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.

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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^3DK [10] and Khorjin [11], that provide different functionalities depending on the application.

S^3DK 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^3DK 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^3DK 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^3DK 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.

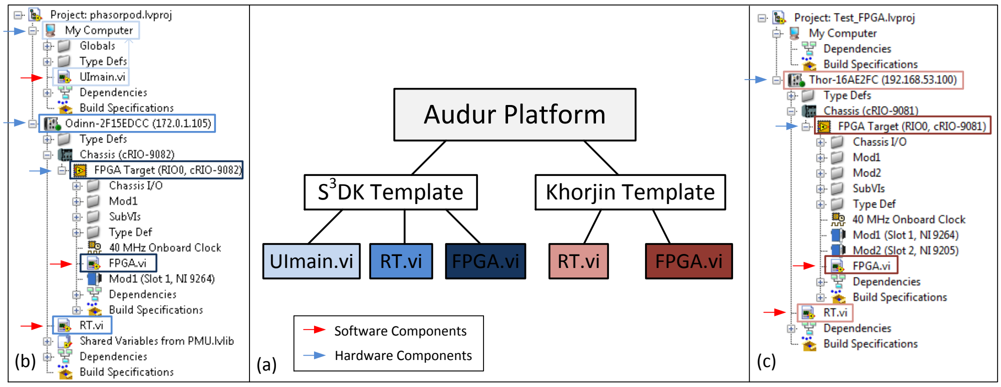

Figure 1: (a) Shows the software architecture of the Audur platform. (b) The LabVIEW project for the S^{3}DK template. (c) The LabVIEW project for the Khorjin template.

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

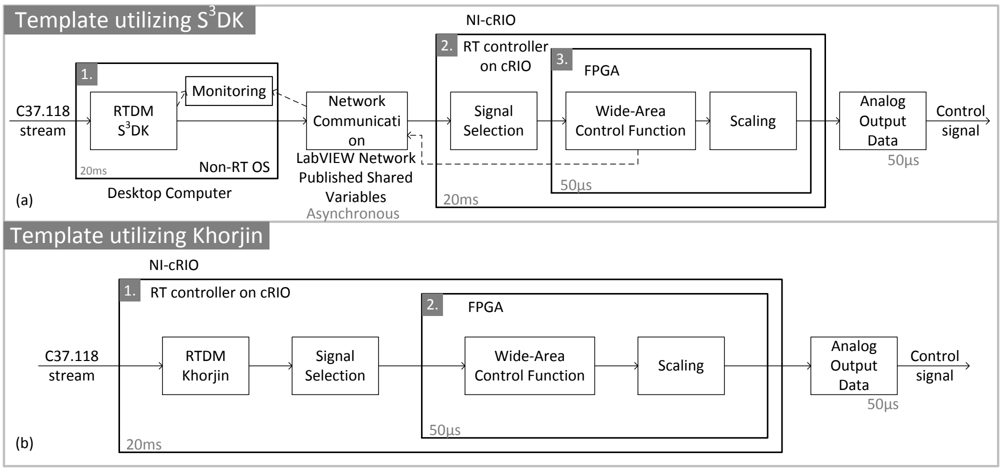

Figure 2: (a) The software functionalities for the template utilizing S^{3}DK. (b) The software functionalities for the template utilizing Khorjin.

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

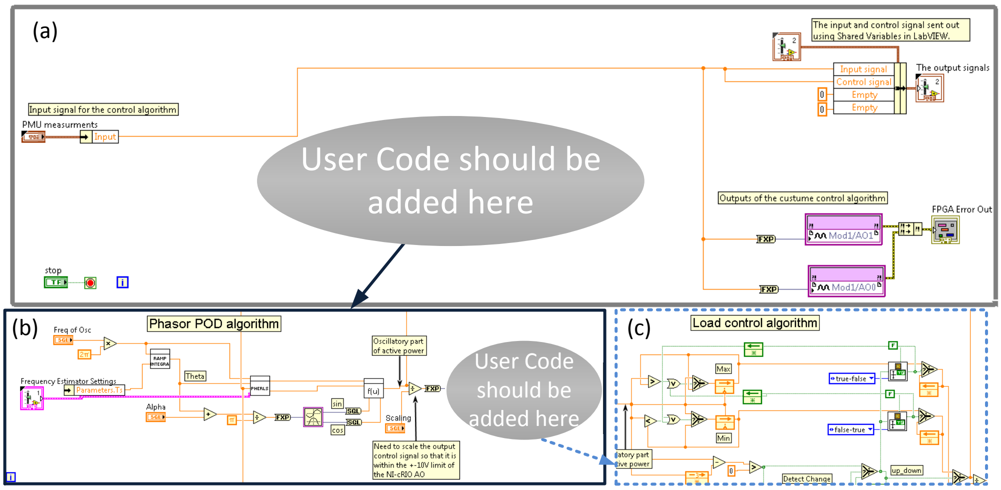

Figure 3: (a) The empty FPGA.vi template where the user can add a custom control algorithm. (b) The Phasor POD code included in the FPGA.vi. (c) The Load control algorithm implentation in LabVIEW that uses the Phasor POD algorithm.

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.

