A Real-Time Platform for Teaching Power System Control Design

G. Jackson, U.D. Annakkage, A. M. Gole, D. Lowe, and M.P. McShane

***Abstract*— This paper describes the development of a real-time digital simulation platform that can be used for the teaching of design principles for power system controls. In the developed approach, a rapid controller-prototyping platform (dSPACE) is interfaced to a real-time power system simulator (RTDS). The real-time platform is very successful when used in a post-graduate University course; but should also prove equally beneficial to the training of practicing engineers. The approach permits developers to physically prototype their designs and via the simulator, have them tested as if in the field. In contrast to off-line simulation, this approach extends the design to the next logical step, and exposes engineers to the important issues of implementation and real-time testing. The use of this platform is demonstrated through the design of a power system stabilizer (PSS) for a One-Machine Infinite Bus (OMIB) system.**

***Index Terms*— Real-Time Digital Simulation, Electromagnetic Transients Simulation, Power System Stabilizer (PSS), Controller Design**

I. Introduction

There is an emerging need for advanced controllers in today's highly complex restructured power networks. Such controllers can permit the reliable operation of these networks closer to their capacity constraints. Training engineers to design such controls is often carried out through the use of small signal and transient stability programs. However, this does not generate experience in the design and testing of a physical controller. Implementing a prototype on hardware is time consuming, and often there is no opportunity to field-test the resulting controller. This paper proposes an approach that interfaces a commercially available rapid controller-prototyping platform to a real-time digital simulator. The rapid prototyping platform offers a simple means for the construction of the physical controller. The real-time digital simulator behaves like an actual power system and provides signals to the controller in real-time. For all practical purposes, this is tantamount to connecting the controller to the actual power system and is the next best option, as closed-loop testing within the grid is not possible due to safety and stability concerns. This stage is critical because while simulations have assured us that the theoretical basis for the designed controller is solid, they have also effectively bypassed many of the implementation issues that must be addressed for any real controller. These implementation issues include but are not limited to input scaling, converter selection, and noise mitigation.

Authors would like to thank Natural Sciences and Engineering Research Council of Canada (NSERC) and RTDS Technologies for the financial support for the project.

Gregory Jackson, U.D. Annakkage, and A. M. Gole are with the University of Manitoba, Winnipeg, Canada.

D. Lowe, M.P. McShane are with the Queens University, Belfast, Northern Ireland, UK.

Presented at the International Conference on Power Systems Transients (IPST05) in Montreal, Canada on June 19-23, 2005
Paper Number IPST05-169

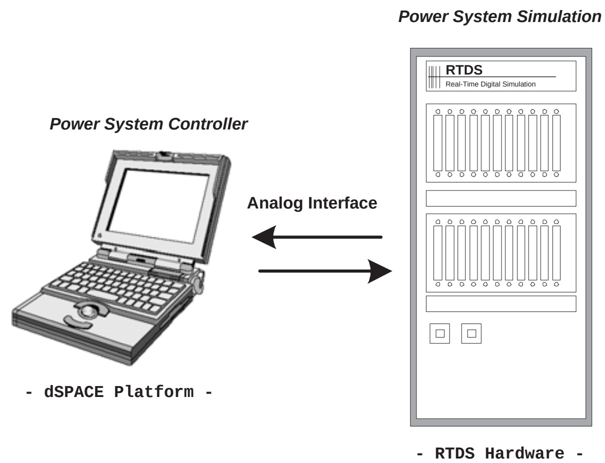

Fig. 1. Control System Design Platform

As shown in Fig. 1 the platform consists of two main parts: (i) a rapid controller-prototyping platform (dSPACE) which is interfaced to (ii) a real-time digital simulator (RTDS). The RTDS provides a means of rapidly building a model of the power system under consideration. The real-time capability allows for the coupling of a physical controller to a simulated system so that its performance may be evaluated. The RTDS has an emtp-type representation and so can provide a very detailed and realistic model of the system, including all non-linearities.

