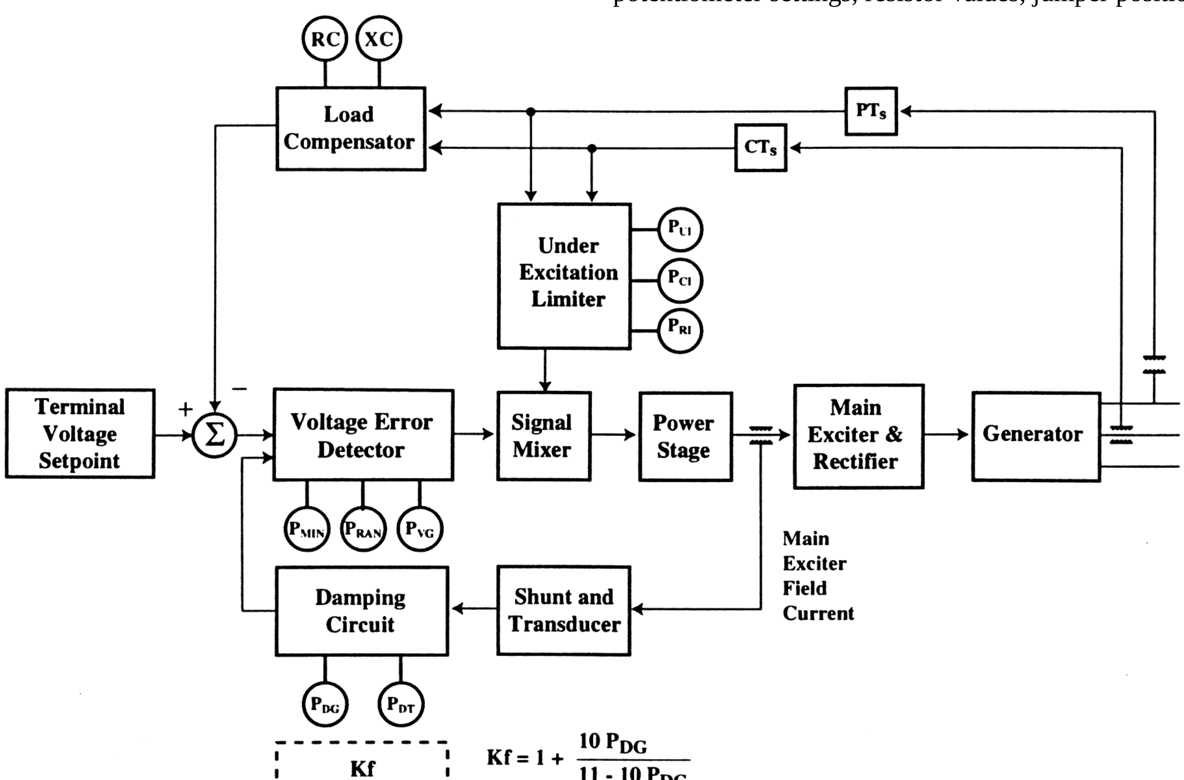
Voltage analysis of voltage stability for large and small disturbances (all time frames are possible, depending on type of phenomenon)

There are obviously overlap in these selected study types, as certain simulations will address multiple categories simultaneously. One row has been added for loads; although they are not part of the generator control systems, inclusion of accurate load models is often critical to the success of detailed simulations /4/.

Select Model Structures

The types of models and tests required are a function of the intended application. For small-signal studies, linearized representations are adequate. For transient or other large disturbance studies, the models must explicitly include all significant nonlinearities, such as saturation and limits. Linearized representations may be derived from the large-signal models, often within the simulation software used in the studies without intervention by the user.