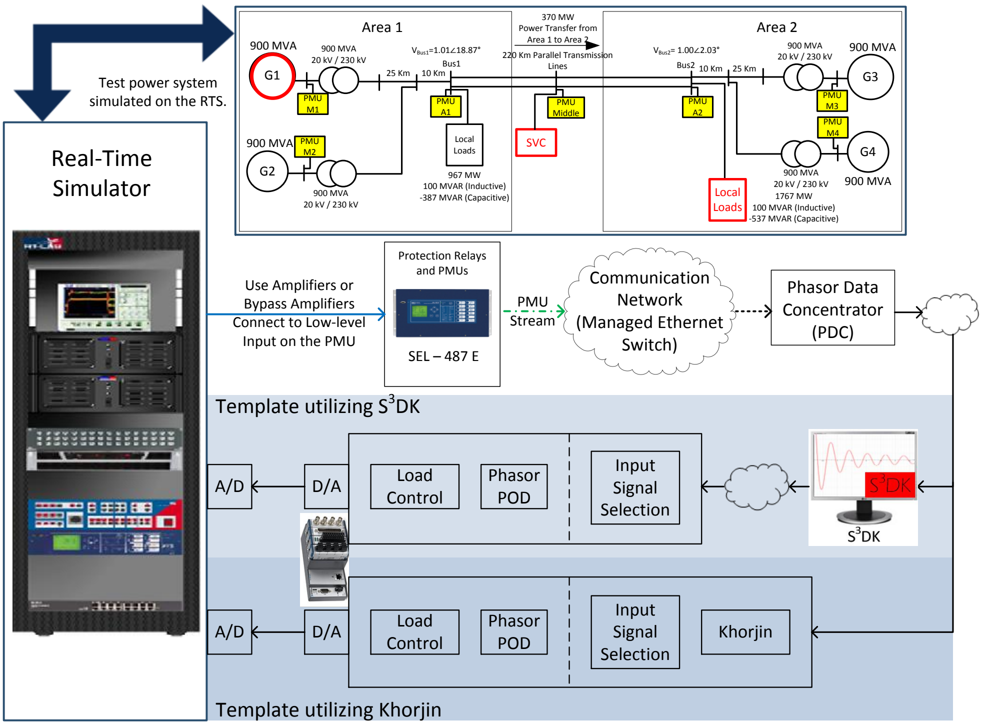

Figure 4: The Real-Time Hardware-in-the-Loop setup.

4. Impact

In 2011 the Smart Transmission System Laboratory (SmarTS-Lab) was established with the aim of designing, implementing 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 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 five years of work. 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.

The options available for users that want to implement WACS are at

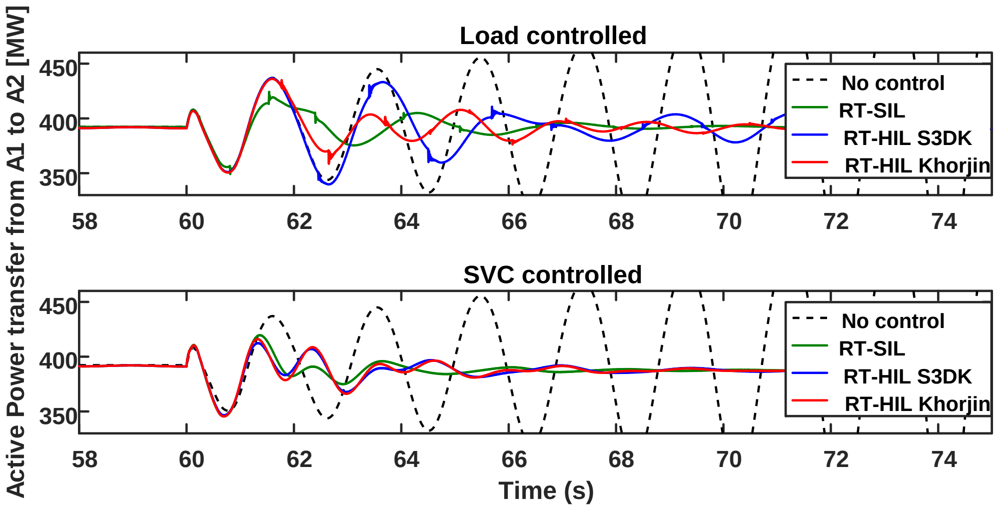

Figure 5: (a) The active power response when the load in Area 2 is controlled to damp the oscillations. (b) The active power response when the SVC is controlled to damp the oscillations.

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 functionalities (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. This provides full access to all functionalities of the control system so they can be analysed and modified to the requirements of the user, and thus, further facilitates rapid hardware prototyping at a lower cost. With the growth in research on synchrophasor technology and real-time simulation, laboratories for developing power system applications, just like SmarTS Lab at KTH have been popping up all over the world [21]. 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 five years of 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 members of the SmarTS Lab research team in Stockholm. 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 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 NI- hardware. Further development of this software is based on the funding available for the first authors research team (SmarTS Lab).

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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 SmarTS Lab research team. R.I.P. 21-08-2016.

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Required Metadata

Current executable software version

Nr.	(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/???*
S3	Legal Software License	???
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	If available, link to user manual - if formally published include a reference to the publication in the reference list	For example: *http://mozart.github.io/documentation/???*
S7	Support email for questions	???

Table 1: Software metadata (optional)