# Audur - A Platform for Synchrophasor-Based Power System Wide-Area Control System Implementation

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**Abstract**

Electrical power systems continue to grow in size and complexity, resulting in new challenges to control and stabilize them. Measurement based Wide-Area Control Systems (WACS) have been extensively researched in the last decade to enhance power system stability. However, very few WACS implementations in the field have been carried out so far. To bridge this gap the LabVIEW package, Audur, presented in this paper, allows users to easily implement their custom WACS design on a National Instruments hardware platform. The hardware controller receives synchrophasor measurements compliant with the IEEE C37.118.2 protocol and generates a control signal that, in principle, can be configured as a supplementary control system to drive any active component in the power system.

*Keywords:* Power Systems, Wide-Area Control Systems, Oscillation Damping, Inter-Area Oscillations, Synchrophasors

## 1. Motivation and significance

Power systems have undergone drastic changes in the last few years with the integration of renewable energy sources, more interconnections and increases in electric power demand. Catastrophic events, such as the US North-East Blackout of 2003 [1], have shown that the traditional monitoring systems and automatic controls are not always sufficient. One specific controller, the Wide-Area Power Oscillation Damping (WAPOD)[1] has been extensively in-

[1]Historically, wide-area damping stabilizers have been termed WAPOD where the P represents a measurement of active power through the line. In this term, the active power here is used as a controller input signal. Although this term is not accurate when other signals are used as control inputs or feedback signals, the term is used here to maintain consistency with existing literature.

vestigated for the last few years [2][3]. Wide-Area Control Systems have been proposed as key means to enhance system stability [4]. WACS can be utilized for different control purposes, damping of electromechanical oscillations being of great interest for system-wide inter-TSO operations [5]. Even though this technology has great potential and is of great interest for system operators, only a few Wide-Area Control System (WACS) implementations have been tested in a real power system [6][7], while simultaneously off-line simulation studies on different types of WACS continue to appear in the literature.

The main motivation behind this project is to create a platform that can bridge the gap between the theoretical/simulation research on WACS and the challenges of an actual implementation. The WACS available today are not only few, but also proprietary. They are closed systems that are difficult or impossible to modify without the intervention of the vendor/supplier. The Audur platform is a general purpose WACS that allows the user to create a hardware controller using the National Instruments LabVIEW environment [8]. It is customizable, it can utilize different synchrophasor input signals and is easily adaptable to control different power system components. The hardware controller receives synchrophasor streams compliant to the IEEE C37.118.2 [9] standard from commercially available Phasor Measurement Units (PMUs) and/or Phasor Data Concentrators (PDCs) that are an essential part of Wide-Area Monitoring Protection and Control (WAMPAC) systems. The output of Audur is a synchrophasor-based control signal that can be configured to control, in principle, any active device in the power system.

## 2. Software description

Audur is a LabVIEW package that executes primarily on a National Instruments Compact Reconfigurable I/O (NI-cRIO) controller [8]. The NI-cRIO was chosen as the development platform because it allows rapid algorithm development and deployment, simplifies embedded control design and provides networking functionalities necessary for WACS. In principle, it can run on any of the other hardware platforms available from NI, provided that they meet certain software/hardware requirements (see Table 1). Audur allows the user to create customized hardware Wide-Area Control System (WACS) that utilizes two different synchrophasor data mediation tool-kits (also developed by the authors laboratory), $S^3$DK [10] and Khorjin [11], that provide different functionalities depending on the application.

$S^3$DK is an user friendly toolkit that provides drag-and-drop blocks and includes examples allowing the user to easily implement code for their needs.

The drawback of S$^3$DK is that it can not execute directly on the NI-cRIO and instead has to run on an external PC with a non Real-Time Operating System (RTOS). If used for a WACS, it adds a non-deterministic time delay to the control loop. Khorjin on the other hand is a C-based library and allows for its deployment in platforms running different OSs. A LabVIEW Real-Time package has been built around the core of Khorjin and is included in the Audur package for its use in WACS development. This allows Khorjin to run directly on the NI-cRIO so that control loop latencies are decreased and also allowing controller encapsulation. By utilizing either S$^3$DK or Khorjin, the user can access raw synchrophasor measurements, which can further be exploited in custom control algorithms.