Students are first required to develop simplified models of the power systems, linearize these and then as instructed in the course, design suitable controllers. Once the controller is designed, it can be physically implemented using the rapid-control prototyping capability of the dSPACE platform. The students can also design a purely analog controller using operational amplifiers if they choose not to use the dSPACE platform. The control signals from the dSPACE platform are fed to the RTDS and the resulting power system signals are observable as computer plots, on a host work station, or on an oscilloscope. Using this approach, students can rapidly evaluate how well a controller designed using approximations works on a real system with its details and non-linearities. They can thus also visualize the limitations of the design.

The paper presents such a design exercise in which a

Power System Stabilizer (PSS) is designed. The stabilizer is physically implemented as a real control system, with the power system being modelled on the RTDS.

Section II describes the components which constitute the developed platform. Section III details the process of designing a PSS and section IV demonstrates the usefulness of the platform using an example of a One Machine to and Infinite Bus (OMIB) system. Finally concluding remarks are made in section V.

II. The Developed Platform

The two main components of the developed platform are (1) The RTDS simulator and (2) the dSPACE rapid controller-prototyping platform.

1) **RTDS simulator**: The RTDS simulator is a powerful computer that accomplishes the task of real-time simulation via parallel computation. Exploiting the delay in travelling waves on transmission lines and using trapezoidal integration, the system is capable of performing time-domain simulation at real-time speed using time-steps less than 50μs. Such small time-steps enable the RTDS to accurately and reliably simulate power system phenomena in the range of 0 to 3 kHz.

   A power system to be simulated is constructed using a dedicated software suite called RSCAD. This software provides an easy to use GUI as well as large libraries containing numerous power system component and control models. The RSCAD suite is separated into different modules, the most important of which are *Draft* and *Runtime*. A system model is first built and compiled using *Draft* before the compiled file is used by *Runtime* to execute the simulation in real-time. If the scale of the model is too large for graphical construction, RSCAD can alternatively accept data files in other commonly used formats (eg. PSS/E). The *Runtime* module enables the user to interact with the simulation in real-time by modifying various parameters within the simulation.
2) **dSPACE rapid controller-prototyping platform**: The dSPACE platform forms the second part of the developed tool and it gives its user the ability to run, in real time, a controller designed using Simulink. Simulink is a very flexible software that includes a large library of conventional controls blocks. It also allows for the creation of custom logic and algorithms used in more advanced control schemes using structures known as S-functions. The dSPACE hardware includes a breakout board that gives access to its converters and digital ports. Controldesk software is used in a similar fashion to RSCAD's *Runtime* module to allow the user to interact in real-time with the simulation. This ability is particularly useful in controller tuning applications described below.

The two components described above are interfaced through their D/A and A/D converters. The laboratory set-up of the complete system is shown in Fig. 2.

Proper scaling of the quantities and signals input and output at each end of the developed platform must be done to ensure both the proper use of each converter's resolution and to avoid their saturation. Fig. 3 illustrates the scaling needed to transfer signals between the two platforms. The K constants shown are implemented in software and scale the signals sent to or received from the converters. K_1 and K_3 were chosen so that converter saturation was avoided then K_2 and K_4 were chosen so that the signals *X* and *Y* are equivalent to $X^{'}$ and $Y^{'}$ respectively.

A second interfacing issue that had to be addressed prior to the successful coupling of the two simulators was the nullification of any DC offsets which appeared when transferring signals between them. The presence of the offset can be determined by outputting a known constant from one platform and verifying that it is correctly transferred to and interpreted by the other. Both the RTDS-to-dSPACE and dSPACE-to-RTDS directions of signal transfer were checked for offsets. A series of constants which are each misinterpreted by the same additive constant confirms the presence of converter offset. The magnitude of the offset is taken as equal to one platform's numerical interpretation of the constant zero sent from the other.

III. Controller Design

The design of a classical PSS is used as an example of how the developed platform can be used in the design and testing of any power system controller. The natural response of a power system when subjected to a disturbance consists of a range of frequencies. Typically it is the electromechanical oscillations, in the range of 0.5 to 2.0 Hz, which are lightly damped and hence more problematic in power systems. The purpose of a PSS is to add damping to these oscillations by modulating the excitation of a generator such that an electrical torque in phase with the deviation of its rotor speed is generated. The speed being the derivative of the rotor position, provides derivative feedback and hence a damping torque.

