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Executive Summary to PDCI Oscillation Damping Controller Software Documentation

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Abstract

This report serves as the executive summary to the comprehensive document that describes the software, control logic, and operational functions of the Pacific DC Intertie (PDCI) Oscillation Damping Controller. The purpose of the damping controller (DCON) is to mitigate inter-area oscillations in the Western Interconnection (WI) by active improvement of oscillatory mode damping using phasor measurement unit (PMU) feedback to modulate power flow in the PDCI. This report provides the high level descriptions, diagrams, and charts to receive a basic understanding of the organization and structure of the DCON software. This report complements the much longer comprehensive software document, and it does not include any proprietary information as the more comprehensive report does. The level of detail provided by the comprehensive report on the software documentation is intended to assist with the process needed to obtain compliance for North American Electric Reliability Corporation Critical Infrastructure Protection (NERC-CIP) as a Bulk energy system Cyber Asset (BCA) device. That report organizes, summarizes, and presents the charts, figures, and flow diagrams that detail the organization and function of the damping controller software. The PDCI Wide-Area Damping Controller is the result of a collaboration between Sandia National Laboratories (SNL), Bonneville Power Administration (BPA), Montana Tech University (MTU), and the Department of Energy (DOE).

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We gratefully acknowledge the support of the BPA Office of Technology Innovation (Project No. 289, Project Managers: Mr. Gordon Matthews and Dr. Jisun Kim, Technical Point of Contact: Dr. Dmitry Kosterev), the DOE Office of Electricity (OE) Transmission Reliability Program (Program Manager: Mr. Phil Overholt), and the DOE-OE Energy Storage Program (Program Manager: Dr. Imre Gyuk). We express our sincere gratitude to BPA staff who have provided us with valuable guidance and advice throughout the project: Mr. Michael Overeem, Mr. Mark Yang, Mr. Jeff Barton, Mr. Greg Stults, Mr. Tony Faris, Mr. Dan Goodrich, Mr. Shawn Patterson, and Mr. Alex Chavez. We also express our sincere appreciation of the algorithmic and design expertise of Profs. Dan Trudnowski and Matt Donnelly of Montana Tech University. Finally, we thank our colleagues, Dr. Ray Byrne, and Dr. Jason Neely for their expertise and contributions throughout the life of the project.

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NOMENCLATURE

Abbreviation	Definition
AC	Alternating Current
BCA	Bulk Energy System Cyber Asset
BES	Bulk Energy System
BPA	Bonneville Power Administration
CIP	Critical Infrastructure Protection
COI	California-Oregon Intertie
DAQ	Data Acquisition
DC	Direct Current
DCON	Damping Controller
DOE	Department of Energy
DOE-OE	Department of Energy Office of Electricity
FERC	Federal Energy Regulatory Commission
FISMA	Federal Information Security Management Act
GPS	Global Positioning System
HVDC	High Voltage Direct Current
Hz	Hertz (cycles per second)
I/O	Input-Output
IEEE	Institute of Electrical and Electronics Engineers
kV	Kilo-Volts
KVM	Keyboard Video Monitor
MTU	Montana Tech University
MW	Mega-Watts
NERC	North American Electricity Reliability Corporation
NI	National Instruments
NIST	National Institute of Standards and Technologies
PDCI	Pacific Direct Current Intertie
PMU	Phasor Measurement Unit
SNL	Sandia National Laboratories
UPS	Uninterruptible Power Supply
WAMS	Wide Area Measurement System
WECC	Western Electricity Coordinating Council
WI	Western Interconnection

1. INTRODUCTION

1.1. Project Background

A collaborative effort between Sandia National Laboratories (SNL), Montana Tech University (MTU), and Bonneville Power Administration (BPA), dating back to 2013, was launched to design, develop, and demonstrate an active damping control system (DCON) to improve damping of inter-area oscillations in the Western Interconnection (WI). The control system accomplishes this goal by using real-time measurement data acquired from phasor measurement units (PMUs) to construct a feedback signal that modulates power flow through the Pacific DC Intertie (PDCI).