Oscillations are inherent in power systems and become observable in synchrophasor measurements when a perturbation occurs and the system is excited. The nature of these oscillations is determined by the power system's characteristics. Thus, in most cases the frequency of oscillation is well defined. As an example of how custom WACS can be deployed using Audur, a Phasor POD project is included in the package. The Phasor POD algorithm uses a recursive least squares filter (or a low pass filter) to separate the average value from the oscillatory content of the input signal for a given frequency of oscillation [12]. This algorithm can be used to create damping control signals for any active device in the power system, using different synchrophasor measurements from the power system as input signals. The application of this control algorithms is practical as it does not depend on a power system model, so it is possible to use it without the need of going through extensive control design studies. For these reasons it is a suitable choice for creating a general purpose damping controller. This algorithm has only been reported in literature and is only available in the proprietary software of control system prototypes [6]. With this paper it is made available and open sourced for the first time and is included in the Audur package. The LabVIEW implementation of the Phasor POD algorithm was created by Rebello in [13]. Also, included as an example of how custom control algorithms can be designed using the Phasor POD is a load control algorithm that is reported in [14].

### *2.1. Software Architecture*

The software architecture for the two templates of Audur is shown in Fig. 1. The architecture refinement process is documented in [13]. There it shows how the initial software architecture was modified due to hardware and software limitations. The software architecture for the template using S$^3$DK is divided into three layers, one running on a non-RTOS (*UImain.vi*), the second on the real-time processor (*RT.vi*) and the third in the FPGA

(*FPGA.vi*) of the NI-cRIO. The software architecture for the template utilizing Khorjin is closer to the initial design of a two layer software architecture that can all be run on the NI-cRIO making it self-contained, compact and fast.

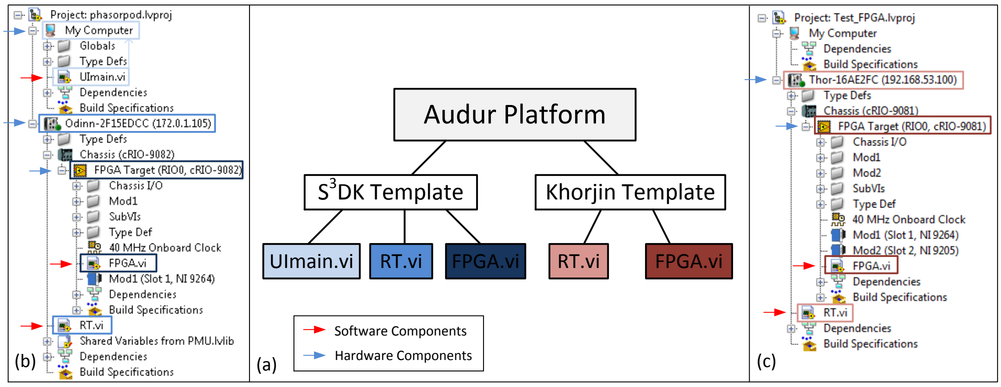


Figure 1: (a) Shows the software architecture of the Audur platform. (b) The LabVIEW project for the S$^3$DK template. (c) The LabVIEW project for the Khorjin template.

## 2.2. *Software Functionalities*

The template utilizing S$^3$DK is shown in Fig. 2 (a). The first layer (*UImain.vi*) is executed on a PC, where S$^3$DK is used to unwrap the IEEE C37.118.2 protocol into raw measurements in LabVIEW and forward them to the real-time processor of the NI-cRIO using LabVIEW Shared Variables. The second layer (*RT.vi*) runs on the real-time processor of the NI-cRIO. It receives the raw PMU measurements from the PC and manages input signal selection. The selected input signal is forwarded to the FPGA of the NI-cRIO. The third and last layer (*FPGA.vi*) runs on the FPGA of the NI-cRIO and receives the selected input signal from the real-time processor. Here the control algorithm is implemented and the control signal is fed to the analog output of the NI-cRIO.

The second template utilizing Khorjin is almost identical to the S$^3$DK template except that *UImain.vi* has been removed and Khorjin is, instead, included in the RT.vi running on the real-time processor of the NI-cRIO. This is shown graphically in Fig. 2 (b).

## 2.3. *Sample code snippets analysis*

The Audur package gives the user a template that can be used without the need for any modifications except in the *FPGA.vi*, where the control

