DEVELOPMENT OF A PHASOR MEASUREMENT UNIT FOR LOW VOLTAGE POWER NETWORKS

by

Ashutosh Deepak Phatak

A thesis submitted to the faculty of
The University of North Carolina at Charlotte
in partial fulfillment of the requirements
for the degree of Master of Science in
Applied Energy and Electromechanical Systems

Charlotte

2018

Approved by:

____
Dr. Maciej Noras

____
Dr. Kamalasadan Sukumar

____
Dr. Umit Cali

Abstract

ASHUTOSH DEEPAK PHATAK. Development of A Phasor Measurement Unit for Low Voltage Power Networks. (Under the direction of DR. MACIEJ NORAS)

With the increase in technological advances of the smart grid, distribution systems have undergone a great change the same as transmission systems: new technology, different types of load, demand response supporting facilities, large quantities of distributed power interconnection to the distribution network. Meanwhile, the capacity of the distribution network, that is, the number of component an size of investment is considerable, even more than transmission grid. Power measurement plays an important role in distribution networks, including income measurement, voltage amplitude measurement for capacitor switching, distribution feeder current measurements, system device protection measurement. As the next point of setup in smart grid, PMU is necessary for components control, fault detection and control, energy management in the distribution network and increasing reliability and power quality. With technological revolution in Solar and Wind farms, energy can be generated at the destination of consumptions. Use of energy storage devices like batteries has also gone up. To use the existing system effectively, the Bidirectional flow of power takes place. This bi-directional flow can cause trip off, causing frequency or voltage problems. The electrical behavior load is changing.

The design of distribution is radial, so more monitoring/measurements points are required. The traditional monitoring at a lower revenue per circuit mile like that of transmission

system, the number of measuring instruments goes up, causing high monitoring costs and larger manpower. At such times, micro PMU can be installed. These micro PMU will monitor and measure data in real time system and communicate with PDCs using GPS signals. The developed PMU offers a wide variety of monitoring options like using web enable browsers and hand-held android or iOS devices.

Table of Contents

List of Figures

Introduction

Generally, a network consist of generators, loads and transmission lines and other different components that are needed to control the power flow and maintain a balance between demand & supply supervisory control and data acquisition[1]. With increase in technology in 20^{th} century, the system became a complex electrical network. Analysis of the behavior of tis complicated system required a great deal of effort and resources. Mathematical methods such as symmetrical components along with iterative computational methods were invented and employed to assist engineers in designing and managing the electric grid.

These relays used symmetrical components of voltage and current to convert the 6-fault transmission line to a single equation using symmetrical components. With time, the microcomputers became sufficiently capable of handling advance algorithms. However, symmetrical component distance relay method was much efficient for measuring voltages and current. [2] This method also found its way into various power system analysis like load flow, short circuit, stability, power flow and state estimations etc.

An alternating current following through an inductor (purely inductive, no resistance) will have the voltage across the inductor will have a phase difference of 90degree with the current. Accordingly, there will be phase shifts in RL, RC, RLC circuits. Since, AC quantities have both magnitude and a phase angle between them it is best to represent them using phasor diagram. It also helps us to find the relationship between two or more AC quantities and find the resultants. A phasor is a complex number which represents a sinusoidal function whose amplitude, angular velocity and initial phase angle are time variant. [3] An AC waveform can be mathematically represented by the equation as follows

$$x(t) = X_m \cos(wt + \emptyset)$$

Where, $X_m = magnitude\ of\ sine\ wave$

$wt = angular\ velocity$

$\emptyset = initial\ phase\ angle$

The phasor notation of this waveform is represented as $x = X_m < \emptyset$

In an electrical system represented below, there are two buses with voltage V1/_ $\delta 1$ and voltage V2/_ $\delta 2$. The bus is at maximum voltage of V1 with initial phase angle of δ1, while bus 2 is at voltage V2 with initial voltage as δ2. The phasor representation of two waveform is shown below.

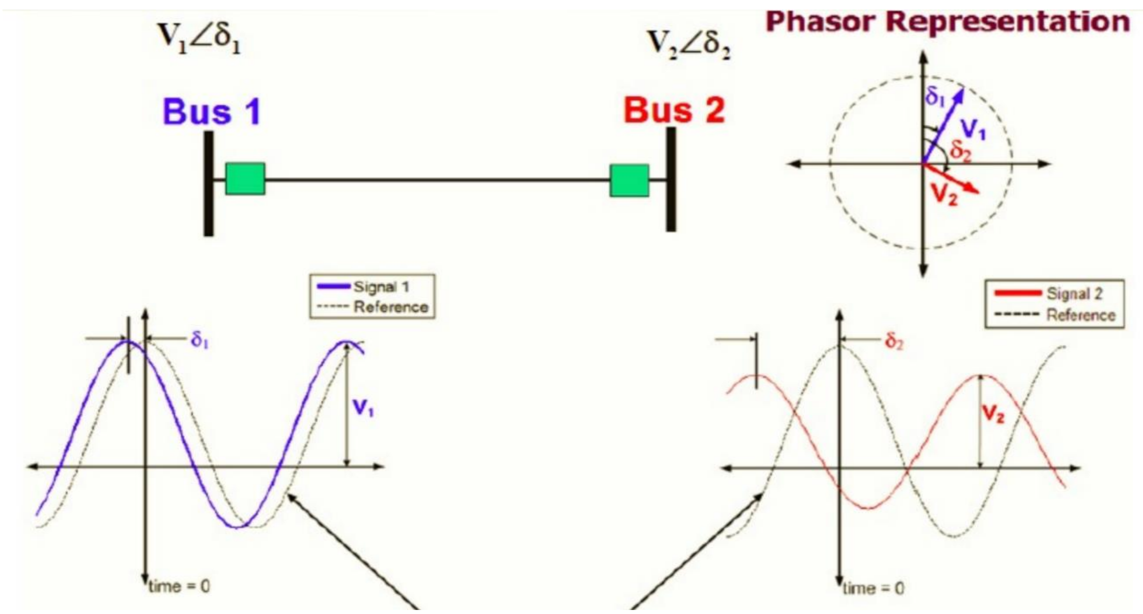


Figure 1: phasor representation of waveforms [2]

The phasor representation of electrical quantities has been well adopted in power engineering. It is commonly utilized in computational algorithms, and its use has been extended to all aspects of power grid control, monitoring and protection. However, to perform all the computations needed in the power network, knowledge of the real values of voltages and currents in the grid are required. Measurements are taken at various strategic locations of the network with a help of current (CT) and voltage (VT) transformers. All that data is then aggregated and processed to give an accurate picture of the grid state. Due to far distances between the measurement points it became important that times at which measurements were taken were somehow determined and reported as well. This may be somewhat difficult when using local time references, as they may be offset with respect to each other. The need for time-coordinated phasor measurements of currents and voltages at the electric grid gave birth to devises known as phasor measurement units (PMUs), where the data are collected and reported using a common global positioning system (GPS) coordinated time base.

Literature and working.

After a catastrophic failure of Eastern power grid in north America in 1965, a great deal of research was being conducted for determining the state of power system in real time. This was achieved by use of real time measurements obtained from GPS enabled measurement devices. The main aim was to collect and analyze the voltage magnitude and phase angle at each nodes or buses.[2] This process is called State Estimation. In 1970s, it was not possible to achieve synchronous measurements. Hence, symmetrical components were used to obtain measurement of the power system. The state obtained consist of positive sequence component of voltage at each bus.

In 1980s large number of GPS satellite were deployed. With the use of these satellites, GPS enabled measurement devices were powerful tools. These GPS enabled devices would be able to provide instantaneous picture of the state of the power system, and in fact would have many outstanding features which would make these measurements become effective immediately even if complete observability of the network could not be achieved with the new measuring devices. Using GPS time signals as input to the sampling clock in measurement system, once can have Real-Time picture of steady state of power system.[1]

By using all the available tools, the Power System Research Laboratory of Virginia Tech. developed first Phasor Measurement Unit (PMU). The PMU has Voltage measuring potential transformers (PTs) and Current Measurement transformers (CTs) connected. The fig below shows the connection of PMU along with CT and PT in electrical grid.

