Augmenting the Power System Toolbox: Enabling Automatic Generation Control and Providing a Platform for Cyber Security Analysis

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***Abstract*—The Power System Toolbox (PST) is a MATLAB-based package for simulating power system electromechanical dynamics. In this paper, we report on code that we developed to augment the capabilities of the PST, which enables the possibility of including the automatic generation control (AGC) system in simulations. In the process, we have also modified the linearization capability of the PST so as to include the effect of the AGC system when enabled in the simulation. The augmented PST package can be easily utilized for simulation studies in different applications. As an example, we focus on its utilization for assessing the impact of cyber events on power system dynamic performance. Specifically, by using the augmented PST package, users can inject various measurement errors and communication delays to signals that are used by the AGC system, and simulate the effect of such cyber events on system dynamic performance. We present several case studies to illustrate the new features added to the PST.**

I. Introduction

The motivation for this work lies in the necessity for re-examining the ability of current automatic generation control (AGC) systems to handle increased variability from, e.g., renewable-based generation, and cyber events. The main function of an AGC system is to maintain frequency at a nominal value and the inter-area power transfers at their scheduled values.

Traditionally, it has been assumed that the time scales on which the AGC operates are longer than those of other power system components, e.g., exciters, and governors. Thus, AGC is usually not included in conventional electromechanical dynamics simulation packages. Also for the studies in which it is necessary to include the effect of the AGC, the response of other system components is assumed to settle down fast enough so as to model the components as a set of algebraic equations rather than as a set of differential equations [1]; however, this assumption is not accurate due to the large inertia of conventional generators in a power system. Moreover, various emerging technologies that are being integrated in the power grid may challenge the operation and performance of current AGC system designs. For instance, the deep penetration of renewable-based generation introduces high variability into the system, which may result in current AGC systems to fail to meet performance requirements. In addition, new types of resources in ancillary service markets (e.g., batteries, and thermostatically-controlled load participating as demand response resources), which although can alleviate the variability and intermittence of renewable-based generation resources, also bring up new questions about the suitability of current AGC system designs. For instance, the AGC command signals to battery-type participants must be properly designed to be energy-neutral (i.e., the mean of the power regulation signals is zero over a certain period). Also the fast response ability of these resources allows the AGC system to send command signals to these resources more frequently, so as to improve the system performance. Thus, for both analyzing power system dynamic performance, and designing new AGC algorithms, it is necessary to include a model of the AGC in power system electromechanical simulation packages.

Although there are a few customized software tools to simulate power system electromechanical dynamics that include a model of the AGC system per the request of customers [2], most commercial power system simulation tools do not. For instance, although PowerWorld is able to set generators to participate in AGC in steady-state simulation, a model of the AGC system is not included in its dynamics simulation capability. Neither is PSS®E capable of including the AGC model in electromechanical dynamic simulations. In order to achieve so, specific modules have to be written by users [2].

In this paper, we augment the Power System Toolbox (PST) [3], a MATLAB-based toolbox for simulating power system electromechanical dynamics. The capabilities of the augmented PST package include the following: (*i*) the dynamics of a power system with AGC can be simulated by a comprehensive nonlinear model including AGC dynamics, turbine-governor control, excitor control, generator dynamics, etc; and (*ii*) the linearized model corresponding to the augmented dynamic systems can also be obtained so that, e.g., small-signal stability analysis can be easily conducted. Major advantages of this open-source MATLAB-based package include the full access to system state variables and the ease of implementing different AGC schemes.

As an application example, and since cyber-physical security has been identified as the one of the priority areas in next generation power systems [4], we use the augmented PST package to study the impact of cyber events on the system performance. As a centralized control system, the measurements and commands used in AGC have to be transmitted between the control center and generators over a communication network. Thus, the AGC system will be inevitably affected by cyber events, such as network traffic or cyber attacks. In this regard, in order to control the AGC-enabled PST package when conducting such cyber security studies, we developed a graphical user interface (GUI). This GUI allows users to easily impose different kinds of measurement noise/errors and communication delays to signals used by the AGC system, and simulate the impact on power system dynamics.