Normally, the models are developed to match industry-accepted standards /5,6,7/. In some cases more complex models are developed; these are usually used for unusual equipment or when a direct correspondence is required between the model parameters and the settings of the physical system. Figure 2 provides a portion of an overview block diagram of an excitation system in which external components are identified for each module. One of the blocks, the damping feedback circuit shows the relationship between the external settings and transfer function constants. The transfer functions and defining equations for each of the blocks is developed in a similar manner to include gains, time constants and limits in terms of the physical components and available settings (e.g. potentiometer settings, resistor values, jumper positions).



$$\frac{K_f}{1 + ST_f} \qquad K_f = 1 + \frac{10\,P_{DG}}{11 - 10\,P_{DG}}$$

$$T_f = 0.2 + 2\,P_{DT}$$

Figure 2: Overview of Block Diagram of Exciter Including External Settings

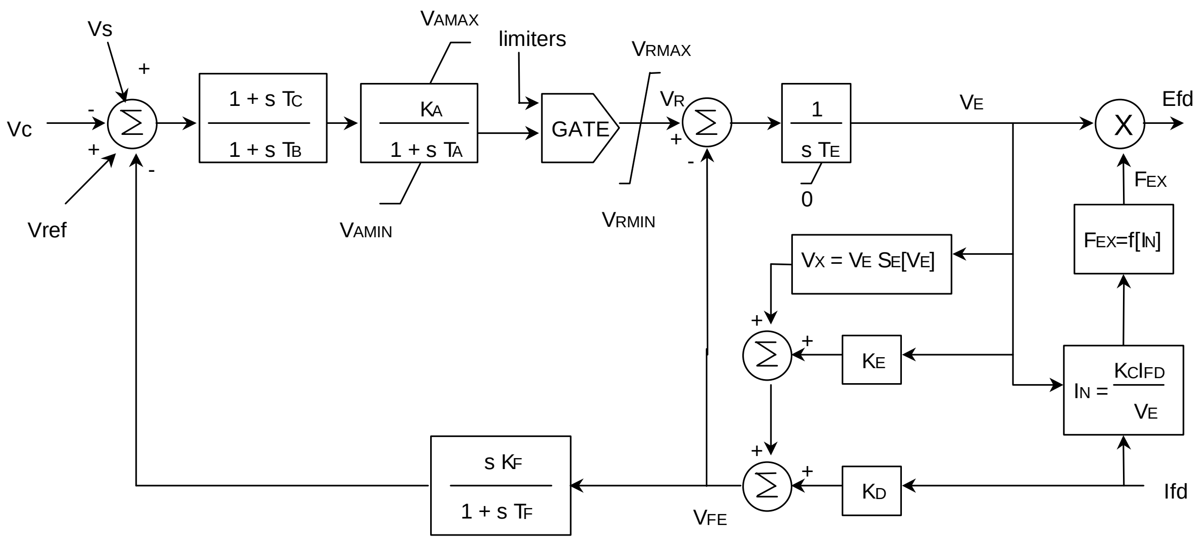


Figure 3: Excitation System Model Type AC1A

The advantage of this type of model is that it allows the results of studies to be translated into recommended changes which can be implemented in the field to obtain performance improvements, and the variables are represented in engineering units (e.g. V, A,…) which can be compared directly with measured results /8/.

The disadvantage of this structure is that the models are complex, manufacturer-specific and are not in a standard format that can be used in commercial simulation software. Therefore, the detailed models are often used as a starting point for developing standard non-linear or linear models. Figure 3 is an example of one such model, IEEE Standard AC1A /5/, representing an alternator-rectifier excitation system with non-controlled rectifiers.

For many studies this kind of representation, the exciter power stage and AVR control, will be adequate, while for other studies the excitation limiters or supplementary controls must be added to reproduce the unit's behaviour /9/. While industry standards also provide guidance for modeling these features, there tends to be a higher level of customization, often requiring user-defined representations.

Testing Methodology

Once the locations and level of modeling detail have been selected, the model parameters must be determined. Field-testing is normally part of the model development and validation. The following is a brief description of the steps which can be included in this process /10/. Not all of these steps are required for each location and each piece of equipment.