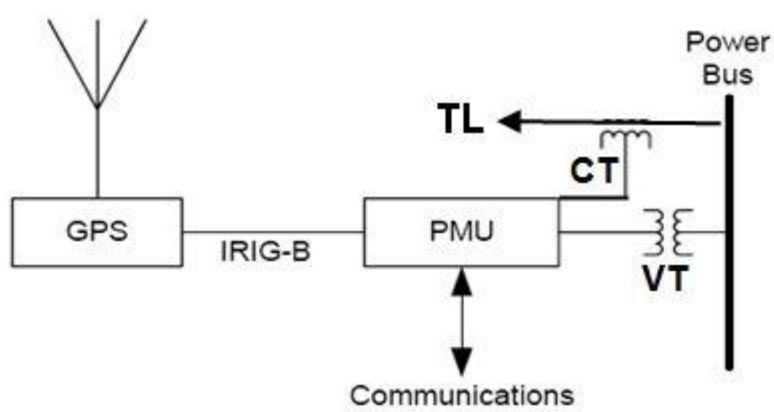


Figure 2 : PMU connection along with CT and PT [5]

This PMU used GPS transmission to synchronize all the sampling clocks across the grid, so that the calculated sequence voltages and phasors will have common reference. This numbers are called as Synchrophasor. Synchrophasor are time synchronized numbers which represents both magnitude and phase angle of a sine wave in an electrical grid. [4]

The system comprises a master system and several local units. The system is arranged as three layers. The bottom layer consists of PMUs with additional protection functionality.

The next layer consists of several Local Backup Protection Centers (LPCs), each of which interfaces directly with many PMUs. The top layer, System Backup Protection Center (SPC), acts as the coordinator for the LPCs. [5] The SPCs are connected via fiber-optic communication links, these devices can process intelligent algorithms based on data collected locally. The image below shows the basic operation of PMU in an electric grid.

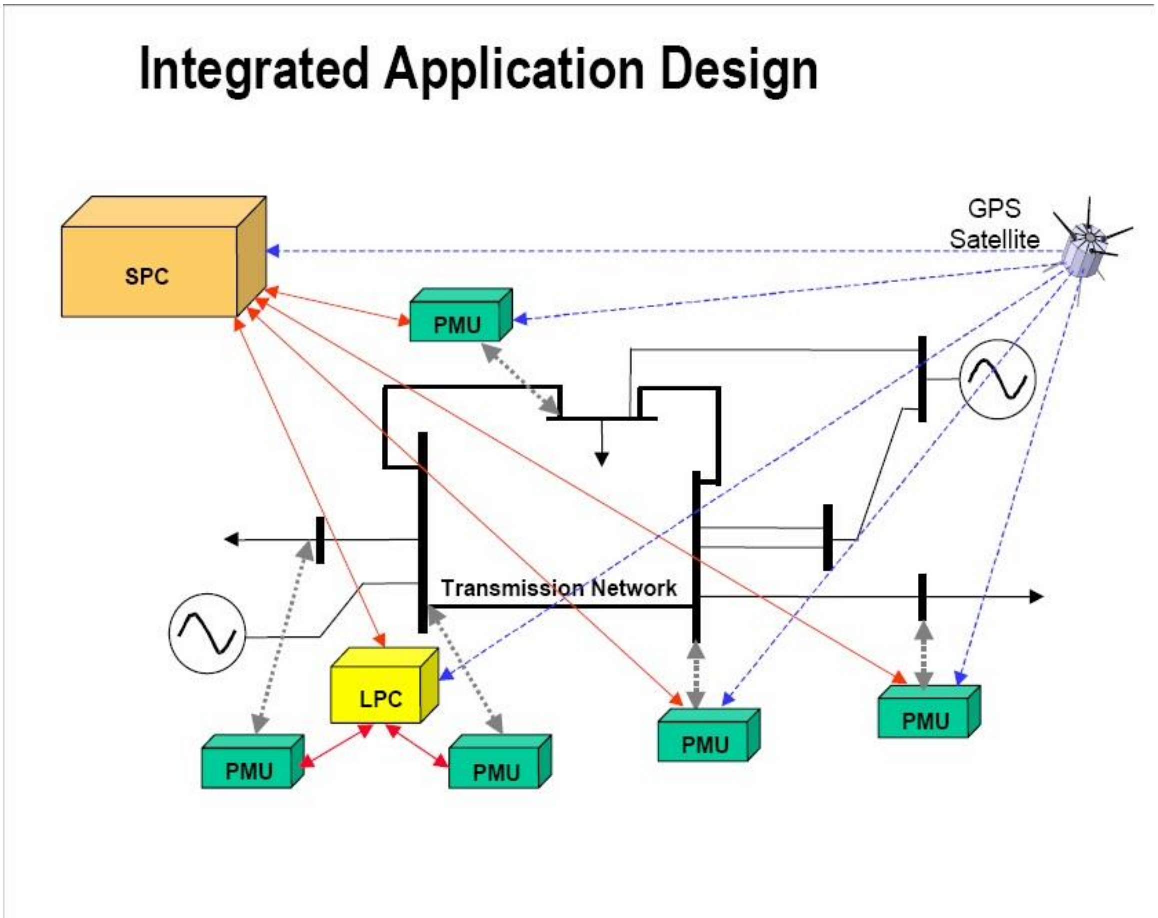


Figure 3: Synchronized Phasor measurement system [5]

Application and Uses

Now-a-days there are several smart grid applications that have been designed for improvement, protection and control of power system in a real time environment. [6] The most known used approach is use of wide-area monitoring, protection and control.

For control

Before the introduction of phasor measurements, the power system was controlled using local measurement devices such as CTs and PTs and mathematical model of the system. However, this approach was highly inaccurate and produced unacceptable system response.

By using high speed PMU, the system can be accurately modelled and controlled. Accurately obtained positive sequence voltage and phasors are used to simulate the system algorithm and provide feedback to the system loop using controllers. Such a system can be controlled and monitored in a real time.

For Protection

In existing system, the protection was based on use of relays and circuit breakers using CTs and PTs. The system mostly relied on backup schemes where the fault was cleared depending upon time it reached the next node. However, the drawback of this approach was false tripping of relays and CBs. and dependability. With simple system, the tradeoff between false trips and clearing of the fault wad tolerable. [7]

With increase in system complexity and use of power electronics, over sensitive remote zones are created. A trip may occur due weather conditions such as High temperatures, wind, rain, fog or fire on these over sensitive zones. This trip is not because of equipment failure or faults occurring on the system. Such trips are called false trips. When such a false trip occurs on a complex system that is already on stress, a cascading failure occurs. This fault multiplied to a large disturbance in the system. If this fault was not cleared by the protection levels, the fault may cascade and damage the whole system. Using well-placed

PMUs, this false trip can be identified at each node and checked for known conditions that occur during a fault. If it's determined that it was a false trip, subsequently the trip is cleared in the next cycle.

For Event Detection

With the increasing loading of the power system, along with the massive interarea transfers enabled by the deregulation of the 1980s and 1990s, there is a clear need to have reliable information about both the local system and external systems. Incidentally four of the six major North American blackouts were due in part to a lack of situational awareness. [8]Although there is a clear need for sharing of information, there is limited real-time sharing of supervisory control and data acquisition (SCADA) or state estimator information in the United States. However, as phasor measurement units (PMUs) have been deployed throughout the North American power grid, there have been significant efforts to ensure that the PMU data are shared between all interested parties. Because PMU data are more widely available in near real-time than other power system measurement data, a fault can be identified of its nature and its impact on the system and cleared without propagation to the system failure. Assuming known nature of steady state system, the event detection algorithms are used to classify different events.

Need of micro PMU

With the start of smart grid, distribution systems have undergone a great change the same as transmission systems: new technology, different types of load, demand response supporting facilities, large quantities of distributed power interconnection to the distribution network. Meanwhile, the capacity of distribution network, that is, the number of component an size of investment is considerable, even more than transmission grid. [9] However, little attention is paid to how to improve the distribution network in the past, and in recent years, the study of distribution automation is gradually getting more attention. Power measurement plays an important role in distribution networks, including income measurement, voltage amplitude measurement for capacitor switching, distribution feeder current measurements, system device protection measurement. [10] These measurements are part of the SCADA in each voltage level of power grid. Measurements area synchronous in the past, in the other word, measurement happened in different time and without a unified clock trigger signal. As we all know, using advanced measurement techniques to achieve control and economic operation in the transmission grid and distribution network is one goal of smart grid. To take full advantage of the measured values, synchronous measuring of current and voltage is even more necessary especially in field of control, which prompt the all- phase measurement. The PMU is used for accurate measurement of synchronous phasor of electric signals at separated points across the power grid and are widely installed at the transmission level.