There are two primary motivations to increase damping of inter-area oscillations. First, if damping is insufficient, oscillations may lead to system-wide tripping events, and in turn to a series of cascading outages. The 1996 system break-up across the west coast of North America can in part be attributed to undamped oscillations. Avoiding these large-scale power outages provides a significant financial incentive in damping inter-area oscillations. Second, power transfer through long transmission corridors in western North America is often constrained due to stability concerns and limited by poorly damped electromechanical oscillations. Thus, additional damping may increase the power transfer capacity. Recent development in reliable real-time wide-area measurement systems (WAMS) based on PMUs has enabled the potential for large-scale damping control approaches to stabilize critical oscillation modes.

The original idea to modulate PDCI power flow to damp inter-area oscillations was first designed and tested in 1975. The original design utilized the real power flow on the California-Oregon Intertie (COI) as the feedback signal. Even though this method provided damping to low frequency modes of oscillation, further analysis determined that the local AC power flow feedback signal, had a transfer function zero, which limited the gain of the controller and worsened oscillations at higher frequencies. The DCON is able to avoid this problem because it incorporates GPS time synchronized PMUs to improve damping. This data is now available due to the recent deployment of PMUs throughout the WI, which provide fast, reliable, system-wide measurements.

Currently, the primary approach to mitigate grid oscillations and avoid blackouts in the WI is to operate well below transmission capacity, which is not economical. The DCON uses measurement data, acquired in real time from PMUs, to serve as a feedback signal to inform the controller as to how much power to add (or subtract) to the power flow on the PDCI. This carefully controlled “injection” of power to the PDCI is the action that damps oscillations in the grid. This control strategy provides damping to the primary north-south oscillatory modes in the WI without interacting with speed governor actions. A supervisory system, integrated into the controller, ensures a “do no harm” policy for the grid in which damping is never worsened. By improving the damping of these inter-area oscillations, the DCON has the potential to allow increased power transfers in the WI.

The DCON is the first successful wide-area grid demonstration of real-time feedback control using PMUs in North America. This is a game-changer, enabling the use of widely-distributed networked energy resources that have the potential to transform the existing power grid into the future smart grid. Benefits that the DCON is capable of delivering, once operational, include: (1) Additional reliability to the grid from improved damping of electromechanical oscillations. (2) Additional contingency management of the grid under stressed system conditions. (3) Higher power limits in specific transmission corridors. (4) Reduction and/or postponement in new transmission capacity expansion.

1.2. Purpose of Document

This report serves as the executive summary to the comprehensive document that describes the software, control logic, and operational functions of the Pacific DC Intertie (PDCI) Oscillation Damping Controller. This report provides the high level descriptions, diagrams, and charts to receive a basic understanding of the organization and structure of the DCON software. This report complements the much longer comprehensive software document, and it does not include any proprietary information as the more comprehensive report does. The comprehensive software document presents the charts, figures, and flow diagrams that describe in substantial detail the design, structure, and operational functions of the DCON software. The level of detail provided in the comprehensive report is intended to serve as an important step in the process to obtain Critical Infrastructure Protection (CIP) compliance required by the North American Electricity Reliability Corporation (NERC) for a device to perform as a Bulk energy system Cyber Asset (BCA).

1.3. Organization of Document

This report is organized as follows. Because the DCON software design uses LabVIEW for coding, Chapter 2 provides sufficient background on the conventions and structures employed by LabVIEW that are needed to detail the DCON software. The DCON software design is based on the LabVIEW conceptual structure known as a Virtual Instrument (VI). There are two main VIs used by the DCON software. One of these VIs handles the asynchronous functions of controller operation (e.g., data logging, user interfaces), and the other VI handles the real-time functions of controller operation (e.g., real-time data acquisition, control law construction). One of the primary objectives of the comprehensive software document is to provide the general description and block diagrams for each LabVIEW VI and subVI used by the DCON software.