II. Power System Dynamics with AGC

In this section, we present the mathematical models that PST uses to simulate power system electromachanical dynamics, along with the AGC system model that we use to augment the current PST capabilities. The resulting model is described by a set of differential-algebraic equations (DAEs). We also present a linearized model of the aforementioned system, which can be used for small-signal analysis purposes.

A. Nonlinear Model

1) Electromechanical dynamics: In the original PST, there are various models to describe the dynamics of power system components (including different synchronous generator models, excitation system models, power system stabilizer models, turbine-governor models, and load modulation models). The details of such models can be found in [5]; in the remainder, we just provide a compact model of the power system electromechanical dynamics that results from interconnecting such individual component models.

Let $x(t)$ denote a vector including the dynamic state variables of all the aforementioned component models at time t, e.g., the angles and speeds of all the synchronous generators. Let $y(t)$ denote the vector of system algebraic state variables at time t, which includes bus voltage magnitudes and angles. Let $p(t)$ denote the vector of active power loads at different buses at time t. Then, the system electromechanical dynamics can be described by a set of DAEs of the form

$$\begin{aligned} \dot{x} &= f(x, y, u), \\ 0 &= g(x, y, p), \end{aligned} \tag{1}$$

with functions f and g representing, respectively, the evolution of the dynamic states and the algebraic constraints that arise from the physics of the system (i.e., the power flow equations); and $u(t)$ denoting a vector containing the governor set points that are determined by the AGC system at time t, as described next.

2) AGC system dynamics: The AGC system calculates the values of governor set points to offset the generation and demand mismatch, so as to regulate the system frequency to its nominal value. In addition, for a power system with multiple balancing authority (BA) areas that are connected through tie lines, the AGC attempts to maintain the inter-area power flows at their scheduled values. Let $\mathcal{A}$ denote the set of all BA areas in the interconnected power system. These AGC objectives are achieved by driving to zero the so-called area control error (ACE) of each BA area $m \in \mathcal{A}$, which is defined as follows:

$$ACE_m = \sum_{n \in \mathcal{A}_m} (P_{mn} - P_{mn}^{sch}) + b_m(f_m - f_{nom}), \tag{2}$$

where b_m is the bias factor, and $\mathcal{A}_m$ denotes the set of BA areas that are connected to area m through tie lines. The variable $P_{mn}(t)$ denotes the actual power interchange from area m to its neighboring area n at time t, while $P_{mn}^{sch}(t)$ denotes the corresponding scheduled value. The variable $f_m(t)$ is the actual system frequency at time t, while f_{nom} is the nominal system frequency.

In order to augment PST to enable simulations that include AGC, we adopt the AGC control logic described in [1], the dynamics of which we describe next. Let $z_m(t)$, $m \in \mathcal{A}$, denote a variable representing the sum of set point values of generators participating in AGC in area m at time t. Then, the evolution of $z_m(t)$ is described by

$$\dot{z}_m = -z_m - ACE_m + \sum_{i \in \mathcal{G}_m} P_{S_i}, \tag{3}$$

where $\mathcal{G}_m$ is the set of generators in area m that participate in AGC, and $P_{S_i}(t)$ is the power output of generator i in $\mathcal{G}_m$ at time t. For each generator $i \in \mathcal{G}_m$, the set point at time t, denoted by $P_{C_i}(t)$, is proportional to $z_m(t)$, i.e., $P_{C_i}(t) = \kappa_{m_i} z_m(t)$, where the participation factors κ_{m_i}'s satisfy $\sum_{i \in \mathcal{G}_m} \kappa_{m_i} = 1$. Then, the set points form the vector $u(t)$ in (1), i.e., $u(t) = \{P_{C_i}(t)\}_{i \in \mathcal{G}_m}$. By defining $z(t) = \{z_m(t)\}_{m \in \mathcal{A}}$, we can compactly write the AGC system dynamics as follows:

$$\begin{aligned} \dot{z} &= h_1(x, y, z), \\ u &= h_2(z). \end{aligned} \tag{4}$$