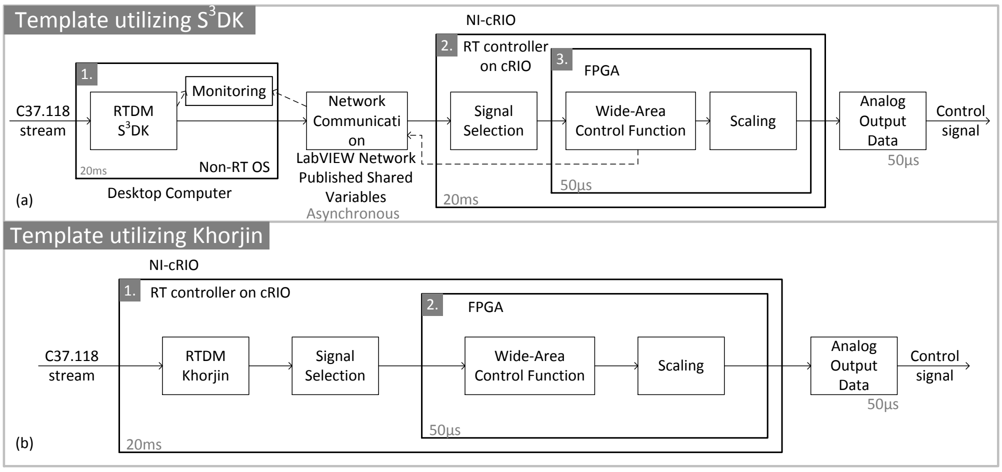


Figure 2: (a) The software functionalities for the template utilizing S$^3$DK. (b) The software functionalities for the template utilizing Khorjin.

algorithm is implemented. Figure 3 shows the three versions of LabVIEW code for the FPGA.vi included in the Audur package. In Fig. 3 (a) the empty FPGA.vi is shown. The user has complete freedom to create a custom control algorithm. Figure 3 (b) shows the FPGA.vi where the Phasor POD algorithm is included. It can be used to create custom control signals for different devices in the power system. An example of this is shown in Fig. 3 (c), where a load control algorithm using the Phasor POD algorithm has been included.

## 3. Illustrative Examples

To illustrate the utilization of Audur, the implementation of control algorithms, and how the platform can be tested, the Real-Time Hardware-in-the-Loop (RT-HIL) setup shown in Fig. 4 is used.

The power system model used to test the control algorithms is the two-area-four-machine Klein-Roger-Kundur power system model [14]. This model is executed in OPAL-RT's eMEGASIM Real-Time Simulator (RTS). The three-phase voltage and current measurements of the desired buses in the system are sent to the commercial PMUs in the lab. The PMUs compute the synchrophasors and stream them to a PDC using the IEEE C37.118.2 protocol. The PDC time aligns the measurements and creates an concatenated output stream. Next, either S$^3$DK or Khorjin unwraps the PDC stream into raw numerical values to be used in the LabVIEW environment. The raw data values are then fed to the control algorithm that is implemented on the

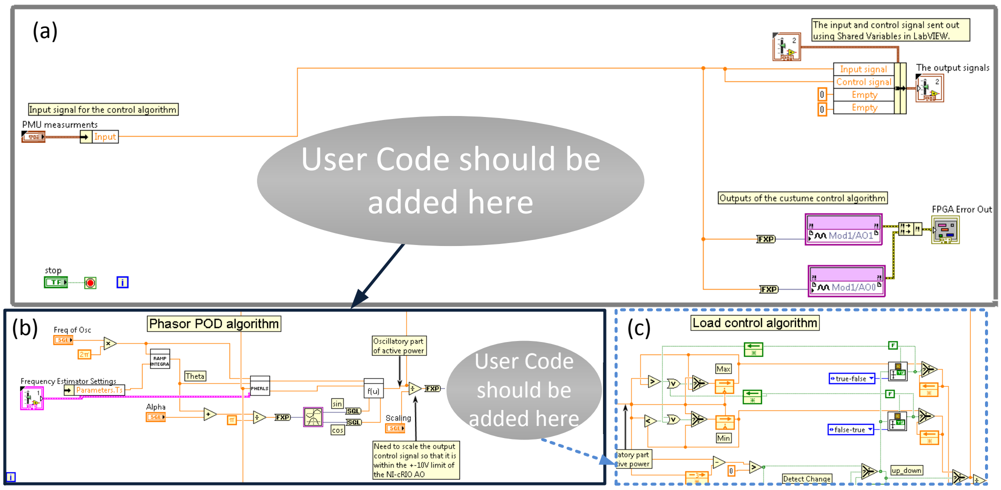


Figure 3: (a) The empty FPGA.vi template where the user can add a custom control algorithm. (b) The Phasor POD code included in the FPGA.vi. (c) The Load control algorithm implentation in LabVIEW that uses the Phasor POD algorithm.

NI-cRIO. Finally, an analog control signal is generated and interfaced with the RTS to provide a supplementary control signal to, either the SVC or the load in the power system model running on the RTS. This test setup was configured in the SmarTS Lab at KTH Royal Institute of Technology Stockholm, Sweden [15].