Step 1 - Review available data: Collect data from the station and from the manufacturer of the equipment. This includes operating manuals, diagrams, capability and rating data, previous test results, and, where available, block diagrams. This stage often provides a significant amount of information reducing the amount of site testing required.

Step 2 - Select model structures: Based on the available data, develop a block diagram of the equipment to be modeled. This often involves selecting the standard model that is the best fit to the equipment.

Step 3 -Develop test plan: The test plan should include measurements to identify all of the key parameters, and provide additional data for validating the final product - the completed model. The plan should clearly identify any special equipment requirements, the station/unit operating state during each phase, and the safety/reliability issues.

Step 4 - Perform site tests: Included in the actual testing should be a review of nameplate data and any equipment modifications and a comparison to the manufacturer's data gathered earlier. It is not uncommon to find differences between field wiring, installed component values, equipment settings and documentation. The functional and dynamic tests also frequently identify latent deficiencies, such as defective components or incorrect settings. These may not be apparent during typical day-to-day operation.

Step 5 - Validate data: Compare measured and modeled responses for modules and/or complete system. In order to expedite this stage digital data acquisition systems are used which format the data for use with simulation and analysis software. Whenever possible parameters are calculated on-site and compared with test results. This provides an opportunity to identify inconsistencies or missing data, which can then be rectified prior to removing the test equipment.

Step 6 - Produce reduced-order model: Eliminate feedback loops, time constants and limits not relevant to the target model. Convert all parameters to per-unit values for use within simulation software.

Step 7 - Train station staff: This step is not always included as part of the process, but it is actually critical to ensuring that the relationship between the derived model and equipment settings is maintained. Ideally, station staff should be provided with enough training to periodically test the unit and confirm that its dynamic performance has not changed significantly. Regular courses are offered, and test facilities have been added to most excitation systems and stabilizers to permit verification of the closed-loop voltage regulator and PSS response /11/.

In order to perform tests on a wide variety of equipment designs, specialized test instrumentation is required. Over the years custom transducers have been developed for measuring all of the quantities associated with generators, excitation systems and governors (e.g. active/reactive power, field voltage and current, shaft speed, frequency, valve position…). These transducers and associated instrumentation differ from multi-purpose hardware in that they have been specifically designed for the bandwidth, isolation and accuracy requirements of these dynamic tests.

EXAMPLE RESULTS AND CASE STUDIES

Generator Testing

In many cases, utilities rely on manufacturer-supplied data in impedance and time-constant form. Depending on the manufacturer, this data may be measured through enhanced short-circuit and stator decrement tests, or derived from numerical analysis of design data /12/. Experience has shown that there can be significant differences between the parameters provided by manufacturers and those obtained through direct measurement.

Generator parameters may be confirmed with some straightforward static and dynamic tests, and can range from simple static and open-circuit measurements to sophisticated standstill and on-line frequency response tests /13/. The open-circuit saturation curve should be measured and compared with the manufacturer's measurements. Static measurements of field current, terminal voltage, active and reactive power, and rotor angle allow the calculation of d- and q-axis and leakage reactances. During these tests, the capability curve shown in Figure 4 may be verified, and limits such as field current, bus voltage, under-excitation limiter or loss of field relay identified.