The first step of the generally accepted means of designing a classical PSS is to develop a detailed model of the power system. This model includes generators, loads, controllers and the

Fig. 2. Laboratory set up of the complete system

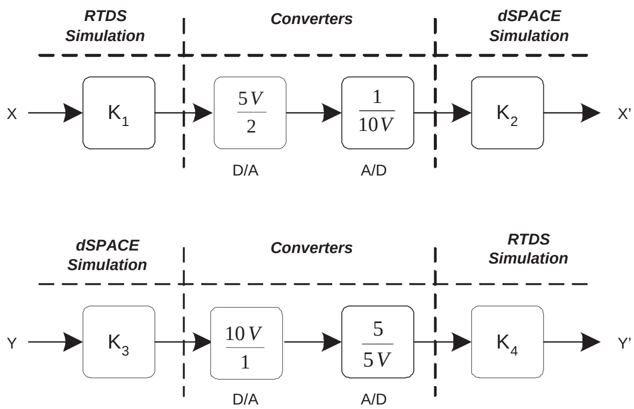

Fig. 3. Scaling of signals for the interface

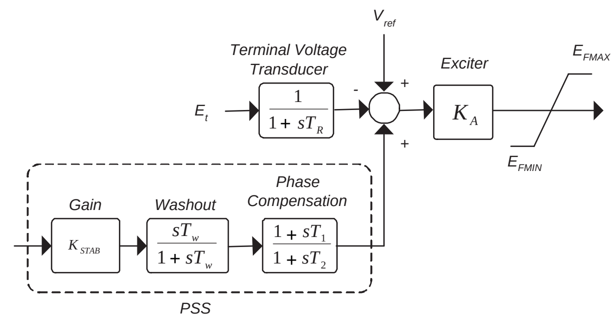

Fig. 4. Control block diagram of AVR and PSS

transmission line impedances connecting theses components together. The power system model is essentially a set of non-linear differential equations together with a set of algebraic equations. This model is linearized about a chosen operating point so as to facilitate the application of linear control systems theory [1]. A brief outline of the linearization process is given below.

A simplified model of a synchronous generator is commonly used for the design of PSSs. The generators with their exciters are represented by the typical fourth order dynamic model (third order generator plus a first order exciter) as shown in (1).

$$\begin{aligned}
\dot{\delta} &= \omega_0(\omega_r - 1) \\
\dot{\omega_r} &= \frac{1}{2H}\Big(T_m - E_q^{'} i_q - (X_q - X_d^{'}) i_d i_q - K_D \omega_r\Big) \\
\dot{E_q^{'}} &= \frac{1}{T_{d0}^{'}}\Big(E_{fd} - E_q^{'} - (X_d - X_d^{'}) i_d\Big) \\
\dot{E_{fd}} &= -\frac{1}{T_a} E_{fd} + \frac{K_a}{T_a}\left(V_{ref} - V\right)
\end{aligned} \quad (1)$$

These equations can be linearized and expressed in the compact form for *m* number of generators as shown in (2) and (3). The derivation of this model is found in [1].

$$\Delta \dot{X}_{gk} = A_{gk}\Delta X_{gk} + B_{gk}\Delta U_{gk} + E_{gk}\Delta V_{gk} \quad (2)$$

$$\Delta I_{gk} = S_{gk}\Delta X_{gk} - Y_{gk}\Delta V_{gk} \quad (3)$$

where, $k = 1 \quad \cdots \quad m$

$$\Delta X_{gk} = \begin{bmatrix} \Delta\delta_k & \Delta\omega_k & \Delta E_{qk}^{'} & \Delta E_{fdk} \end{bmatrix}^{'}$$

$$\Delta U_{gk} = \left[\Delta T_{mk} \quad \Delta V_{refk}\right]^{'}$$

Above, ΔI_{gk}, is the change in current injected by generator k to the network and ΔV_{gk} is the change in voltage of the network node to which generator k is connected.