The control algorithms were tested in three steps. First, in Real-Time Software-in-the-Loop (RT-SIL), the control algorithm and the power system model are both simulated on the RTS but on separate cores that are connected together through the digital inputs and outputs of the simulator. Testing the algorithm in RT-SIL is the first step towards creating a hardware controller. It serves to validate the design and derive the requirements for the hardware implementation. The second and third step are used to test the algorithm in RT-HIL using S$^3$DK and Khorjin.

To test the damping performance of the algorithms a small disturbance of a 5% change in the voltage reference of Generator 1 in the power system model is applied. The controlled SVC is located in at the mid-point of the lines between Area 1 and Area 2. The load control algorithm is used to modulate the load in Area 2 [14]. In Fig. 5, the RT-SIL and RT-HIL results are shown. The controls are tested individually, not simultaneously, i.e. either the SVC or load are controlled at a time.

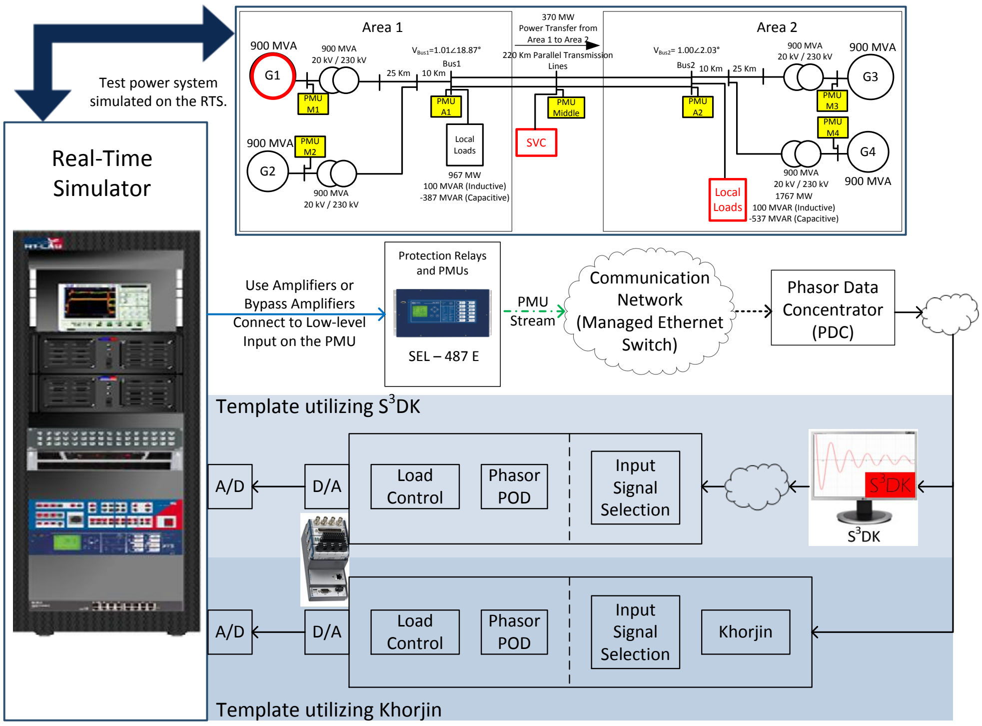


Figure 4: The Real-Time Hardware-in-the-Loop setup.

## 4. Impact

The main motivation behind this project is to facilitate design, implementation and testing PMU-based Wide-Area Monitoring Protection and Control (WAMPAC) applications [15]. To enable the development of PMU-based applications, a protocol parser had to be implemented to extract raw synchrophasor values from the IEEE C37.118.2 format stream. The work on parsers and synchrophasor tools was initiated in 2011 resulting in S$^3$DK [10], BabelFish [16][17] and Khorjin [11], which are all slowly being made available as open source software. The Audur package is the last piece needed for potential users to implement real-time controllers using a fully open source software solution. By making this package available, the loop is closed on the work started in 2011 and this serves as a capstone for many years of work and research. Several projects have used S$^3$DK to create different monitoring tools, [18][19], including a mode-estimation tool [20]. In these projects there is potential to combine monitoring tools with WACS applications where the Audur platform could be utilized, as described below.