Chapter 3, which presents an overview of the DCON software organization, is divided into three sections. Section 3.1 describes the hierarchical structure for each of the two main VIs. Section 3.2 presents the high level block diagrams and flowcharts that provide an overview of the operational flow employed by the DCON software design. Section 3.3 contains some brief explanatory notes on the conventions and nomenclature used by the comprehensive software document in presenting LabVIEW software structures. In the more comprehensive software document, there is a Section 3.4 that provides substantial detail for the two main VIs, their associated subVIs, and the software libraries needed by the VIs and subVIs. This report does not contain the detail provided in Section 3.4 of the comprehensive report.

Following Chapter 3 is a list of relevant references to find additional details on the DCON hardware design, performance of the DCON in PDCI tests, simulation analysis, modeling details, and project background. In addition, seminal papers describing work performed in the decades leading up to the commencement of this project are also provided. Finally, in the comprehensive software document, Appendix A contains the oversized figures, describing some of the VIs and subVIs, that are too large to be neatly displayed in the main text of that document. This report does not contain an appendix.

1.4. How to Read the Comprehensive Software Document

Due to the length of the comprehensive software document, it is recommended to use Microsoft Word's built-in search tools to navigate the report. Clicking the 'Navigation Pane' checkbox under the 'View' tab will display all the entry levels of the documentation's numbered list. The Navigation Pane also contains a search bar (which can also be accessed via the keyboard shortcut 'CTRL+f'). Use the shortcut 'CTRL+scroll wheel' to zoom, as many VIs have large block diagrams. The command 'CTRL+Left Click' can be used to follow any hyperlinks present in that document. This executive summary report does not contain these search tools.

2. LABVIEW PROGRAMMING

This chapter provides a general introduction to some of the common symbols and control structures used in LabVIEW programming. Included in this section are: data types/wires, structures/loops, and VI symbols. This section was written with the assumption that the reader has both knowledge of fundamental programming skills and an understanding of basic programming terms. If the reader knows a common programming language (such as C/C++ or Java), then most of the terms introduced in this section should be familiar to them.

Figure 1 shows some of the common VI symbols used in LabVIEW. Since there are many types of individual VIs present in LabVIEW, only the two general types are shown.

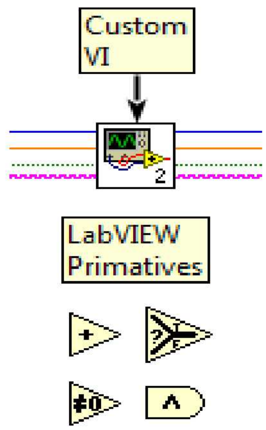

Figure 1. LabVIEW VI Symbols

Custom VIs are user-defined functions that are generally used to simplify more complex programming. The inputs to the custom VI are on the left of the icon, and the outputs are on the right. The icon image can be customized, as well as the number of inputs and outputs. The lower group of tan-colored VIs, known as LabVIEW primitives, contains the more common VI symbols present in many LabVIEW programs. These VIs are built into LabVIEW to preform basic programming tasks such as addition and array indexing. Only a few of the LabVIEW primitives are shown here, as there are hundreds of primitives that perform all basic programming functions.

Figure 2 shows some of the common data types and wire connections used in LabVIEW. Note that only common LabVIEW data types are shown, and more complex data types such as typedefs and objects are not.