The voltage-current relation of the network is modelled as:

$$\Delta I = [Y]\,\Delta V \quad (4)$$

The state space representation of the complete power system can be obtained in the standard format of (5) and (6), by eliminating ΔV and ΔI from the differential-algebraic equations of the generators (2) and (3), and the network equations (4).

$$\Delta \dot{X} = A\Delta X + B\Delta U \quad (5)$$

$$\Delta y = C\Delta X \quad (6)$$

The state space representation obtained in the above described manner is useful in determining the dynamic characteristics of the power system. For example, the eigenvalues of the system matrix **A** give the frequency and damping of oscillations, and the mode-state participation factors obtained from the eigenvectors of **A** can be used to identify the electromechanical oscillation modes.

At the generator where the PSS is to be installed the transfer function relating the change in electromagnetic torque, produced by a change in its excitation, can be established using the linearized model (5) and (6). Next the transfer function can be used to calculate the phase relation between the electromagnetic torque and excitation at those electromechanical oscillation frequencies deemed problematic through eigenvalue analysis. Recalling that the goal is to modulate the generator excitation so that the resulting change in electromagnetic torque is proportional to the change in speed the controller must compensate for the phase difference between excitation input and the electromagnetic torque. Fig. 4 shows a control block diagram of an excitation system consisting of an automatic voltage regulator (AVR) whose function is to regulate the machine terminal voltage, and a PSS to damp out oscillations. The washout block is essentially a high pass filter that prevents constant or slowly changing speed deviations from affecting a generator's excitation. The time constants T_1 and T_2 of the PSS are selected such that the required phase difference is obtained at the electromechanical oscillation frequency, and the gain of PSS is selected to provide sufficient damping to the oscillations. The reference [1] describes the procedure given above in detail.

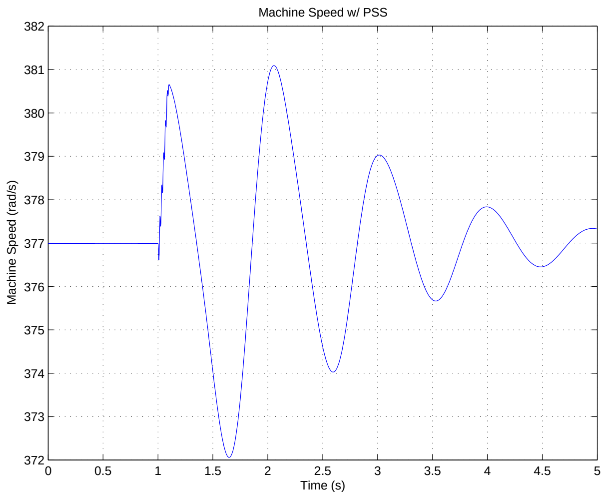

Fig. 5. Generator speed with PSS from off-line simulation

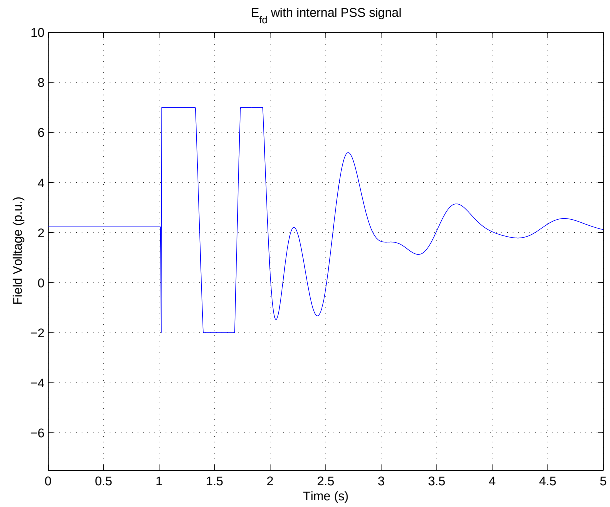

Fig. 6. Excitation with PSS signal calculated internally (in RTDS)