In order to further establish the significance of the developed software

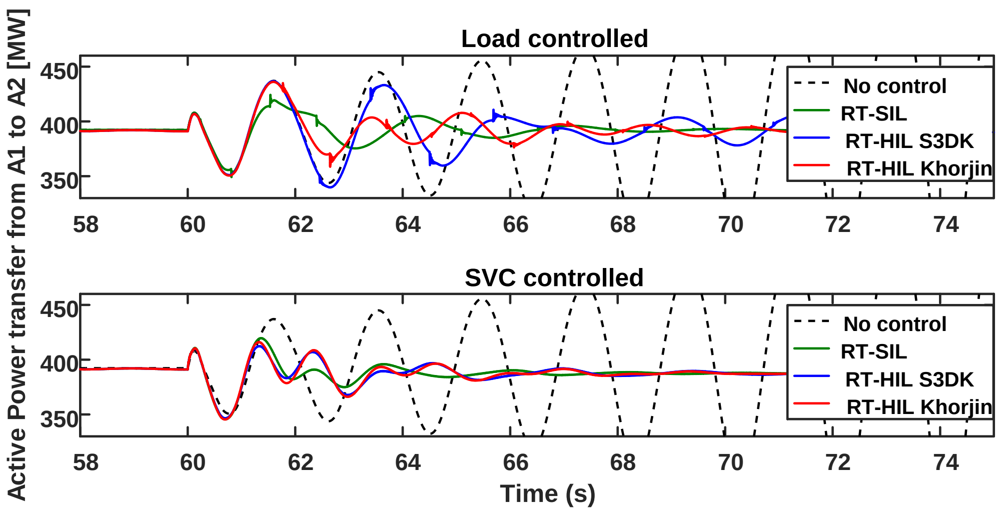


Figure 5: (a) The active power response when the load in Area 2 is controlled to damp the oscillations. (b) The active power response when the SVC is controlled to damp the oscillations.

package Audur, a brief summary of various research studies which utilized this software package are presented below.

1. Audur is used in a study to analyze the impact of time synchronization signal loss on synchrophasor-based control application [21]. Audur package was used to deploy a synchrophasor-based power oscillation damper configured to supply damping control signals to excitation control of generator. The experimental setup used for this study is shown in Fig. 6, whereas the performance of the damping controller when subjected to time synchronization signal loss is shown in Fig. 7. The study concluded that a loss of time synchronization signal degrades the performance of wide-area controller.
2. In subsequent study, Audur was utilized to investigate the impact of time synchronization spoofing on wide-area damping controller [22]. In this respect, "Audur" was used to deploy a synchrophasor-based power oscillation damping controller configured to provide supplementary damping signals to a Static VAR Compensator (SVC) connected at the mid-point bus of the Klein-Rogers-Kundur power system. The experimental setup used for this study is shown in Fig. 8, whereas the performance of the damping controller when subjected to time synchronziation signal spoofing is shown in Fig. 9. The study concluded that a loss of time synchronization signal degrades the performance of wide-area controller. This study concluded that time synchroniza-

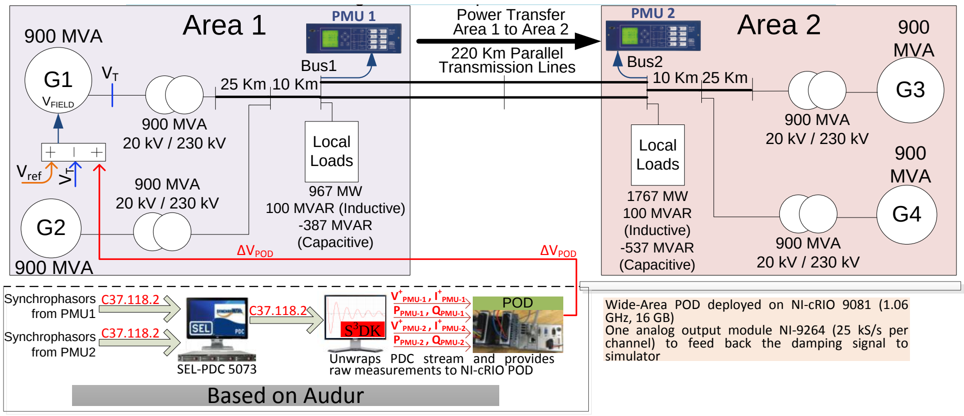


Figure 6: RT-HIL test setup to analyze the impact of time synchronization signal loss on wide-area control applications. The damping controller is based-on Audur and is shown outlined.