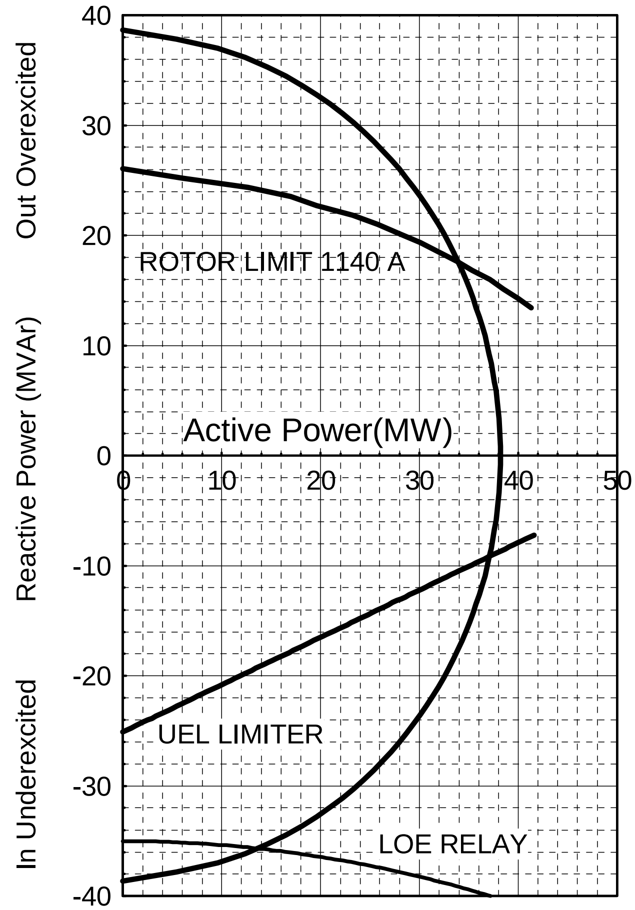


Figure 4. Capability Curve

Two load rejection tests have been used to verify transient parameters. A zero power factor test with excitation on manual, shown in Figure 5, allows d-axis parameters to be fitted to terminal voltage and field current response.

A partial load rejection test, as in Figure 6, allows confirmation of generator inertia, and is also useful in analyzing off-line governor performance.

Although the models derived through detailed tests can be significantly different, one of the conclusions of reference /13/ is that, for modern generators, there is not always a significant improvement in the accuracy of simulations when compared with those conducted using manufacturer's data. In fact, the accuracy of the excitation system models is often far more significant in determining the outcome of most simulations. Once accurate exciter and governor models are available, then improving the generator representation can provide incremental improvement, where special controls are being simulated or tuned.