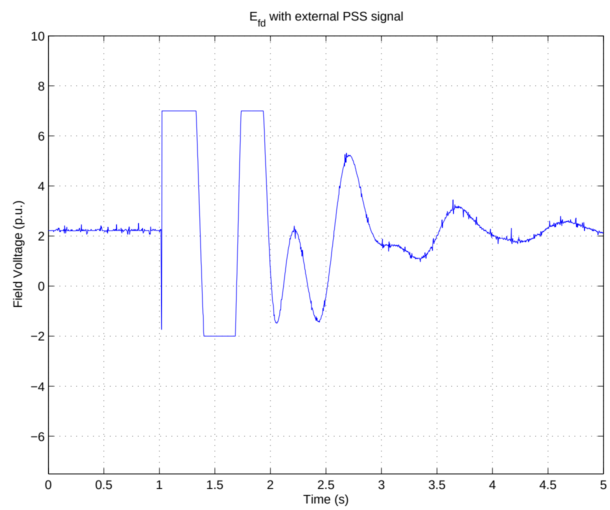

Fig. 7. Excitation with PSS signal calculated external to RTDS simulation

IV. Controller Implementation and Testing

For the purpose of demonstration, an OMIB system based on an example given in [1] was constructed and simulated on the RTDS. The controller, designed using the procedure described in section III (also given in [1]), was implemented in Simulink and transferred to the dSPACE environment.

The utility of the developed platform as an educational tool is two fold. The first being as a validation tool to verify that a controller developed using a simplified model performs well with a detailed non-linear model. Second, the developed tool can be used to assist in the tuning of controller parameters.

A. Validation Tool

A validation of the designed controller's effectiveness was done by applying a three phase fault for 0.06s at Bus 2 of the OMIB system given in the Appendix. The system is unstable without PSS due to the action of AVR. Fig. 5 illustrates the simulated response of the generator speed with the PSS. From educational point of view, this simple off-line simulation demonstrates the improvement of damping achieved through excitation modulation.

The next step involves separation of the controller (PSS) from the process it controls (Power System) and interfacing them in real-time. This achieves two benefits, the first of which is that it exposes students to practical issues such as signal sampling and noise mitigation. The second is that separating the controller and controlled process provides some reassurance that the controller can be physically realized in real-time, something that isn't necessarily a forgone conclusion when computationally intensive control algorithms are used. Fig. 6 shows the field excitation yielded by off-line simulation. Fig. 7 shows the same signal when the PSS is simulated on the dSPACE platform and the remaining system simulated on the RTDS. The two signals are in good agreement, except the excitation signal produced from the externally implemented PSS contains noise artifacts which are absent in the off-line simulation.

Fig. 8 and 9 show the machine rotor angle and phase 'a' machine terminal voltage respectively. Each demonstrates that both the off-line and on-line real-time simulations yield similar results.

B. Tuning Tool

Beyond using the platform as a means of confirming what is expected, it can be useful in refining a controller's parameters. Using the Controldesk software described in Section II, parameters of a design such as gain can be varied and the effects of such changes can be monitored in real-time. In the case of PSS fine tuning of its time constants, which were obtained using an approximate model of the system, would be desirable. Additionally, the operating point of the test system can be easily modified and thus the robustness of a designed controller under varied operating conditions such as off-nominal loading can be readily evaluated. This platform can therefore be extended to a tuning tool by adding necessary

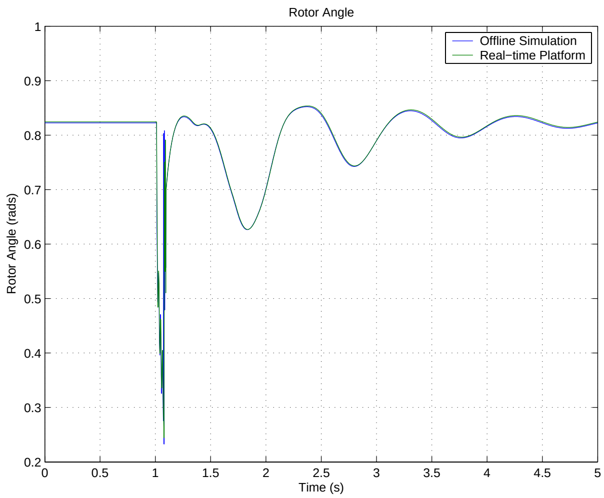

Fig. 8. Rotor angle (on-line and off-line)