As the next point of setup in smart grid, PMU is necessary for components control, fault detection and control, energy management in distribution network. Customer expectations regarding reliability and power quality are getting higher every day. People expect continuous uninterrupted power all the time. Loss of power can cost millions in the economic development.

There are more and growing amounts of Distributed Energy Resources in distribution systems. With technological revolution in Solar and Wind farms, energy can be generated at destination of consumptions. Use of energy storage devices like batteries has also gone up. To use the existing system effectively, Bidirectional flow of power takes place. Energy is generated in surplus during daylight using solar panels and concentrated solar powers. This surplus energy is supplied to meet the peak demands during day time using the existing transmission system. At night, the same system is used to supply back power from generation to the distribution sectors. Due to this Bi-directional flow of power takes place in same system. This bi-directional flow can cause trip off, causing frequency or voltage problems.

Changing behavior of load

The design of distribution is radial, so more monitoring/measurements points are required. The traditional monitoring at lower revenue per circuit mile like that of transmission cannot be used to monitor the complex distribution system. With increase in the radial system, the number of measuring instruments goes up, causing high monitoring costs and larger man power. At such times, micro PMU can be installed. These micro PMU will monitor and measure data in real time system and communicate with PDCs using GPS signals. The Technology for PMU is already implemented for transmission system, but was needed to be cheaper to be deployed in distribution system. In this project, we can see that using same technology, the cost of PMU has been reduced from $22,000 to $7,000 saving $15,000. The installation cost may be up to $200. The saved cost can be used to deploy another two micro PMUs and achieve better response, dependability and reliability. The developed micro PMU is much smaller in Size and more easily deployable (i.e. like hot stick mounted devices). The size is reduced to ¼th of the PMU used in transmission system. The developed PMU also offers wide variety of monitoring options like using web enable browsers and hand-held android or iOS devices.

Chapter 3: components of PMU

The Architecture of micro PMU is built with keeping National Instruments Grid Automation System as benchmark for the PMU. The choice of NI Grid Automation System was based on cRIO advantages along with interchangeable plugin modules available for different applications. Below are all the components described along with their advantages.

3.1 cRIO 9068

CompactRIO is a real time embedded industrial controller made by National Instruments for industrial control systems. The CompactRIO is a combination of a real-time controller, reconfigurable IO modules, FPGA module and Ethernet expansion chassis. [11]

Increased technical performance

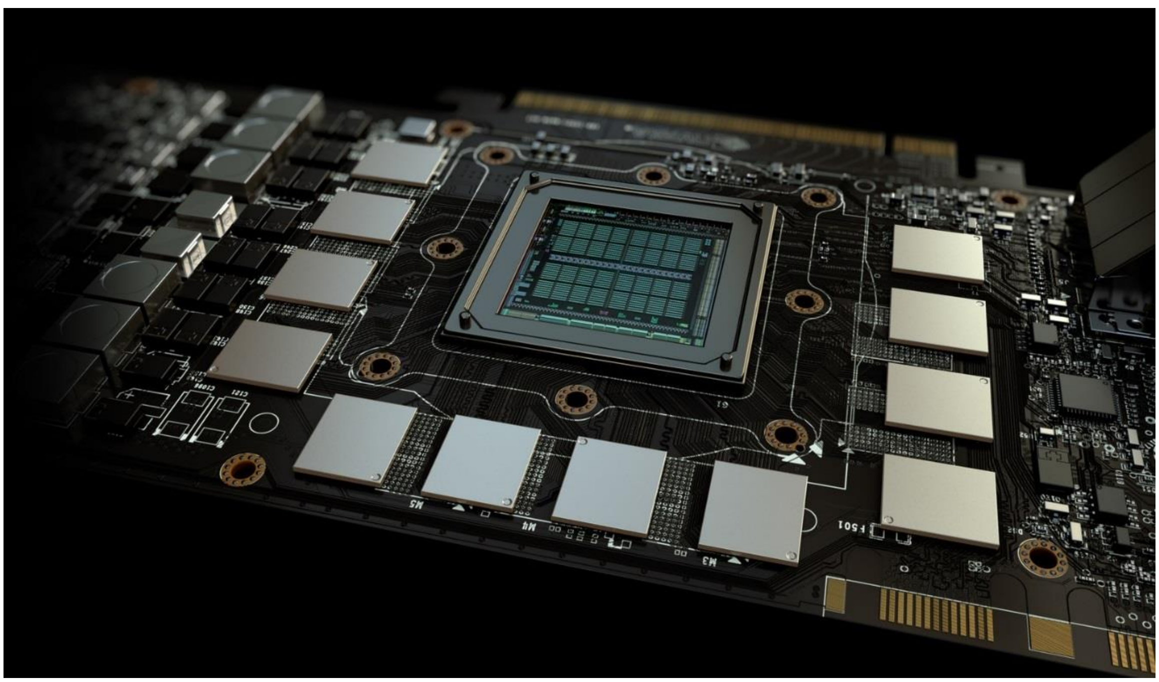


Figure 4: Boost technical performance with intel chips

CompactRIO controllers offer the performance to execute advanced control algorithms with deterministic response times and low latency. Take advantage of the latest advancements in processing and heterogeneous computing elements including ARM-based

Xilinx Zynq SoCs as well as quad-core Intel Atom processors and Xilinx Kintex-7 FPGAs. [8]

Simple design and addon modules

Figure 5: cRIO with different modules for variety of application

Eliminate the need for separate subsystems by connecting to sensors, displays, cameras, motors, databases, and the enterprise directly from CompactRIO controllers. Create a powerful system that you can customize and reconfigure through software—even after deployment. [8]

Innovative platform for different applications and needs.

Figure 6: Plug and play modules for wide applications

With highly integrated software, a community of users and IP, extensive I/O, and a range of embedded controllers across a variety of form factors, a single platform can help you to meet the unique needs of any embedded application. [8]

Advantages of FPGAs

Figure 7: Graphical environment for better user interaction

From high-speed signal and image processing to custom timing and ultra-precise control, FPGAs deliver the performance and reliability to meet even the most demanding technical requirements. Use the LabVIEW graphical environment to program the onboard FPGA and unlock the incredible power of these devices without any knowledge of hardware description languages or placing and routing tools. [8]

3.2 measuring modules (voltage and current)

Voltage measurement module 9242

Ni Module 9242 is a 250 Vrms L-N, 400 Vrms L-L, 50 kS/s/ch, 24-Bit, 3-Channel C Series Voltage measuring Input Module. This module performs single ended analog signals. The wide measurement range makes it ideal for high-voltage measurement applications such as phasor measurements, power metering, power quality monitoring, standard potential transformers, and motor test. [9] We can also perform transient and harmonic analysis with high-speed simultaneous sampling. The NI-9242 offers three channels, so we can connect single-phase or three-phase measurement configurations such as WYE and delta. We can incorporate the NI-9242 into systems to meet standards of IEEE c37.118

Acquiring signals from NI 9242

To acquire voltage signal and test the working of NI 9242 module, following steps were implemented.