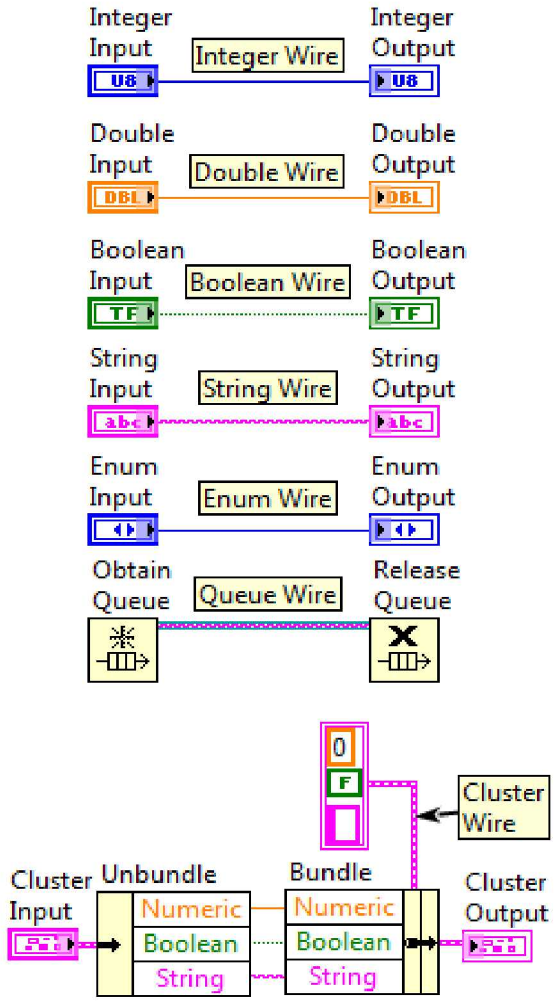

Figure 2. LabVIEW Data Type Symbols

The first five date types (Integer, Double, Boolean, String, and Enum) are primitive data types that behave the same way in LabVIEW as they do in other programming languages. A 'Queue' is an abstract data type used for data handling and processing, which can also be found in object-oriented languages like C++ and Java. The 'Cluster' data type is unique to LabVIEW, and operates similarly to a structure in C. Clusters are commonly used as a more efficient way to pass large groups of variables between VIs.

Figure 3 shows some of the common control structures used in LabVIEW.

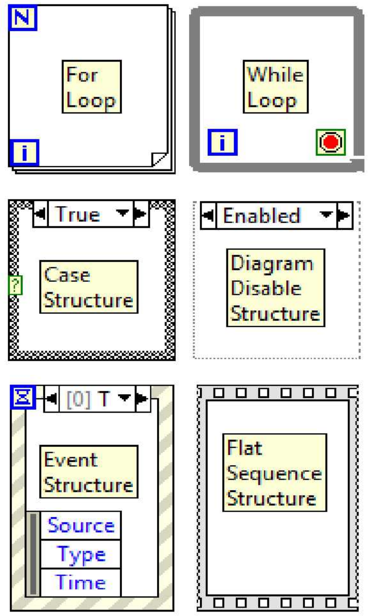

Figure 3. LabVIEW Control Structure Symbols

The For and While loops shown behave the same way in LabVIEW as they do in other programming languages. The Case structure operates similarly to an If statement in other programming languages. Although, a Case structure can also have more than two cases, where it behaves like a Switch Case. The Diagram Disable Structure is LabVIEW's way of disabling or 'commenting out' large sections of code. It behaves like multi-line comments in other languages. The Event and Flat Sequence structures are unique to LabVIEW. The Event Structure waits until a certain event occurs and executes the code in its sub diagram upon that occurrence. The Flat Sequence structure behaves and looks like a film reel, in that it executes one 'frame' of code at a time, from left-to-right. It is commonly used for control over program flow.

3. OVERVIEW OF DCON SOFTWARE DOCUMENTATION

3.1. Software Structure

The project documentation is organized into a numbered list, creating a hierarchy like that of the actual project file structure. This numbered list is divided into two main sections, one for each top level VI file (async_pc_main.vi and rt_damping_controller_main.vi). Each main section is then further divided into smaller entries for each of the programming libraries. The library sections are then furthered divided into smaller entries containing the documentation for each of the individual VI files. Some of the libraries have one main VI file that calls many subVIs, so each subVI is put on the next level of the numbered list after the main VI. Figure 4 contains an example showing how the documentation is structured.