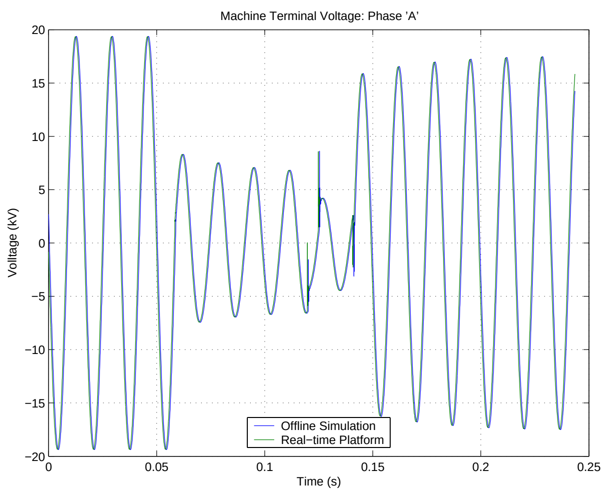

Fig. 9. Machine terminal voltage of phase 'a' (on-line and off-line)

components to quantify and display a chosen performance measure.

V. Conclusions

The development and use of a real-time platform for teaching Power System Control design has been presented in this paper. Such a tool can be integrated into the education of power system control engineers because it facilitates a number of benefits over purely off-line simulation based teaching. The most important of these being the exposure of students to many of the practical problems associated with physical controller design such as noise and signal sampling. Other advantages gained include (1) it provides a means of verifying that a designed controller is actually realizable, which is a critical issue with computationally intensive algorithms (eg. adaptive controllers), and (2) that it facilitates tuning of controller parameters.

References

[1] P.Kundur, *Power System Stability and Control*. McGraw-Hill International Book Company, 1994.
[2] *RTDS Manual, RTDS Technologies Ltd, Winnipeg, Canada*.
[3] *dSPACE Help-file; dSPACE, Germany*.
[4] *Simulink Help-file; The MathWorks, Inc; Massachusetts, USA, Germany*.

Appendix

Data for the OMIB system are as follows:

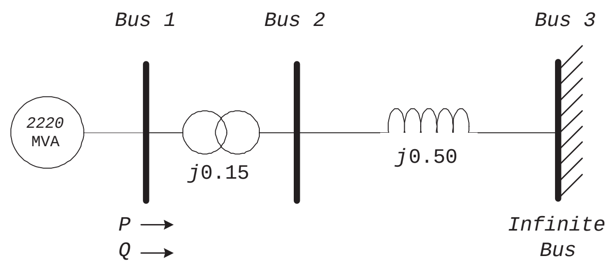

Fig. 10. OMIB system diagram

<u>System Data</u>

Rated MVA of Generator	2220	MVA
Rated RMS line-to-line voltage	24	kV
Base frequency	60	Hz
Transmission line reactance	0.50	pu
Transformer reactance	0.15	pu
Infinite Bus voltage, E_t	0.995	pu
Real power injected to Infinite Bus	0.9	pu
Reactive power injected to Infinite Bus	0.3	pu

<u>Generator data</u>

X_d	1.81 pu	R_a	0.003	pu
$X_d^{'}$	0.30 pu	$T_{do}^{'}$	8.0	s
$X_d^{''}$	0.23 pu	$T_{do}^{''}$	0.03	s
X_q	1.76 pu	$T_{qo}^{'}$	1.0	s
$X_q^{'}$	0.65 pu	$T_{qo}^{''}$	0.07	s
$X_q^{''}$	0.25 pu	H	3.5	s

<u>Exciter and PSS data</u>

K_A	200	K_{STAB}	9.5	s
T_1	0.154 s	T_R	0.02	s
T_2	0.033 s			

Acknowledgments

Authors would like to thank Heather Meiklejohn at RTDS for technical support.