Steps:

1. Open "getting started with NI 9242" from LabVIEW examples as shown in fig 8.

2. Right-click RT CompactRIO under the LabVIEW project and select NEW, select Target and Devices.

3. Select Discover the existing chassis and select CompactRIO with the IP-address of the chassis.

4. Expand the project under the chassis and select the FPGA main.VI.

5. Compile the FPGA main.VI.

6. Attach connecting wires to measure the voltage from source.

7. Check for broken Run arrow, if not the VI can be operated to test sample signals.

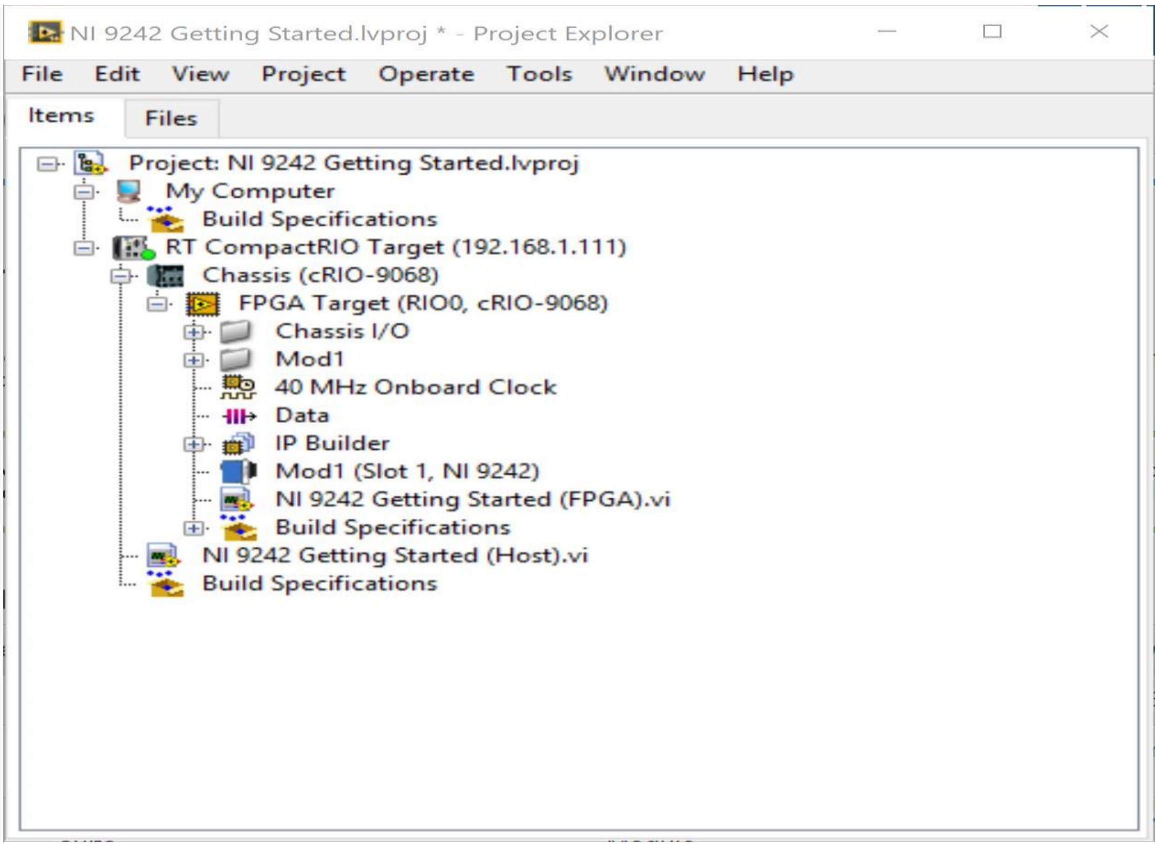


Figure 8: Getting started with NI 9242 project

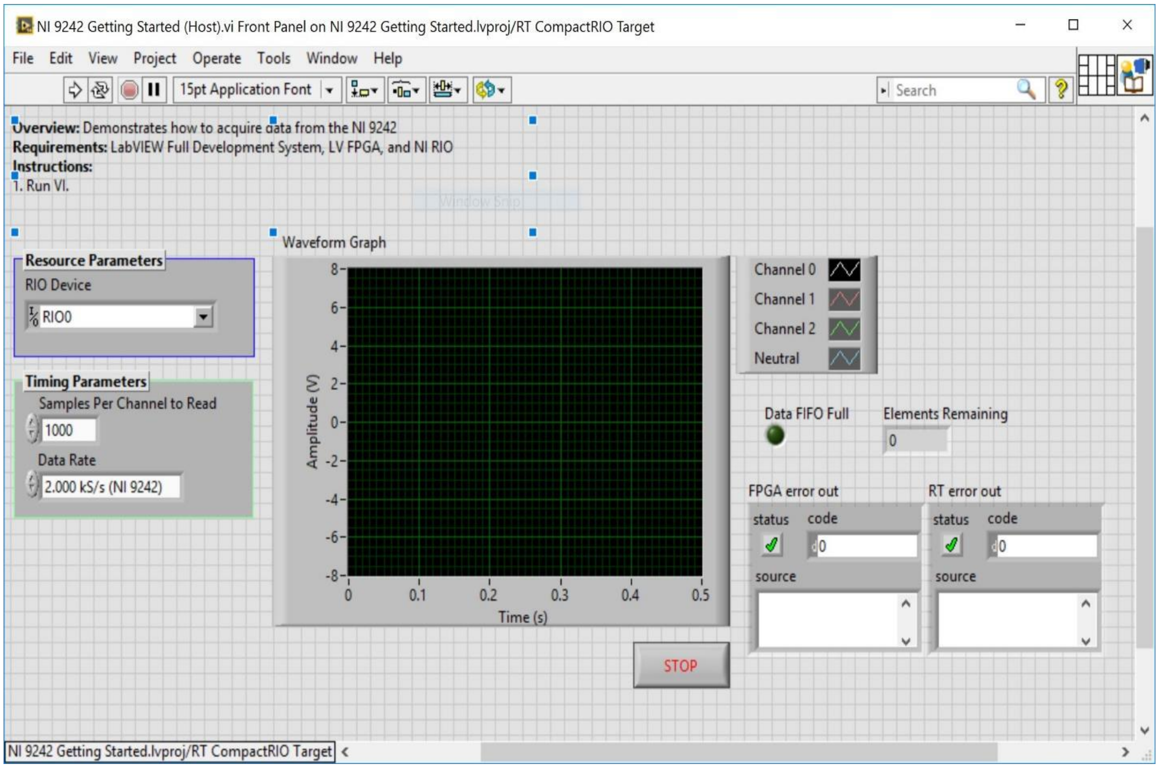


Figure 9: Front panel of NI 9242 project

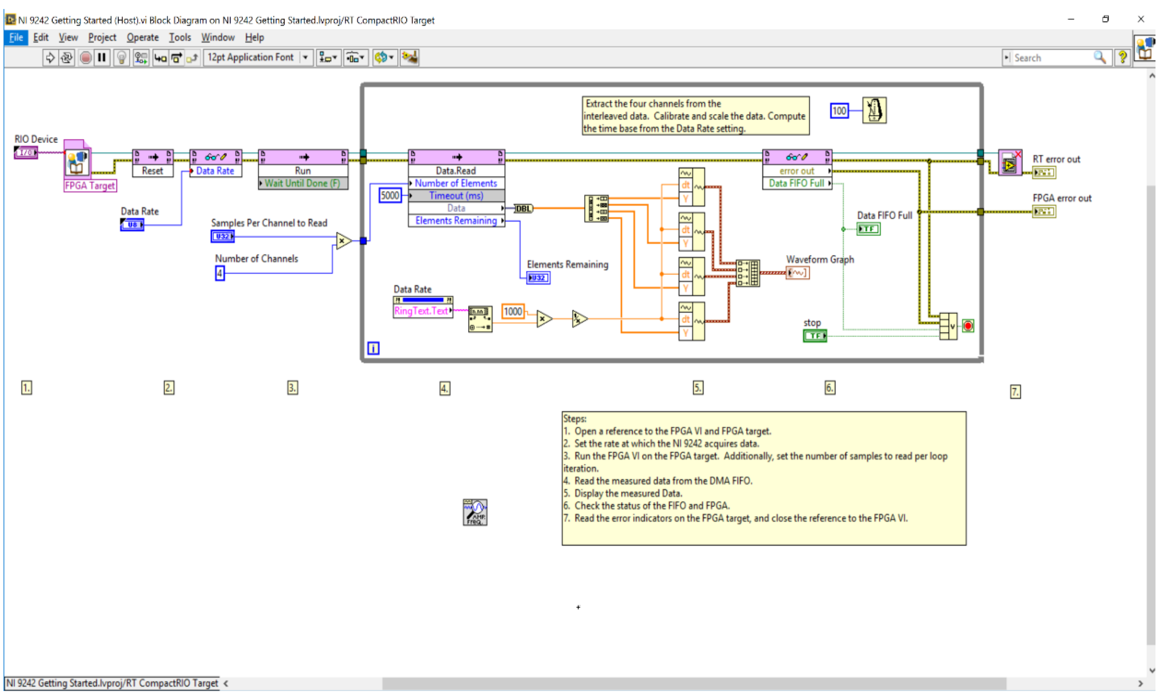


Figure 10: Block diagram of NI 9242 Host VI

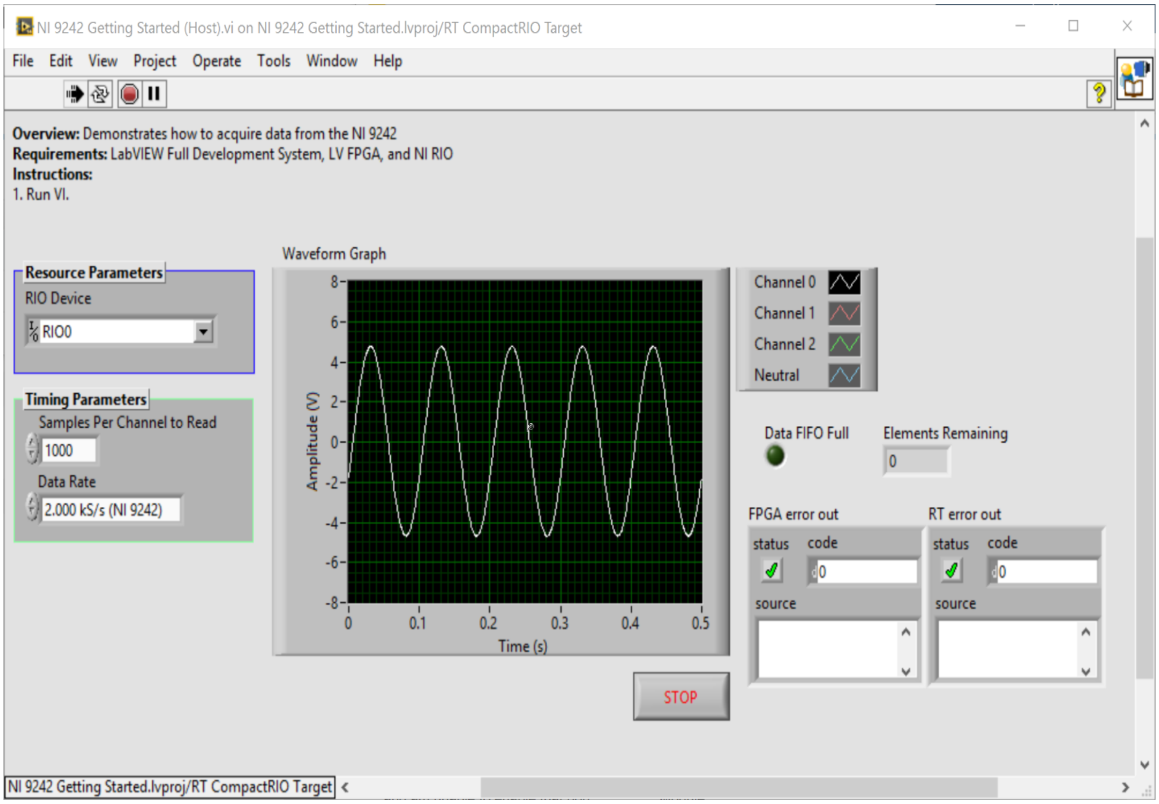


Figure 11: waveforms measured by NI 9242 Host VI

Current Measurement Module NI 9238

NI module 9238 is ±500 mV, 50 kS/s/ch, 24-Bit, Simultaneous Input, 4-Channel C Series a current measuring Module. This module (NI-9238) performs differential analog input. The measurement range is compatible with many low-voltage sensors such as current shunts and current transducers in high-current applications. When used with higher-voltage C Series Voltage Input Modules, the NI-9238 can measure power and energy consumption for applications such as appliance test, industrial machine monitoring, power quality analysis, phasor measurements, and harmonic analysis. [10]

Acquiring signals from NI 9238

To acquire voltage signal and test the working of NI 9242 module, following steps were implemented.

Steps:

1. Open “getting started with NI 9238” from LabVIEW examples shown in fig 12.

2. Right-click RT CompactRIO under the LabVIEW project and select NEW, select Target and Devices.

3. Select Discover the existing chassis and select CompactRIO with the IP-address of the chassis.

4. Expand the project under the chassis and select the FPGA main.VI.

5. Compile the FPGA main.VI.

6. Attach connecting wires to measure the current from source.

7. Check for broken Run arrow, if not the VI can be operated to test sample signals.

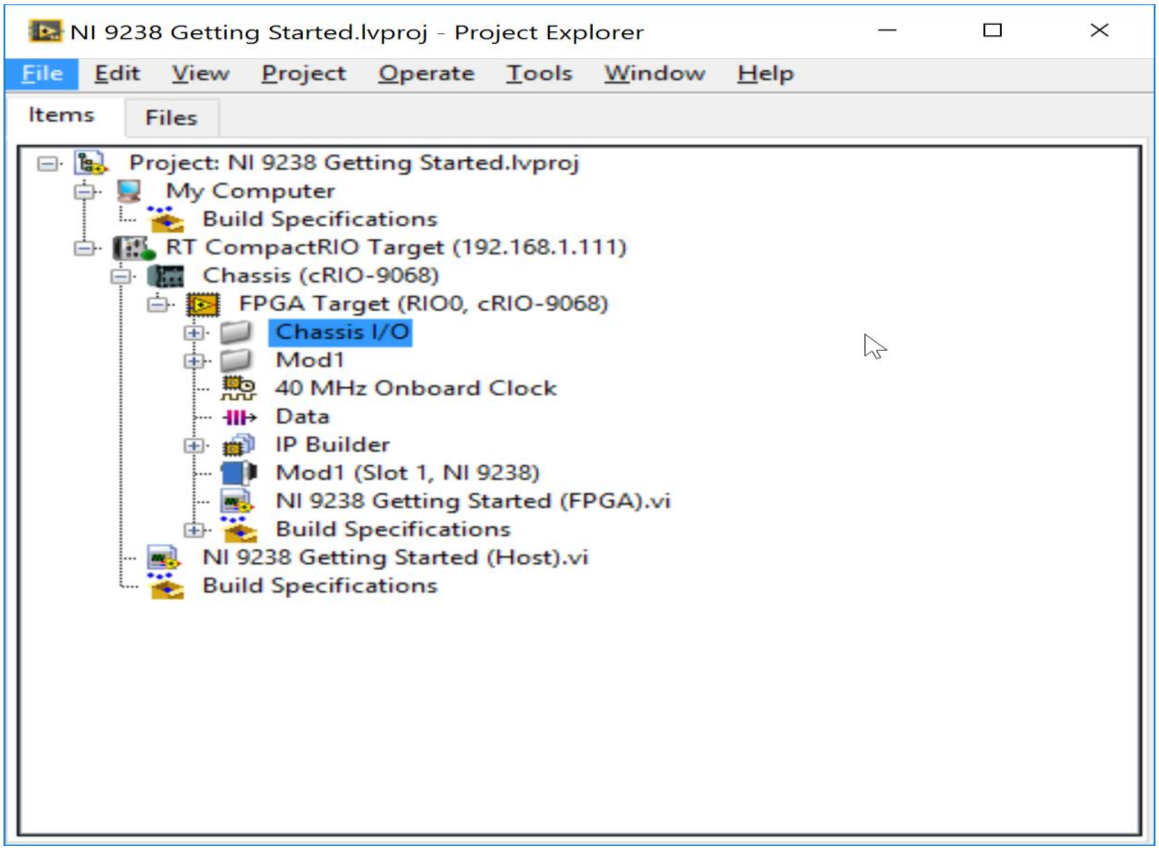


Figure 12: Getting started with NI 9238 labVIEW project

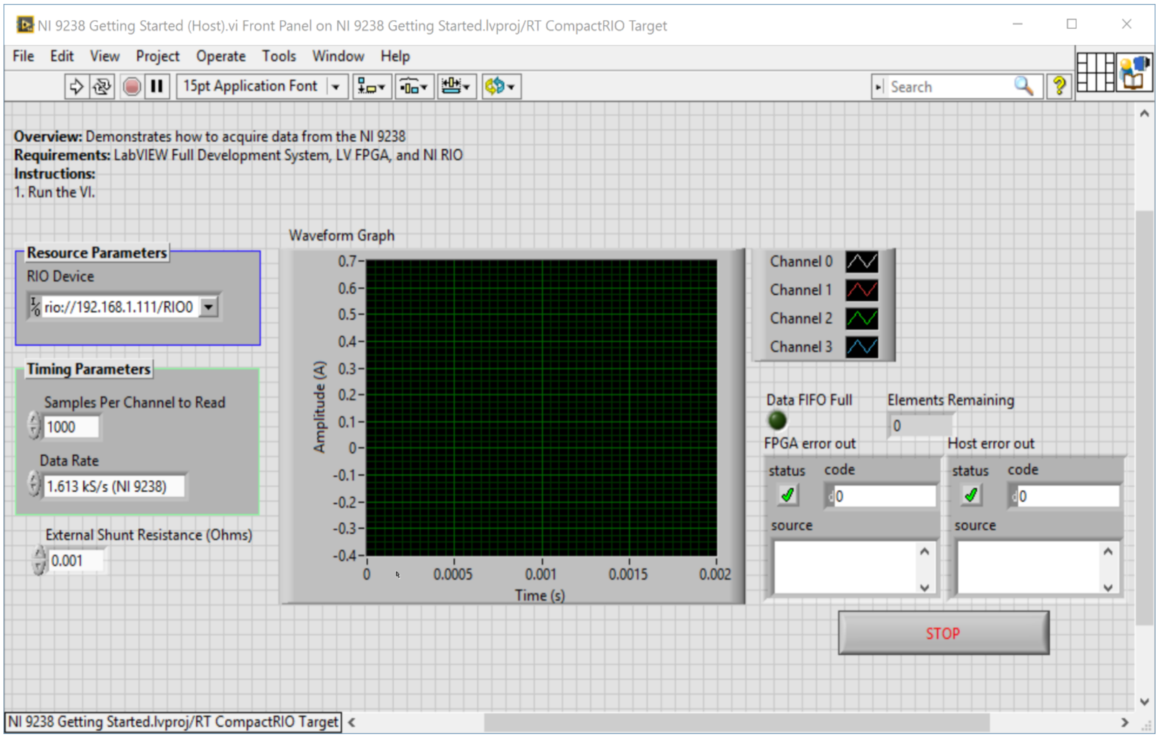


Figure 13: Front Panel of NI 9238

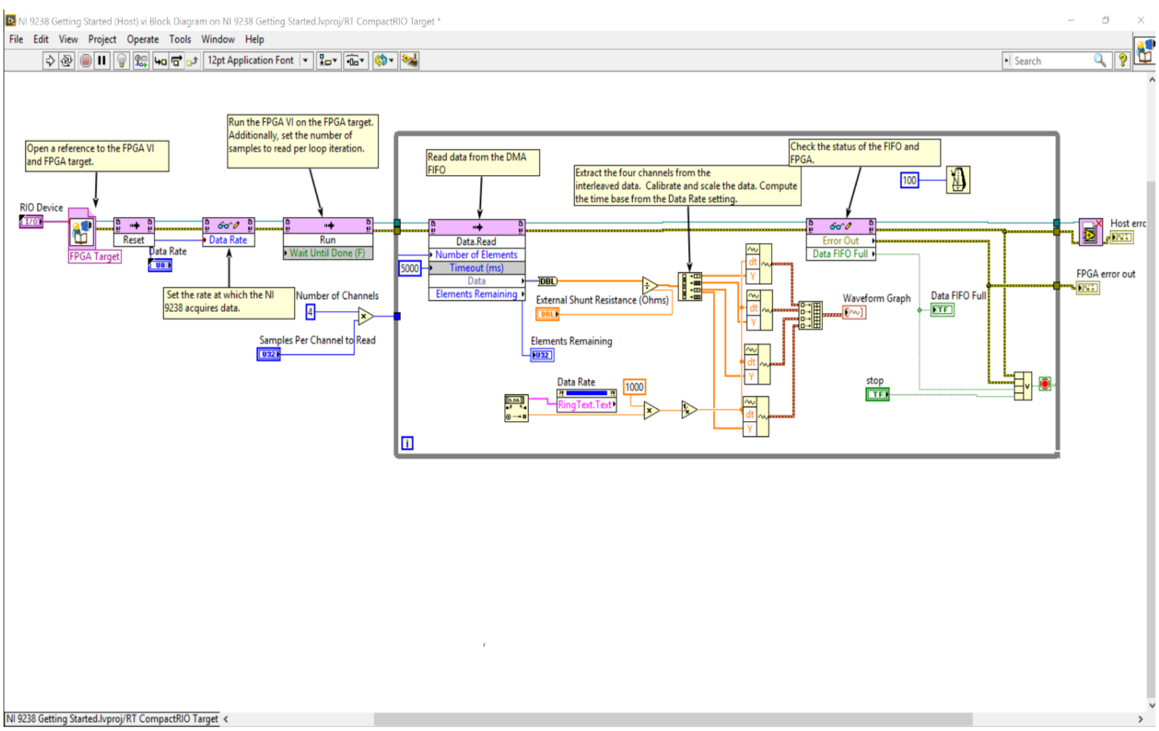


Figure 14: Block diagram of NI 9238 Host VI

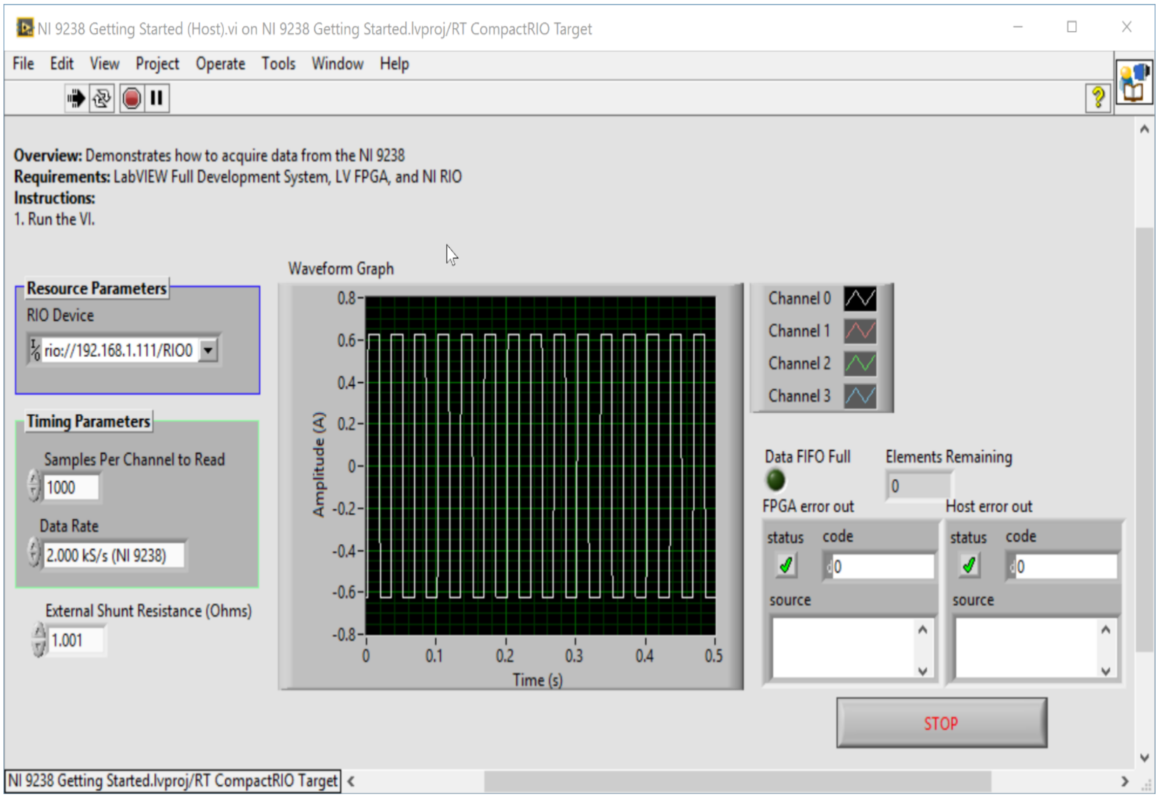


Figure 15: waveforms measured by NI 9238

Chapter 4: Experimental setup

Once we have our CompactRIO system up and running, we should be able to open the "PQ Starter Kit" and run it. If we get a broken arrow related to the bit file error, Double-click and find the “. lvbitx" file that is in the starter kit folder.

Using the Starter Kit with Different CompactRIO Hardware [12]

This example was developed for deployment with the starter kit hardware. To run this project on different hardware, you need to configure a project to run your specific hardware connected to your computer. The following steps guide you through the process of creating a new project for your hardware.