B. Linearized Model

Assume that (1) and (4) evolve towards an equilibrium point (x^*, y^*, z^*, u^*) under a constant load profile p^*. With a change in load profile, $\Delta p(t) = p(t) - p^*$, the system state trajectory becomes $x(t) = x^* + \Delta x(t)$, $y(t) = y^* + \Delta y(t)$ $z(t) = z^* + \Delta z(t)$, and $u(t) = u^* + \Delta u(t)$. For sufficiently small $\Delta p(t)$, by linearizing (1) and (4) around (x^*, y^*, z^*, u^*), we obtain a linearized model described by a set of linear DAEs of the form

$$\Delta \dot{x} = A_1 \Delta x + A_2 \Delta y + B_1 \Delta u, \tag{5}$$

$$0 = A_3 \Delta x + A_4 \Delta y + C_1 \Delta p, \tag{6}$$

$$\Delta \dot{z} = A_5 \Delta x + A_6 \Delta y + B_2 \Delta z, \tag{7}$$

$$\Delta u = B_3 \Delta z, \tag{8}$$

where the matrices $A_1 - A_6$, $B_1 - B_3$ and C_1 are obtained by evaluating the partial derivatives of the functions f, g, h_1, and h_2 for (x^*, y^*, z^*, u^*).

Assume that the invertability of matrix A_4 always holds, then by plugging Δy and Δu into (5) and (6), we have that

$$\begin{aligned} \Delta \dot{x} &= A_1^l \Delta x + B_1^l \Delta z + C_1^l \Delta p, \\ \Delta \dot{z} &= A_2^l \Delta x + B_2^l \Delta z + C_2^l \Delta p, \end{aligned} \tag{9}$$

where

$$A_1^l = A_1 - A_2 A_4^{-1} A_3,\ B_1^l = B_1 B_3,\ C_1^l = -A_2 A_4^{-1} C_1,$$
$$A_2^l = A_5 - A_6 A_4^{-1} A_3,\ B_2^l = B_2,\ C_2^l = -A_6 A_4^{-1} C_1.$$

We claim that the linear model in (5)-(9) is useful for small signal stability evaluation and analysis, although there are two issues that need to be considered. First, for certain operating points, if constraints or hard limits of the states of some electric components (e.g., exciters, and governors) are hit; then (1) and (4) are not differentiable. However, this has been addressed in the PST by numerically calculating the Jacobian matrix by applying a small perturbation to each state variable, rather than analytically differentiating the corresponding functions. Second, the AGC is implemented in a discrete-time fashion with a relatively large time step by appropriately discretizing the continuous-time representation in (4), rather than in a continuous way as presented above. However, we will show in Section V that although large AGC time steps will slow the process, the system stability characteristics are preserved.

III. Implementation of the AGC System Model

In this section, we present a procedure for implementing a model for the AGC model described in Section II-A in the PST, as well as a procedure for obtaining the matrices of the corresponding linear model, as defined in (9).

A. AGC System Model Implementation

The PST includes a function called "mtg_sig" to modulate the governor set point values during simulation. The modulation signals are defined in a matrix called "tg_sig" and passed as a global variable. In terms of implementation, it is worth noting that according to the PST setup, the modulation signals are not exactly the governor set-point values, but the difference between the set-point values determined by the AGC and the scheduled generation values determined, e.g., by economic dispatch. Therefore, without AGC, "tg_sig" is set to zero by default.

To implement the model of the AGC system in Section II-A, we modified the function "mtg_sig" enabling it to take measurements of system frequency and the power flow on tie lines, and to perform the calculations described in (2) and (3). Then, the set points for participating generators are calculated based on their participation factors. After subtracting the scheduled generation values, the set points are assigned to the modulation signal "tg_sig". Note that we use the average of the generators' speeds as an approximation of the actual system frequency. Also, note that since the power bases for the system and generators are different, the set point values have to be properly scaled in order to get the correct values to be passed to the generator governors. Finally, we comment on the time step of the AGC system. Typically, the AGC signals are sent out to the generators every 2 to 4 seconds. Therefore, we set the AGC time step as a parameter in our toolbox, which the user can define in the case files. Then, the value of "tg_sig" is recalculated according to this AGC time step parameter (e.g., every 2 seconds) rather than the system simulation time step. The value of "tg_sig" is kept constant in between times.