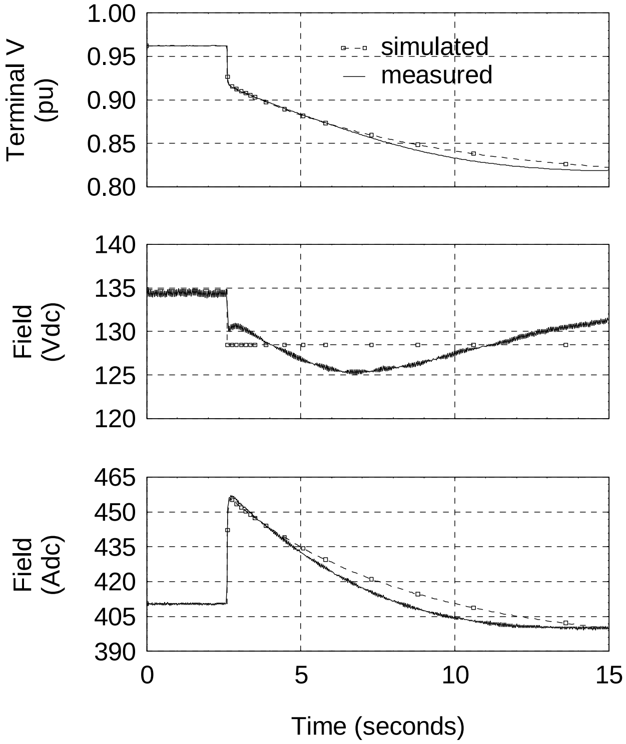


Figure 5. 0 pf Load Rejection Test

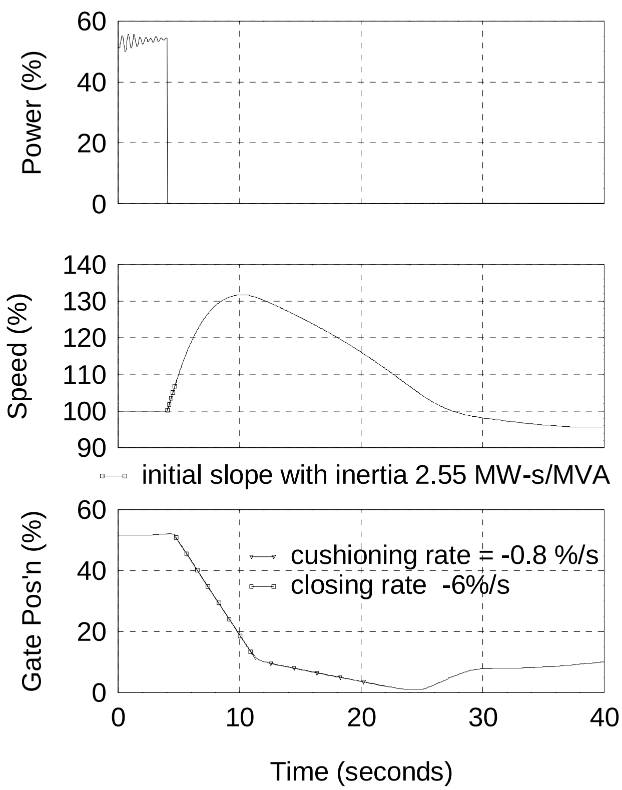


Figure 6. Partial Load Rejection Test

Excitation System Modeling

It has been our experience that generator excitation system settings and performance can have a dramatic effect on the overall behaviour of individual units and the power system as a whole. Some form of excitation system model is required in virtually every type of power system simulation. Our approach has been to maximize transmission capability through the use of high-initial-response (HIR) excitation systems and supplementary controls such as power system stabilizers (PSS) and transient excitation controls (TSEC). Consequently, we test all excitation systems and derive detailed large-signal models for inclusion in the system dynamic database.

Excitation system tests are normally performed in one, or more, of the following operating conditions:

- excitation system energized via test supplies and isolated from the generator field winding. These tests are often scheduled during routine maintenance outages, and provide an opportunity to obtain detailed measurements of the transfer functions of the various sub-assemblies (e.g. AVR, UEL, PSS, …)
- generator on open circuit at rated speed. The excitation system is operated in its normal configuration and generator excitation and field voltage are adjusted to various levels. This provides an opportunity to measure closed-loop response and test the various power stages under normal and forcing conditions.
- generator synchronized to the grid, operating at a variety of active and reactive power loads. These tests provide an opportunity to test excitation limiters, and supplementary controls (e.g. PSS, VAR regulator) under realistic operating conditions.

A wide variety of testing techniques have been developed for determining the model parameters. In general, they all involve performing measurements of the time or frequency response of the system, and comparing the result against simulated responses calculated using different model parameters. Various system identification techniques are available for extracting the model parameters directly from overall test results /14/. Some caution must be used when interpreting results from overall tests to ensure that they are valid for a variety of operating conditions. Regardless of the technique applied, the final step should include validating the model, by comparing simulated time-domain results against measured field data.

Figure 7 provides an example comparison between simulated and measured data for a generator equipped with an alternator-rectifier excitation system.

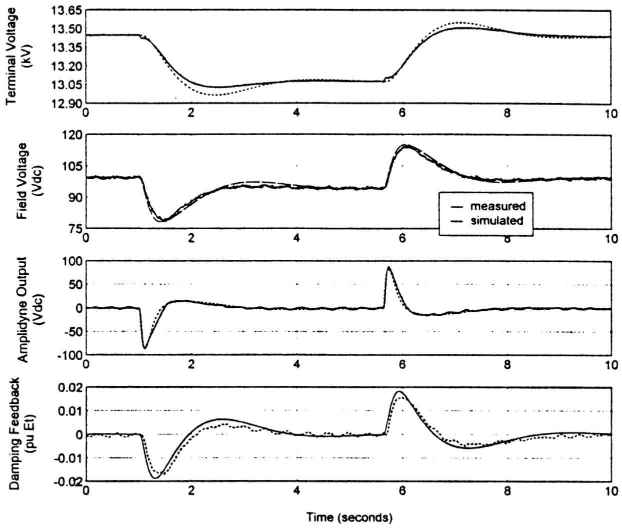


Figure 7: Comparison of Measured and Simulated Response for Alternator-Rectifier Excitation System