From the example LabVIEW Project Explorer, choose **File » Save As...**

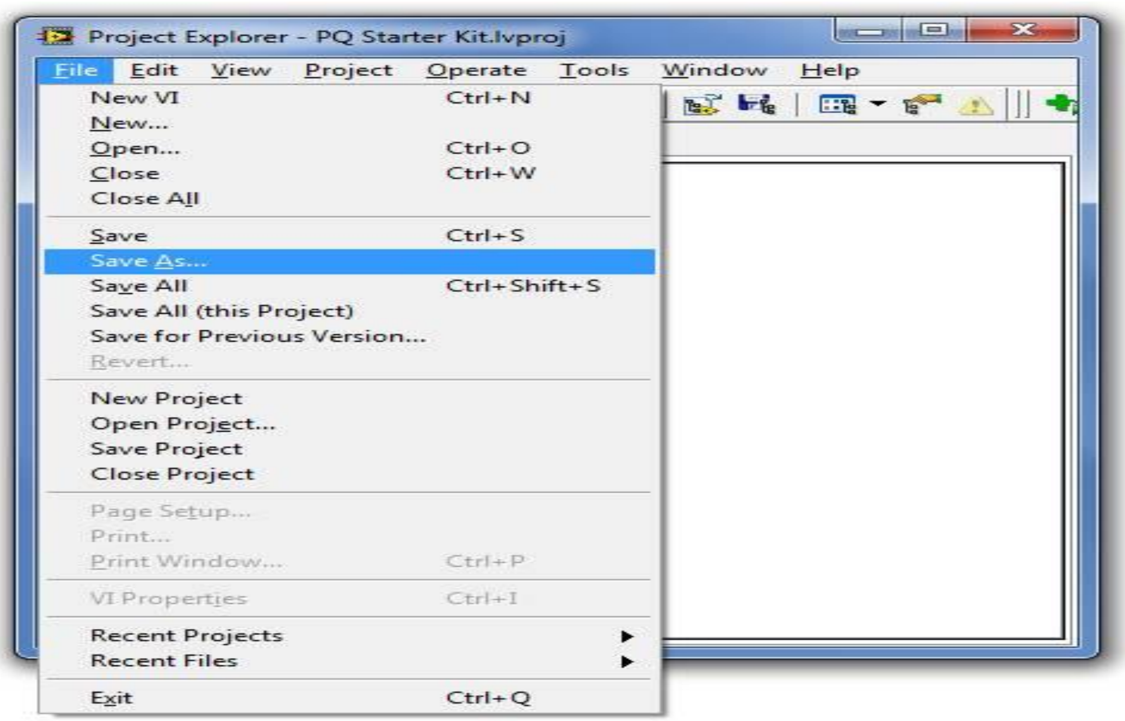


Figure 16: Saving PQ starter kit project

1. In the Save dialogue that appears, choose the **Duplicate.lvproj file and contents** radial button and ensure that the **Include all dependencies** radial button is selected. Then press **Continue…**

Figure 17: Duplicating all dependencies from original project to New project

2. Select a folder to store your new project and its associated files. Choose an appropriate name for the project file as well. All other project contents maintain the same name as used in the original example.

3. Close the original example project.

4. Open the newly saved project and right-click the top-level Project: <Name>, where <Name> is the title of your project. Then choose **New » Targets and Devices…**

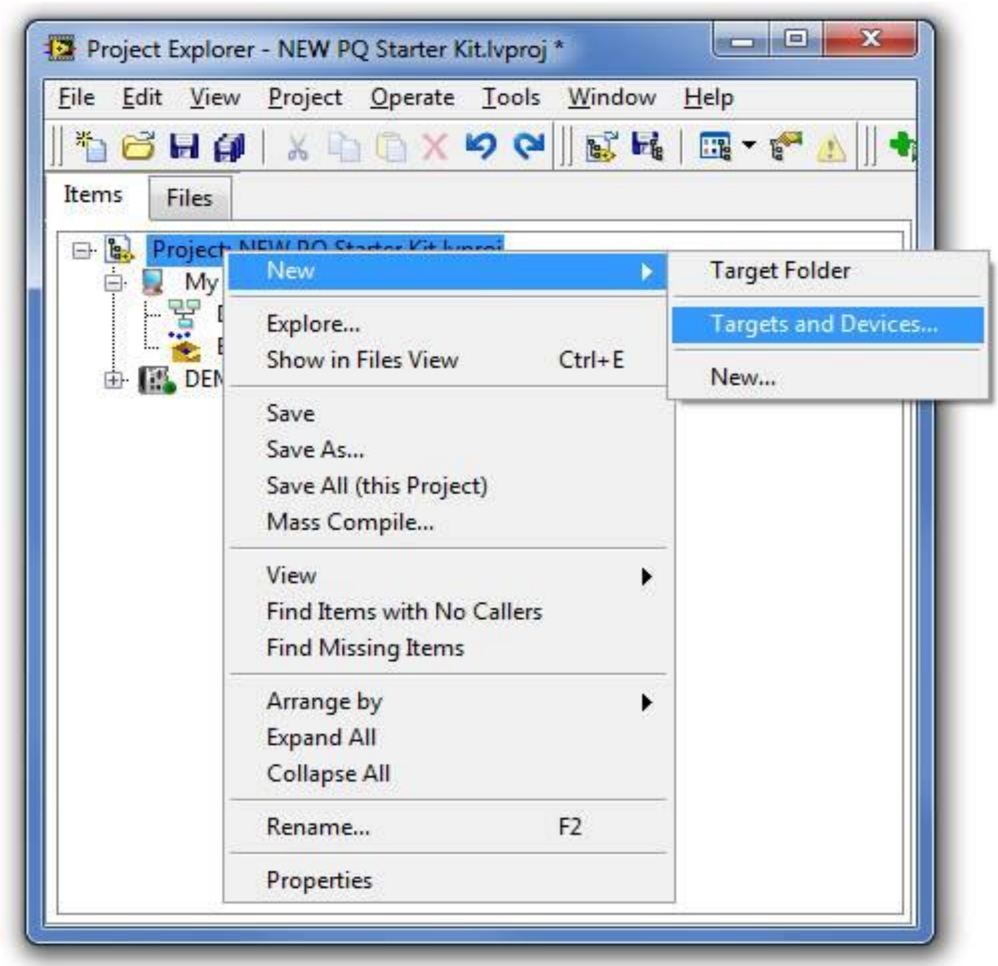


Figure 18: adding target cRIO from connected devices

5. From the Add Targets and Devices dialogue that appears, choose the **Existing target or device** radial button and ensure that **Discover an existing target(s) or devices(s)** radial button is also selected if your device is on the same subnet as your development computer.