B. Linearized Model

The PST possesses a linearization capability that provides a linear dynamic model of the form:

$$\begin{aligned}\Delta\dot{x} &= A_1^{PST}\Delta x + B_1^{PST}\Delta u + C_1^{PST}\Delta p,\\ \Delta v &= D_1^{PST}\Delta x + D_2^{PST}\Delta u + D_3^{PST}\Delta p,\end{aligned} \tag{10}$$

where $\Delta v(t)$ denotes the variation on the measurement variables used in AGC at time t, i.e., the generator output and the power flow on the tie lines between areas. The superscript PST indicates that these matrices can be obtained by executing the original PST code. The details regarding how to calculate these matrices can be found in the description of the driver function "svm_mgen" in [5]. Note that the sensitivity matrix of the generator electrical output (in per unit) with respect to system state is on each generator base; therefore, it has to be scaled properly when used in the ACE calculation.

With AGC enabled, one way to obtain a linearized model for the whole system is to fully modify the PST source code to re-evaluate the Jacobian matrix of the nonlinear electromechanical dynamic system model together with the AGC model; instead, we implemented a method that makes use of (10). To this end, we rewrite the AGC evolution equation (7) as

$$\Delta\dot{z} = A_{10}\Delta x + A_{11}\Delta v + B_2\Delta z, \tag{11}$$

where the entries of A_{10}, A_{11} and B_2 can be determined by combining (2) and (3). Then, by combining (8), (10), and (11), we obtain a linear dynamic model of the form in (9), where

$$\begin{aligned}A_1^l &= A_1^{PST}, & A_2^l &= A_{10} + A_{11}D_1^{PST},\\ B_1^l &= B_1^{PST}B_3, & B_2^l &= A_{11}D_2^{PST}B_3 + B_2,\\ C_1^l &= C_1^{PST}, & C_2^l &= A_{11}D_3^{PST}.\end{aligned}$$

IV. Graphical User Interface and Applications in Cyber Security

We also developed a graphical user interface (GUI) for users to easily run simulations; the control panel of this GUI is shown in Fig. 1. After the user selects the case file and checks the AGC-ON box in the first row, the simulation results will be displayed upon the user's request (e.g., frequency, and voltage magnitudes and angles at certain buses). The user can also choose to execute a simulation using either one or both of nonlinear and linearized models as discussed in Section II.

This GUI also provides an interface to directly compromise the measurements used by the AGC system, and evaluate the effects on power system dynamic performance. First, the user can choose the measurement variable (among those that are used by the AGC system) to be compromised. Let $r(t)$ denote the actual value of the selected variable at time t, and $\hat{r}(t)$ denote the corresponding compromised value. The user can introduce errors and delays to this measurement variable. Both deterministic and random measurement errors can be added.

The error parameters, denoted as ϵ, can be determined either by adjusting the first slider (see Fig. 1), or by directly entering the parameter value in the textbox under this slider. Then, for

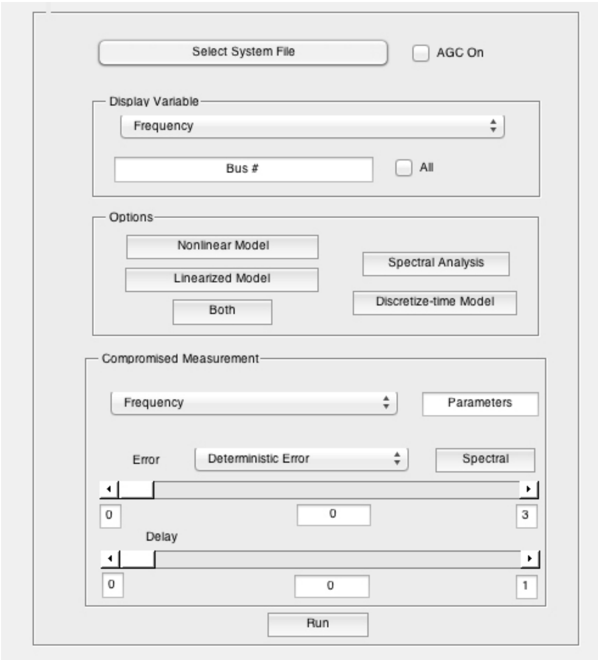
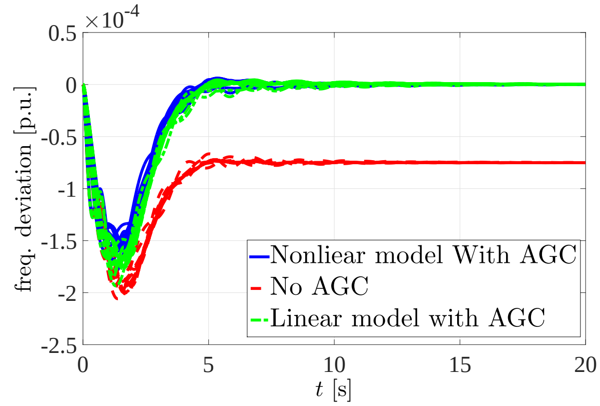