1. async_pc_main.vi

1.1. Library #1

Library description...

1.1.1. VI #1

1.1.2. VI #2

1.2. Library #2

Library description...

1.2.1. Main VI

1.2.1.1. SubVI #1

1.2.1.2. SubVI #2

More Entries

2. rt_damping_controller_main.vi

2.1. Library #1

Library description...

2.1.1. VI #1

More Entries

Figure 4. Numbered List Organization Example

Each VI documentation entry follows a similar format. The entry will start with the same title as the file name for the VI, followed by the VI description and icon, and then finally a figure for the VI block diagram. Any hidden control structure frames will be placed after the main block diagram. Figure 5 shows how each entry is organized.

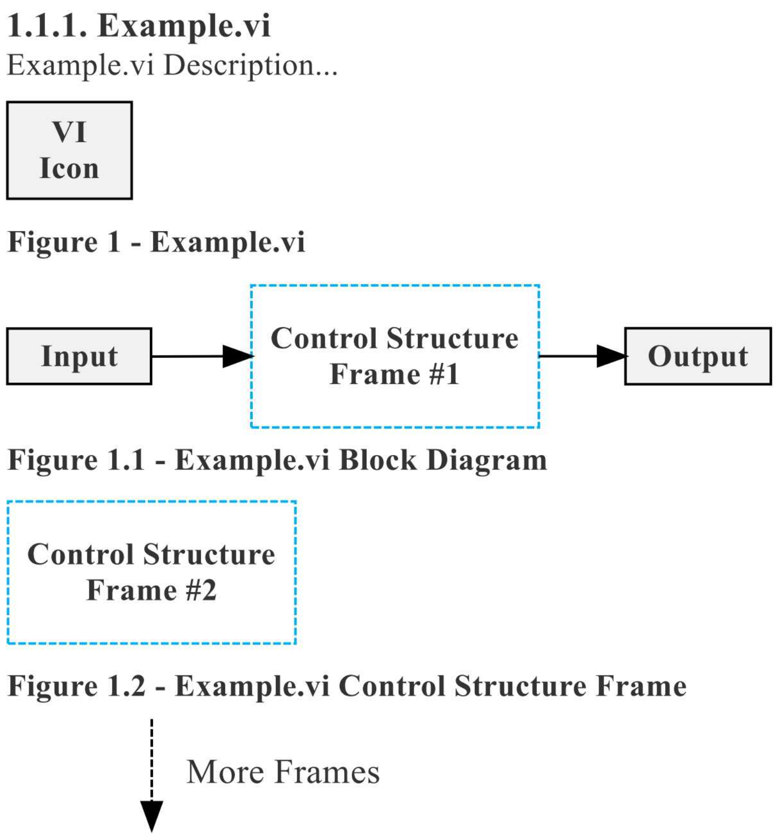

Figure 5. VI Entry Organization Example

3.2. Project Flowcharts

Figure 6 shows how the controller interacts with the Pacific DC Intertie (PDCI) and receives the Phasor Measurement Unit (PMU) data.