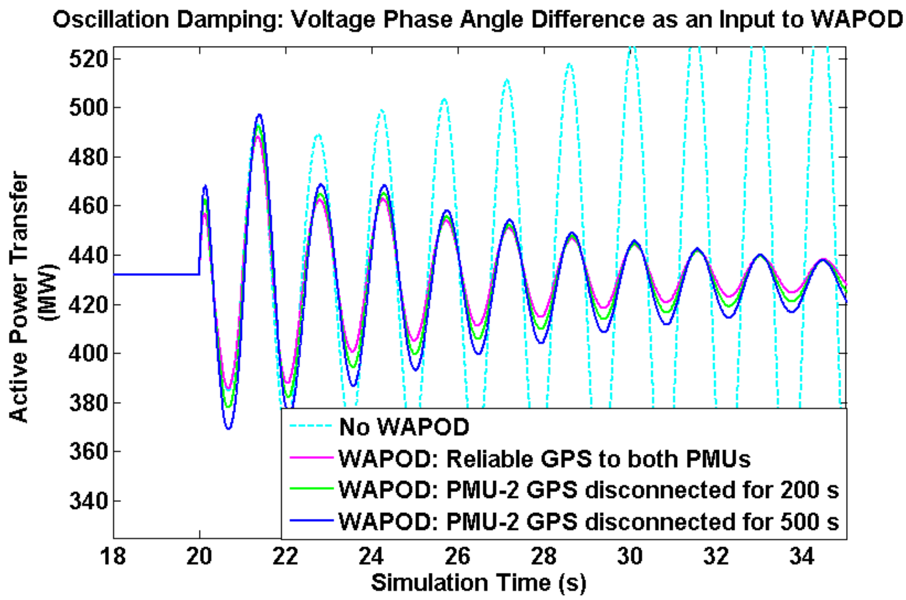


Figure 7: Performance of synchrophasor-based damping controller when subjected to loss of time synchronization signal.

tion spoofing attacks on a wide-area controller can introduce negative damping in the system and thus resulting in system instability.

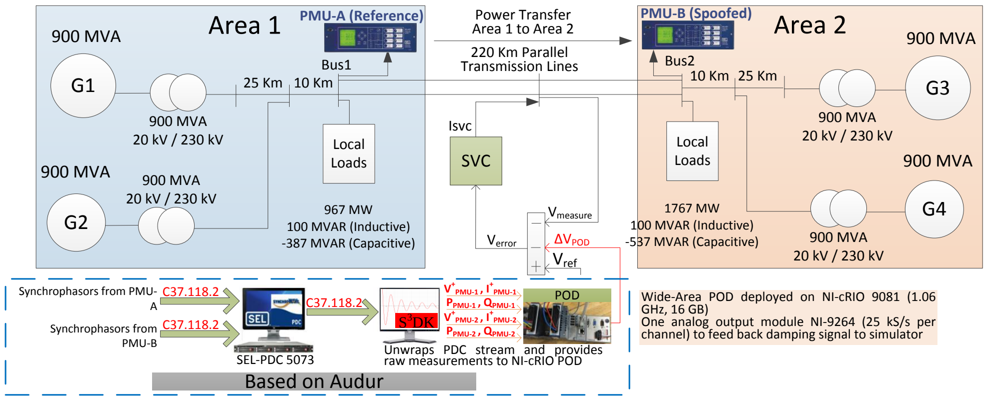


Figure 8: RT-HIL test setup to analyze the impact of time synchronization signal spoofing on wide-area control applications. The damping controller is based-on Audur and is shown outlined.

3. In a similar context, Audur was extended to prototype a wide-area damping controller that provides synchrophasor-based damping signals to a commercial excitation control system [23]. This controller comprised of the following components: (i) a real-time mode estimation module, (ii) synchrophasor's communication latency computation module, and (iii) phasor-based oscillation damping algorithm executing in a real-time hardware prototype controller. The experimental setup used to prototype this controller is shown in Fig. 10, whereas the performance of this WADC to damp multiple oscillatory modes is shown in Fig. 11. Through real-time hardware-in-the-loop simulation, it was concluded that the developed controller effectively identified critical oscillatory modes in the power system and compensated for communication latencies associated with the synchrophasor measurements to provide adequate damping to local and inter-area modes in the power system.
4. In another study, Audur was used to deploy a wide-area controller capable of exploiting synchrophasor measurements to improve transient stability of the system by modulating excitation booster voltage [24]. This controller was deployed using Audur and its main functions are shown in Fig. 12. This study concluded that the developed controller can improve the critical clearing time of the system by up to 60%.