Power System Stabilizer Tuning and Testing

Power system stabilizer testing and tuning is performed using a combination of off-line and on-line time- and frequency-domain tests. Transfer functions of the input filters, gain, and phase lead-lag stages are measured with the stabilizer off-line. The stabilizer tuning requirement may be determined using an on-line frequency response test, shown in Figure 8.

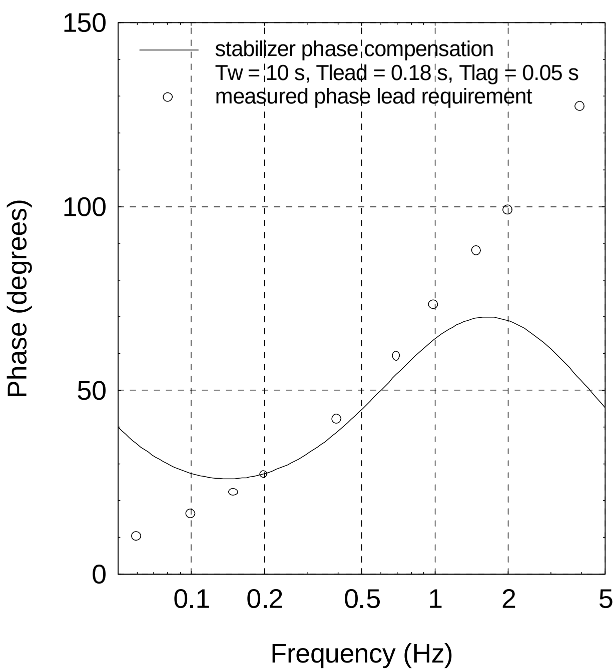


Figure 8. Stabilizer Phase Lead Requirement

The desired stabilizer gain and phase lead were implemented and on-line step responses with the stabilizer on and off, shown in Figure 9, were used to demonstrate the results.

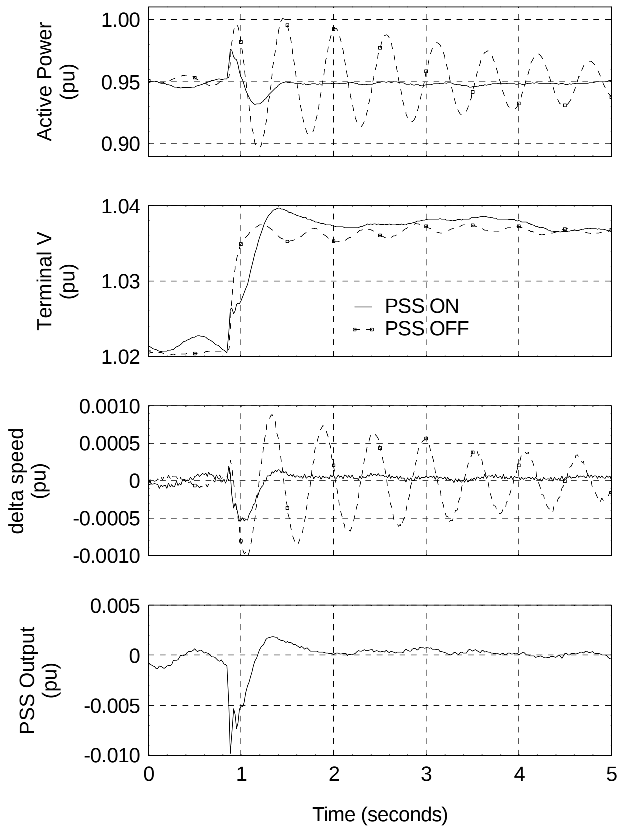


Figure 9. Power System Stabilizer Test

Hydro Governor Modeling

Detailed hydro governor models are normally only included in simulations intended to reproduce long-term dynamics and system operation during which large frequency deviations occur, such as islanded operation. The structure of the local bulk electricity system includes numerous pockets of hydroelectric generation, which are connected to the remainder of the system via limited transmission connections. As a result, we have performed measurements and simulations of islanded operation on several occasions, and have developed standard procedures for tuning for optimal damping /16/.