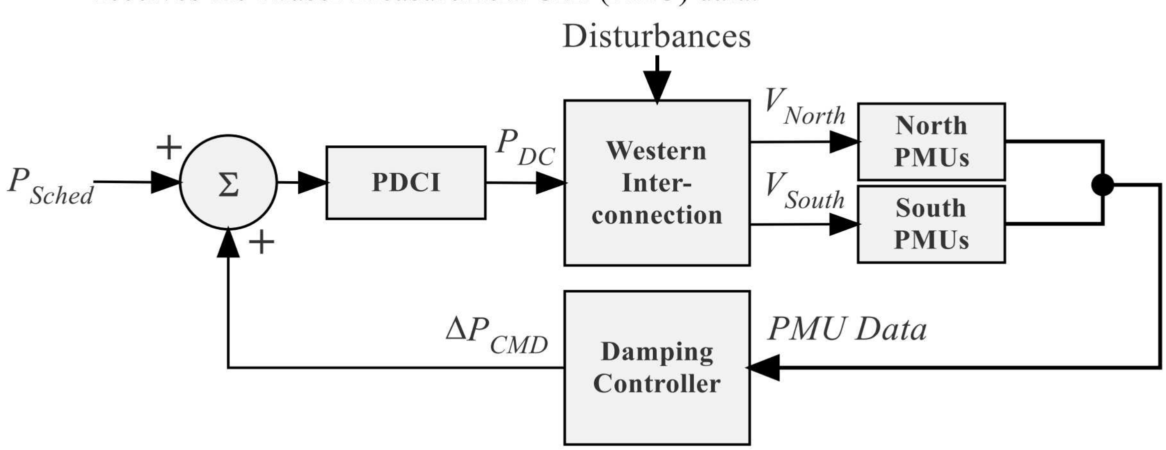

Figure 6. Controller Project Overview

Figure 7 provides a high-level view of the controller software. The software has two main components: the real-time controller and the asynchronous supervisor. The real-time controller is handled by the NI PXI Unit and the asynchronous supervisor is contained in the Windows Server. The User interacts with the asynchronous GUI, which then communicates to the PXI Unit through the shared variables in LabVIEW. The watchdog circuit checks the controller reliability with a 'heartbeat' response from the controller components.