Figure 1: AGC simulation package interface.

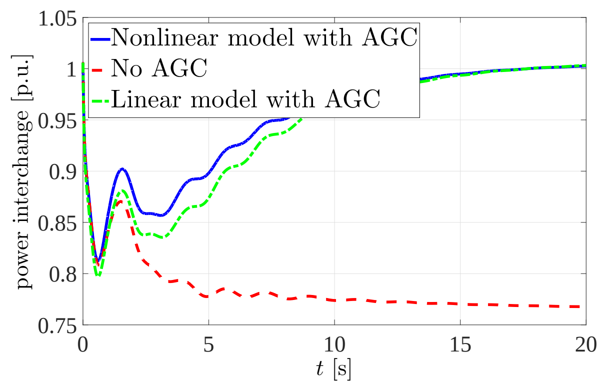
the deterministic error case, the corresponding variable will be shifted by ϵ, i.e., $\hat{r}(t) = r(t) + \epsilon$; for the random error case, the variable will be shifted by $\epsilon N(t)$, i.e., $\hat{r}(t) = r(t) + \epsilon N(t)$, where $N(t)$ is a standard Gaussian white noise process. Similarly, the communication delay, denoted as τ, can be introduced through the second slider (see Fig. 1), or in the textbox underneath. Then, the corresponding variable will be delayed by time τ, (i.e., $\hat{r}(t) = r(t - \tau)$), and then used in the calculation of (2).

V. Case Studies

In this section, we demonstrate the capabilities of the augmented PST using a 68-bus 16-machine system, which is a reduced-order model of the New England/New York interconnected system. Its one-line diagram and detailed description can be found in [6]. The parameter values are defined in a data file, which is part of the PST suite [5]. To implement AGC, extra data fields to define the BA area topology, and AGC parameters (e.g., bias factors, participation factors, scheduled power interchange values) are added to the data file. In this case, we assume that there are two BA areas, and the tie lines are Line 1-2, 1-27, and 9-8, according to the one-line diagram in [6]. The scheduled power interchange value is assumed to be one determined by the initial steady-state conditions. Note that in the first two simulations, we set the AGC time step equal to the simulation time step in order to illustrate the accuracy of the linearized model. However, we understand that this is not practical; therefore, in the following studies, we investigate the impact of relatively larger AGC time steps.



(a) Frequency.



(b) Power interchange.

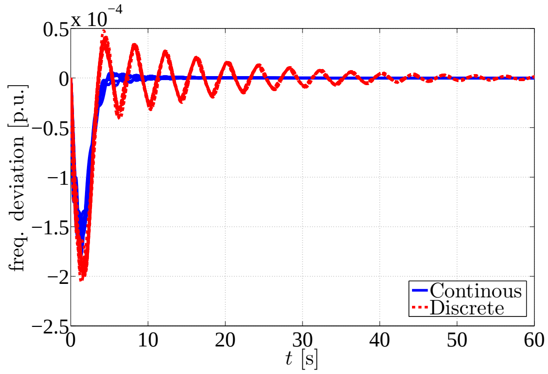
Figure 2: System performance with and without AGC.