The approach taken for hydro governor testing is similar to that used for excitation system testing, although additional specialized test equipment is required to introduce test inputs and measure the intermediate and output quantities. With the advent of electro-hydraulic governors, which employ analog and digital regulators, the need for specialized hardware has been reduced, as all critical quantities are converted to electrical form.

Electronic governors may be tested in the same way as analog electronic exciters, with a combination of time- and frequency-response tests. Static measurements are used to establish the permanent droop and turbine operating curve (gate or fuel flow versus power output). Step tests, shown in Figure 10, may be used to confirm and tune PID gain parameters.

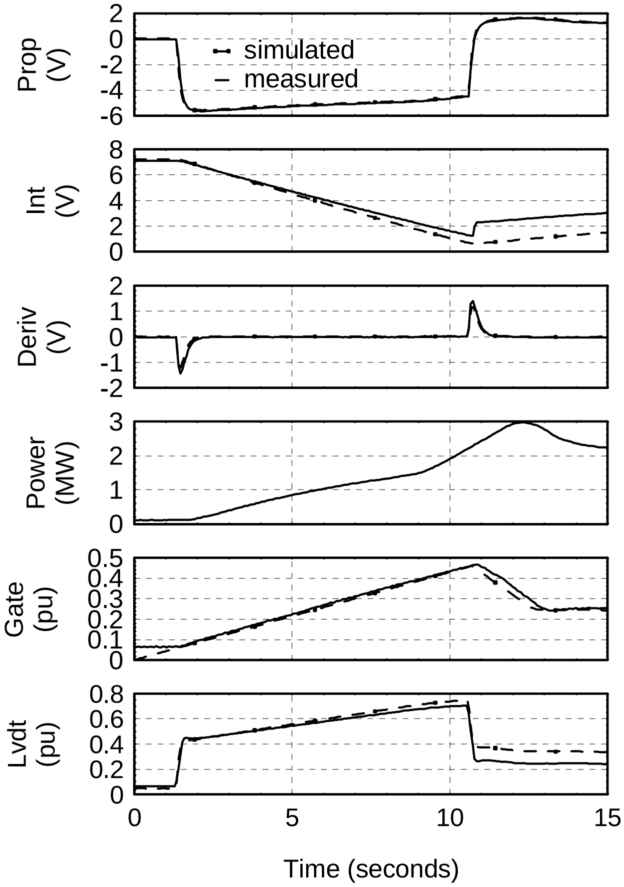


Figure 10. PID Governor On-Line Response

Thermal Governor Modeling

Detailed thermal governor models are normally only developed when simulation of partial/full load rejections are required. Reference /2/ describes simulations performed to understand the nature of a failed load rejection test on a nuclear unit. The failure was a result of large induction motors stalling, causing protective relays to operate. Potential remedial measures were simulated and a final solution adopted and implemented to prevent further failures. The simulations allowed different remedial measures to be studied, thereby eliminating costly re-testing on the unit.

Gas Turbine Governor Modeling

The advent of gas turbines and co-generation has created a new class of facility, which is becoming widespread as the choice for new construction. A simplified simulation model of a single-shaft gas turbine is presented in reference /17/.

The controls are typically analog-electronic or digital electronic. In both cases, step-response tests and steady-state measurements have been successfully used to characterize both the turbine and governor (Figure 11). Instrumenting and performing dynamic tests on digital versions presents more of a challenge. However, even if the manufacturer has not provided built-in test facilities, dynamic response tests can usually be performed with some guidance from the manufacturer. The testing environment (typically the plant control room) is decidedly more attractive.