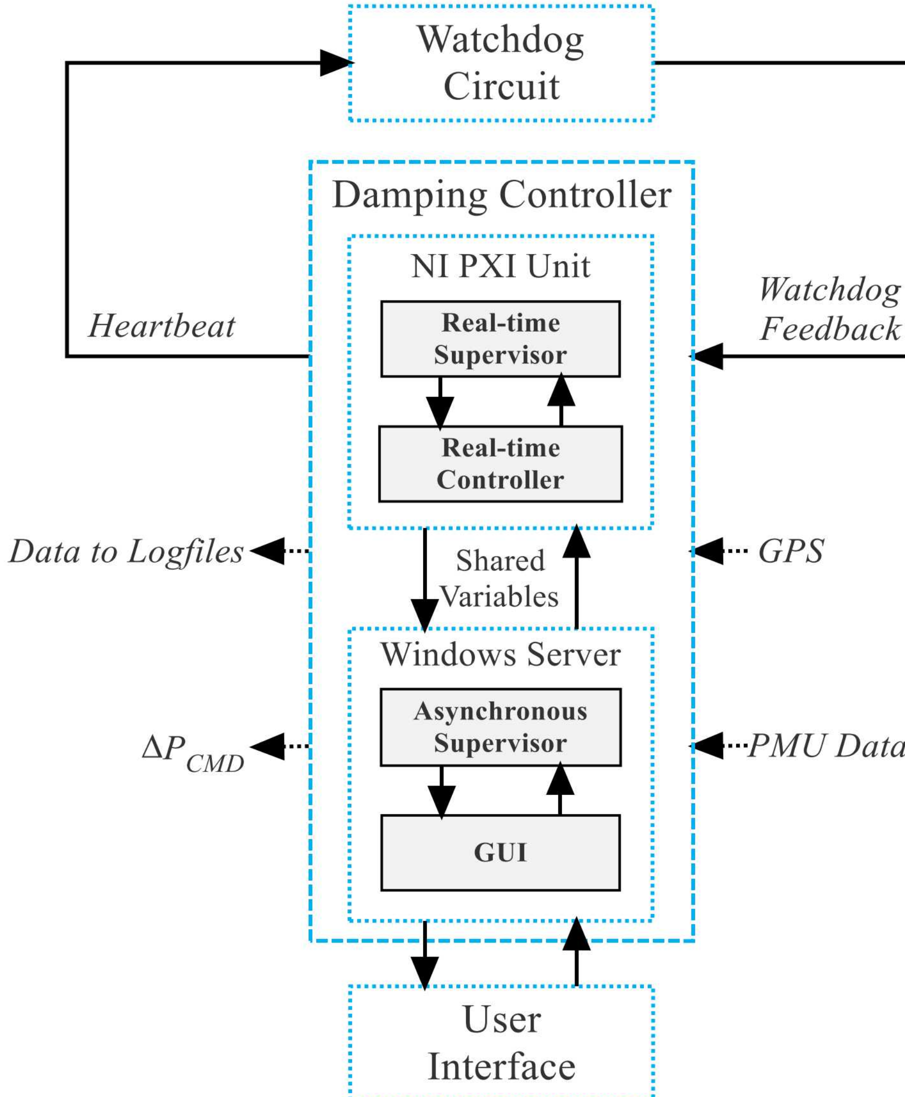

Figure 7. Software Project Overview

Figure 8 provides a high-level view of the overall structure of the damping controller project. It also demonstrates how the startup and shutdown of the controller functions as well as how the damping controller instances are handled.

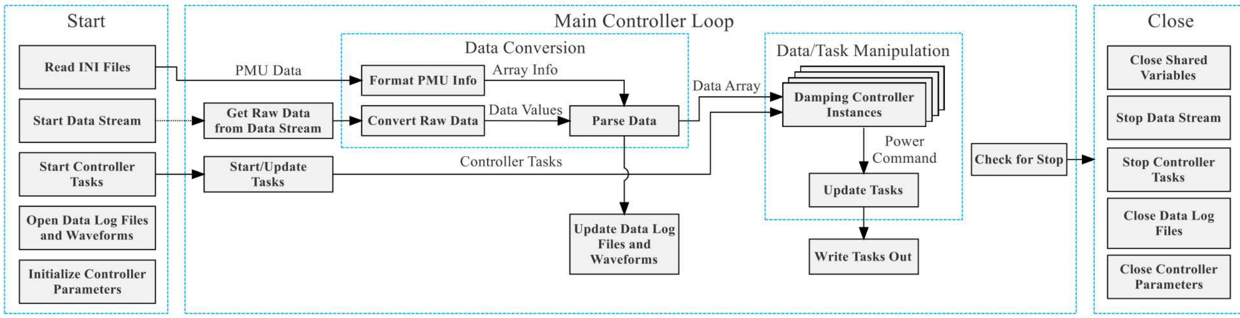

Figure 8. Project Overview

Figure 9 shows the supervisory system for the controller. This includes the asynchronous and real-time control loops. The Watchdog circuit acts as both a hardware and software response check to ensure the controller's reliability.

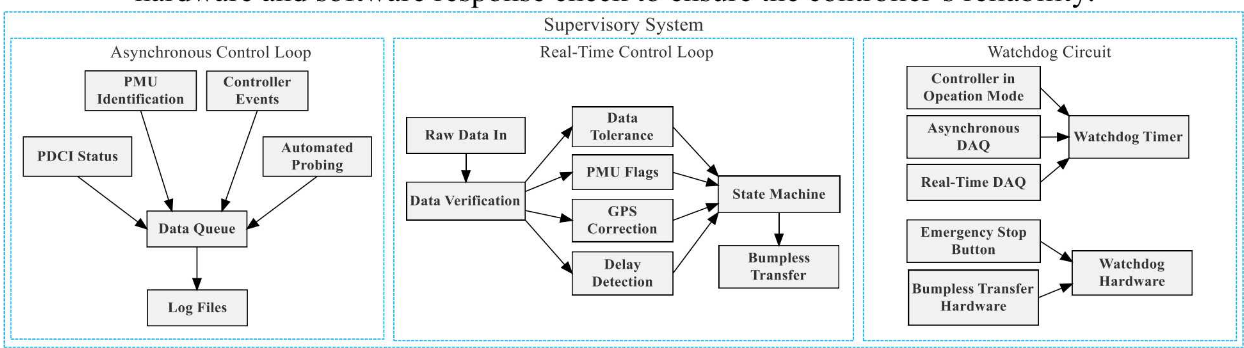

Figure 9. Supervisory System Overview

Figure 10 gives a more detailed view of the 'Real-time Controller' block found in Figure 7. This shows how the controller uses the PMU data to output the power command to the PDCI.