It is worth noticing that without Audur, these studies would have been

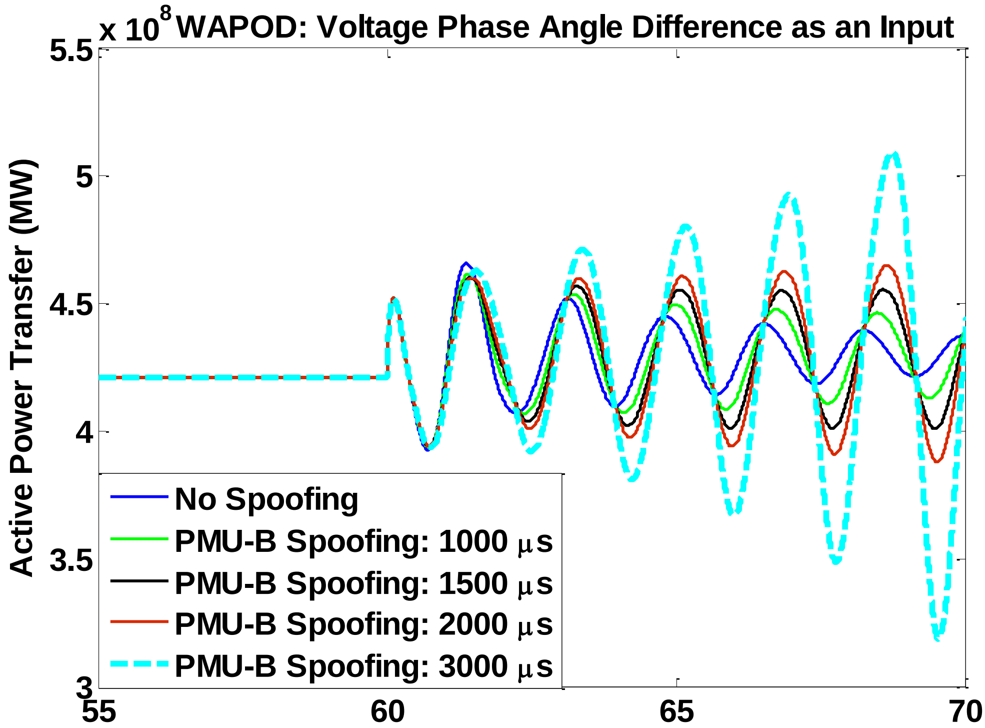


Figure 9: Performance of synchrophasor-based damping controller when subjected to time synchronization signal spoofing.

impossible to carry out or would have required entirely different design and implementation strategies, thus increasing the complexity and overall testing/deployment time.

The options available for users that want to implement WACS are at present limited to proprietary equipment from traditional vendors in the power industry, which favours the proprietary software development approach and only provides closed systems as in [12]. This locks researchers and end-users to a particular vendors system and the low-level functions (e.g. Phasor POD [12]) are inaccessible. In addition, the users do not have the freedom to modify and adapt the implementation to their requirements by themselves or through third parties. Even though the platform enabled by Audur locks the user into using LabVIEW and the cRIO, it still gives the user the freedom to use a National Instruments platform of their choice and to modify the controller's internal functions. This provides full access to all functions of the control system so they can be analyzed and modified to the requirements of the user, and thus, further facilitates rapid hardware

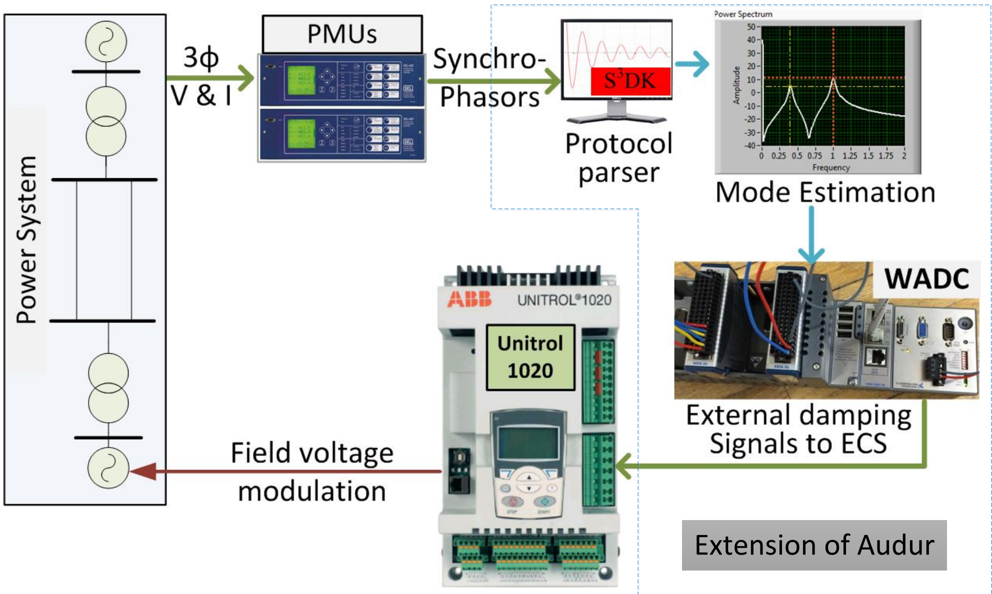


Figure 10: Prototyping of Wide-Area Damping Controller (WADC) using Audur. The WADC utilizes synchrophasor measurements to generate damping signals, which are fed directly to the commercial Excitation Control System (ECS) to provide oscillation damping.