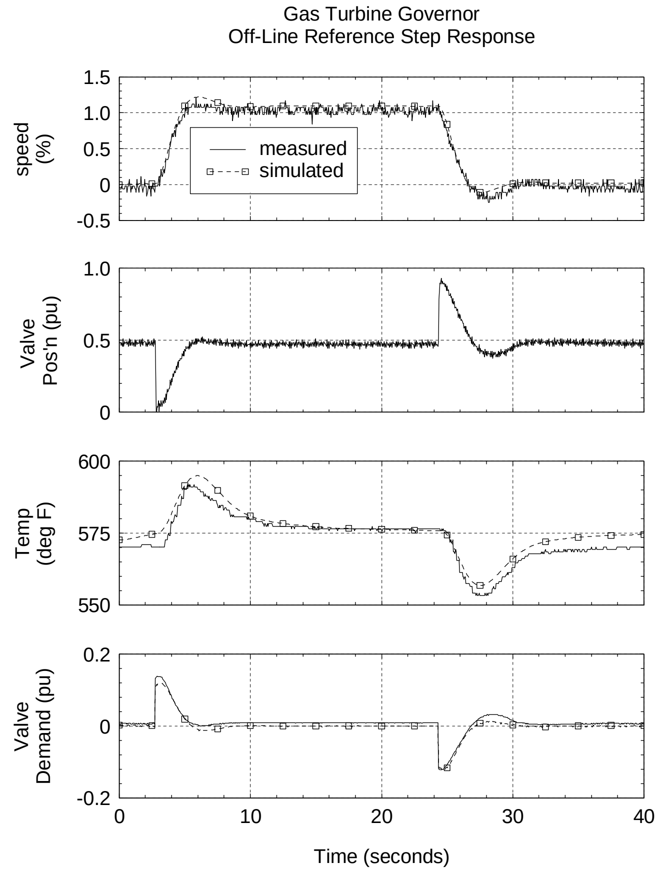


Figure 11. Gas Turbine Governor Response

Standards for control tuning for such equipment have not yet evolved, so reporting a model, rather than tuning is the primary test objective. It should be noted that the available models include several control modes: droop control (the familiar mode for partial load conditions), acceleration control (for startup and maneuvering), and temperature control. For economic reasons, these units are invariably loaded to near full output, and are controlled to respect temperature, pressure and emission constraints. In this mode, the speed/load droop control is not active. As these facilities may represent a significant portion of the total generation in an area, new control guidelines and models are being developed to correctly model their overall load and frequency control performance. Plant load controls are also becoming common in thermal and multi-unit hydro plants, and models and tests are presently under development.

Conclusions & Recommendations

The preceding paper and case studies are intended to illustrate that models, test techniques, and control guidelines are available to meet the NERC testing and modeling recommendations. The equipment models and tests shown have been drawn from IEEE standards and are widely available in power system simulation programs.

Our experience has been that the most critical models for system stability limit studies are those of the exciter and associated controls, such as power system stabilizers. Up-to-date manufacturer's data, confirmed with spot measurements usually provides adequate representation of generators. Governor models are required for islanded operation studies or for simulation of plant dynamics, such as load rejections. Induction motor and nonlinear load models may be required for specific event reconstruction. Representation of over- and under-excitation limiters, voltage and volts/Hertz limiters and power factor/var controllers may be required for detailed simulations; in addition, site tests provide an opportunity to confirm settings for adherence to contractual agreements for available reactive support

Prior to embarking on a test program, the utility should define exactly what the results will be used for or describe the problem which has initiated the requirement for testing and modelling. Once this has been done, determine what pieces of equipment should be tested at what locations. Select the types of tests based on the types of models required. Produce a test plan for the location based on combining the standard tests and location-specific details. As much as possible, validate the models on-site, and train staff to collect appropriate data for future performance review. Finally, the testing methodology should conform to the utility's normal operating and maintenance practices.

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