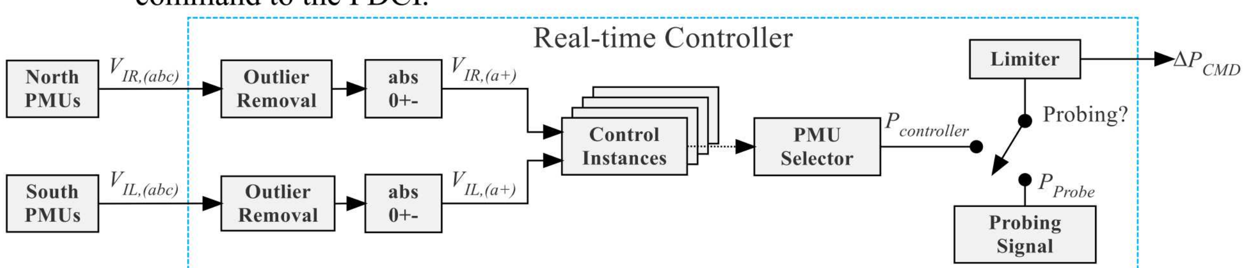

Figure 10. Real-time Controller Block

Figure 11 gives a more detailed view of the 'Control Instances' block found in Figure 10. This figure shows how the positive-sequence voltage data is used to output a power command from the controller.

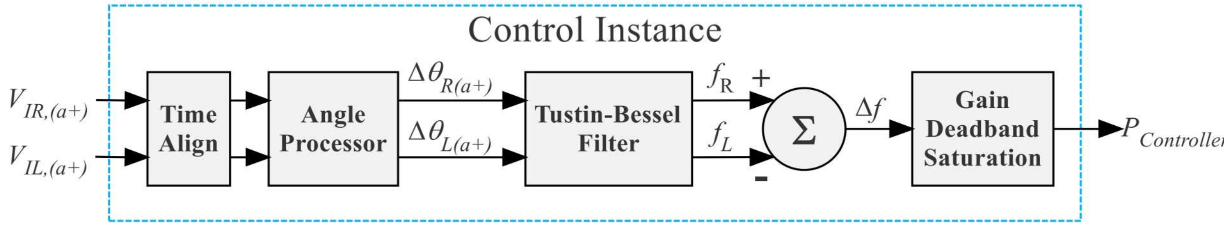

Figure 11. Control Instance Block

3.3. Special Notes Regarding the Comprehensive Software Document

The controller software project contains several VIs and libraries that are not called in the project, and will not have any documentation listed in the comprehensive software report. Besides the VI documentation, there is also a small amount of typedef documentation in the comprehensive report. This includes the typedefs for the variables passed between the real-time and asynchronous systems. Only the two main VI and typedef sections have an additional 'front panel' figure in their documentation. These are the only documentation sections in the comprehensive report where the front panel is relevant to the overall project. Basic LabVIEW primitives will not have any documentation listed in the comprehensive report. Some VIs have large figures that are too large to be neatly displayed. These figures are located in Appendix A of the comprehensive software document. Some of the documentation libraries (bumplessTransfer.lvlib, rtDampingControllerSubs.lvlib, and rtSupervisorChecks.lvlib) have additional flowcharts and descriptions to aid the understanding of their programming structure. Note that the figure numbering and documentation section numbering do not coincide. This was done to make the documentation's numbered list easier to read.

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