Figure 11: Experimental results: 1.2 Hz local mode and 0.5 Hz inter-area mode damping using the internal-PSS and external damping signals from WADC.

prototyping at a lower cost. With the growth in research on synchrophasor technology and real-time simulation, laboratories for developing power system applications that have emerged during the last decade all over the world [25]. The Audur platform could give these laboratories a jump start at creating their own custom hardware WACS, and other wide-area synchrophasor applications for Wide-Area Protection Systems (WAPS).

## 5. Conclusions

This paper provides an overview of the Audur platform that was developed as the final piece to close the loop on many years of research and work focused on developing a custom WACS for damping of inter-area oscillations. This work is the result of the joined effort of previous and current students of the first author. The package is LabVIEW-based and enables the user to create hardware WACS on a NI platform. Even though this requires the user to adopt NI products, it provides the user the freedom to modify and

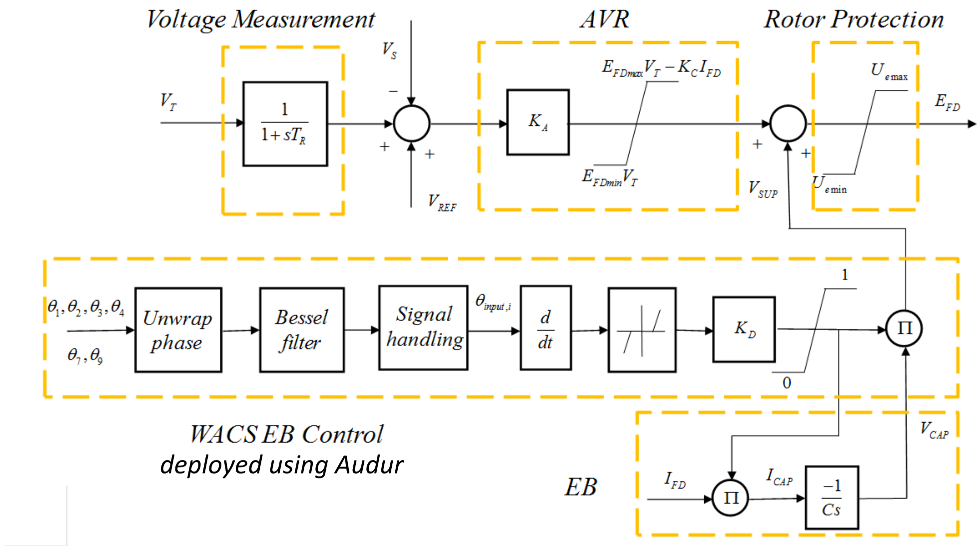


Figure 12: AVR, EB and WACS control deployed using Audur.

customize the implementation to their requirements, which has not been an option when using the very few commercial proprietary WACS available today.

The Audur platform includes examples that can be easily modified by the user to deploy custom WACS on National Instruments hardware. Further development of this software is based on the funding available for the first authors' research team at Rensselaer Polytechnic Institute, ALSETLab.

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## Dedication

This paper and OSS release is dedicated to the memory of the former R&D vice-president of Statnett SF, Jan Ove Gjerde, the first to believe and support the first author and his research team. R.I.P. 21-08-2016.

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## Required Metadata

## Current executable software version

| Nr. | Source and executable software metadata description | Please fill in this column |
|---|---|---|
| S1 | Current software version | v1.0.0 |
| S2 | Permanent link to executables of this version | `https://github.com/ALSETLab/Audur` |
| S3 | Legal Software License | GNU General Public License version 3 |
| S4 | Computing platforms/Operating Systems | National Instruments Compact Reconfigurable I/O (NI-cRIO) |
| S5 | Installation requirements & dependencies | LabVIEW 2013 SP1, LabVIEW Real-Time, LabVIEW FPGA, NI-cRIO driver |
| S6 | Quick Start Guides and Documentation | `https://github.com/ALSETLab/Audur` |
| S7 | Support email for questions | luigi.vanfretti@gmail.com |

Table 1: Audur - Software metadata