A. Nonlinear Model Validation

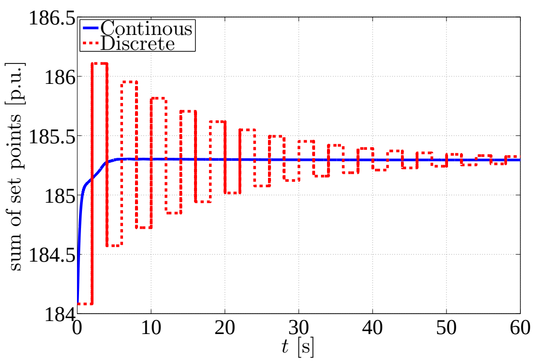
First, to showcase the new AGC simulation capability, we arbitrarily increase the load at buses 4, 8, 37, 41, 42, and 52 by 0.1 p.u. Without the AGC system, the frequency deviation at each generator is depicted in Fig. 2(a). For the case when the AGC system is enabled in the simulation, the frequency deviation at each generator is also depicted in Fig. 2(a). In this case, we can observe that the AGC restores the system frequency back to nominal frequency. The power interchange values from one area to the other with and without AGC are depicted in Fig. 2(b), where we can see that the AGC works as expected by bringing the power exchange back to its scheduled value.

B. Linearized Model Validation

With the same data set, we obtained the linearized model as described in Section III-B. In order to verify its correctness, we plot the approximate frequency deviation of each generator using the linearized model in Fig. 2(a), and the approximate power interchange in Fig. 2(b) respectively. As one can see, the simulation results agree with the trajectories obtained using the full nonlinear model.



(a) Frequency.



(b) Sum of set points.

Figure 3: System performance with discrete AGC signal.

C. Impact of AGC time steps

Originally, we implemented the AGC system as described in (4) with the AGC time step equal to the simulation time step (i.e., 0.005 second), with the corresponding system response as shown by the blue (solid) lines in Fig. 3(a). Here we change the AGC time step to 2 seconds; the resulting frequency deviation at each bus is plotted in Fig. 3(a) in red (dashed) lines. Similarly, the sum of set points to all the governors with continuous and discrete time intervals is displayed in Fig. 3(b) by blue (solid) and red (dashed) lines respectively. From these two figures, we can observe that convergence is preserved with both time intervals, except that the system converges slower with 2-second time step.

D. Cyber Security Studies

As an illustrative example, we investigate the impact of measurement noise on the system performance. White noise is added to the frequency measurement. The frequency trajectories at bus 1 obtained using the nonlinear and linearized models are plotted in Fig. 4. First, one can notice that both trajectories are very close to each other, which validates the linearization capability of the AGC-enabled PST. Moreover, the results indicate that the AGC system is generally robust to white noise. Further analysis on the impact of different types of measurement errors and delays on the system dynamic performance was investigated in [7], [8], where this toolbox has been utilized extensively to comprehensively evaluate the impact of compromised measurements due to malicious attacks (e.g., measurement delays caused by Denial-of-Service attacks and measurement errors caused by man-in-the-middle attacks).

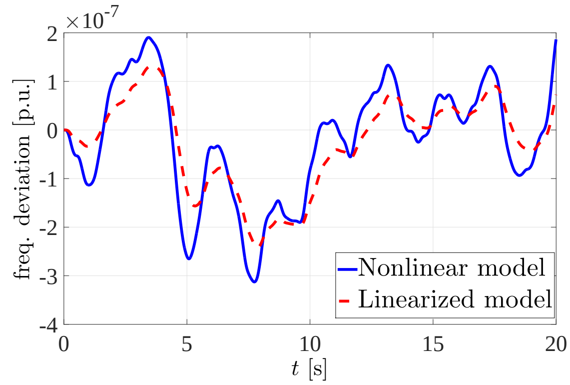


Figure 4: System performance with measurement noise.

VI. Concluding Remarks

The AGC-enabled PST presented in this paper can simulate power system dynamics with a comprehensive nonlinear model that includes the system network, generator dynamics, excitation control, turbine-governor response, power system stabilizer, along with AGC. This AGC-enabled PST also provides a linearization capability that can be used for small-signal stability analysis. These capabilities have been validated with a two-area test case.

This toolbox can facilitate simulation studies in different applications. As an example, we use this package to evaluate the impact on system dynamic performance of cyber events. To this end, we developed a GUI, which allows users to easily inject errors and delays on the measurements used in AGC.

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