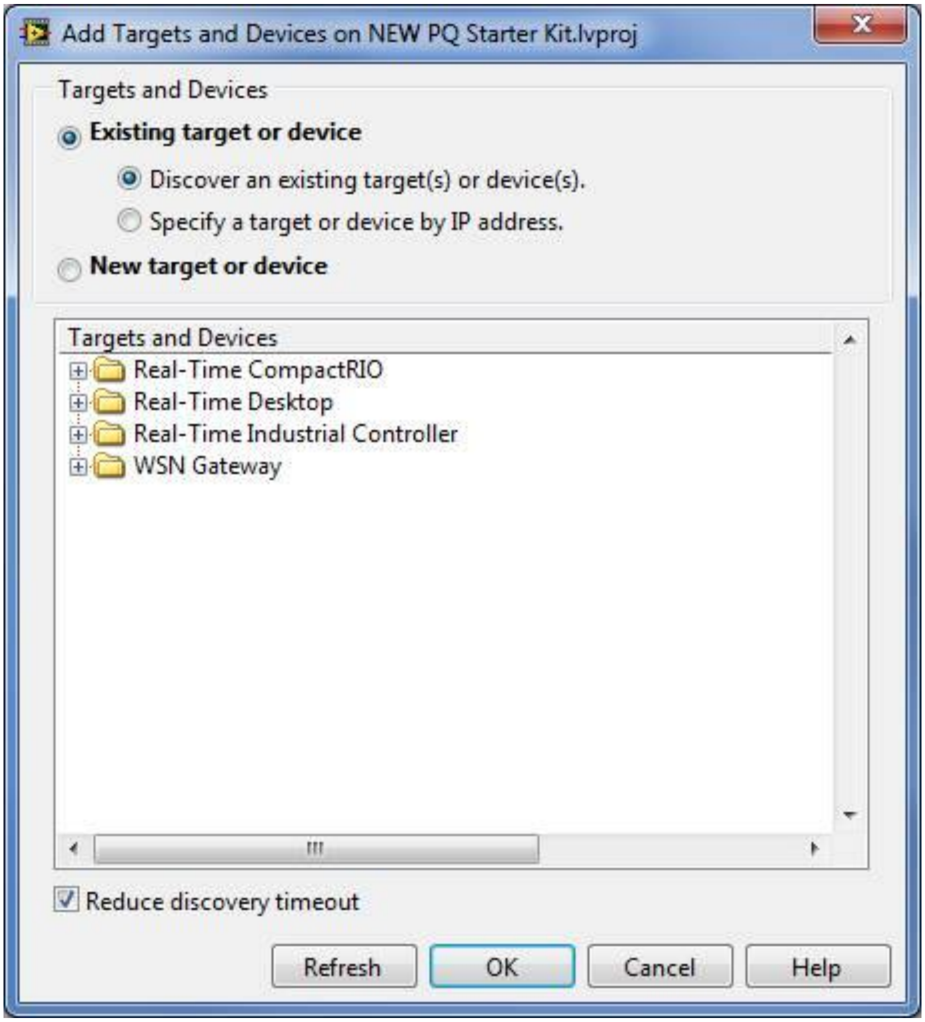


Figure 19: Dropdown list for Target and devices

7. Expand the **Real-Time CompactRIO** folder under Targets and Devices and choose your CompactRIO option from the list.

8. Press **OK**.

9. The Select Programming Mode dialogue box appears. It is important to choose the correct programming mode for your example. The Power Monitoring Starter Kit needs the chassis to be configured for FPGA interface mode rather than scan mode. You have the choice to discover installed modules. Though either way works, adding

the modules later is easier. You should now have a project (as depicted below) with two targets, the original "DEMO-9024" target and the new one you just added. The idea now is to drag all the components from the original target to your new target.

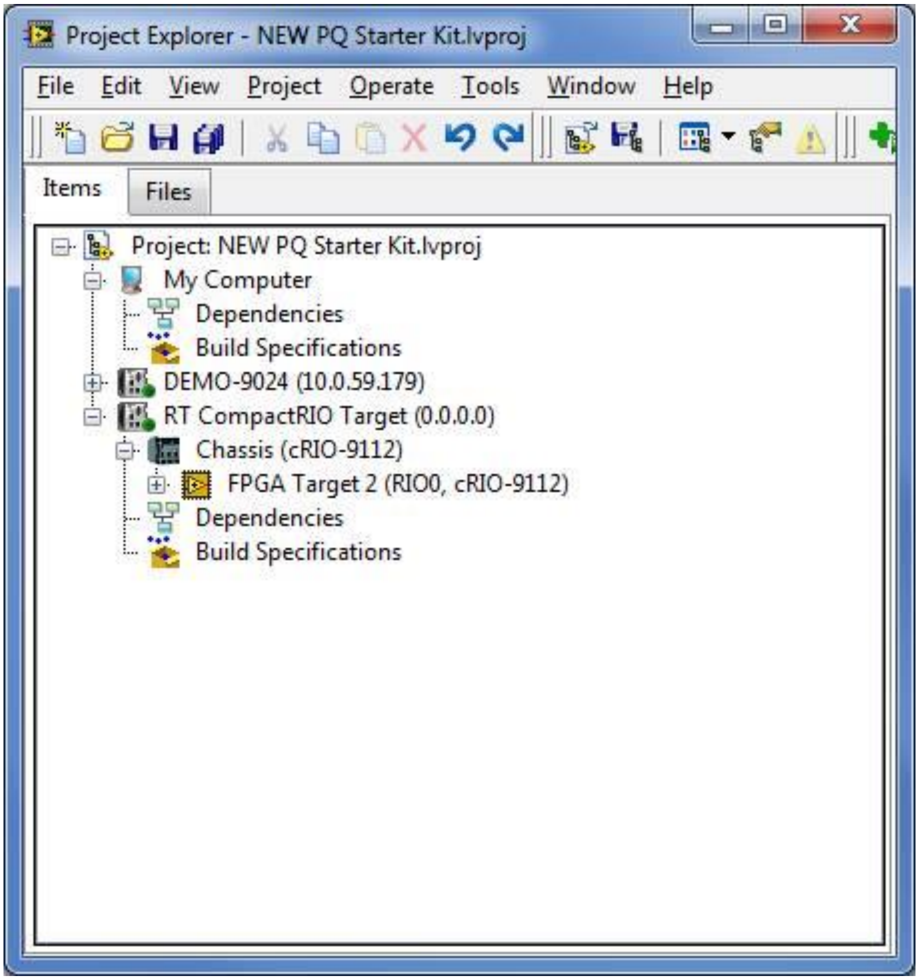


Figure 20: adding FPGA from Demo project to New project

10. Drag the VI under the old RT CompactRIO controller and place it under the new CompactRIO controller you just added to the project in the same relative location. Note that the VIs need to be placed under the proper targets. "PQ Host Program" should live under the RT target, and "[FPGA] Main" should be pulled under the FPGA target on

the chassis. Don't forget the “DATAU32” DMA channel from the FPGA target. The image below shows the “PQ Host Program” after it has been moved from the original target to the new one.

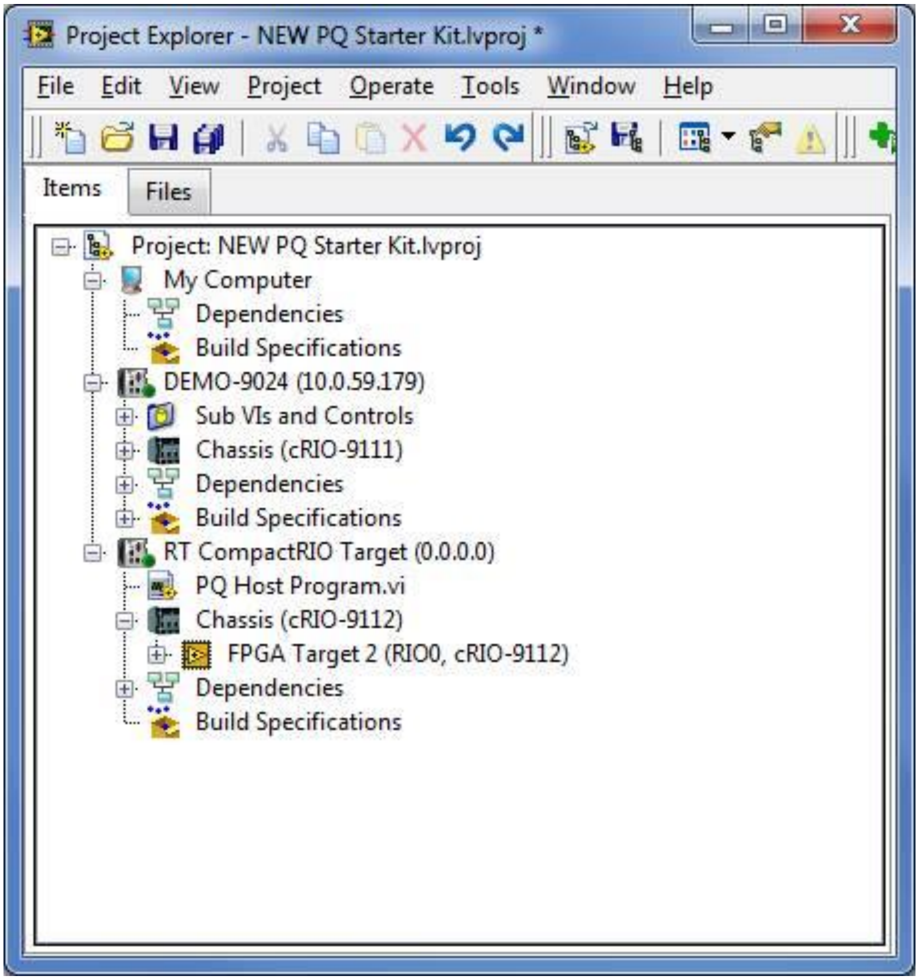


Figure 21: Adding Sub VIs and Control from Demo project

11. For the folders, create a virtual folder and convert it to “auto-populating” to pull in all the sub VIs. Select the appropriate folder from the project folder on disk.

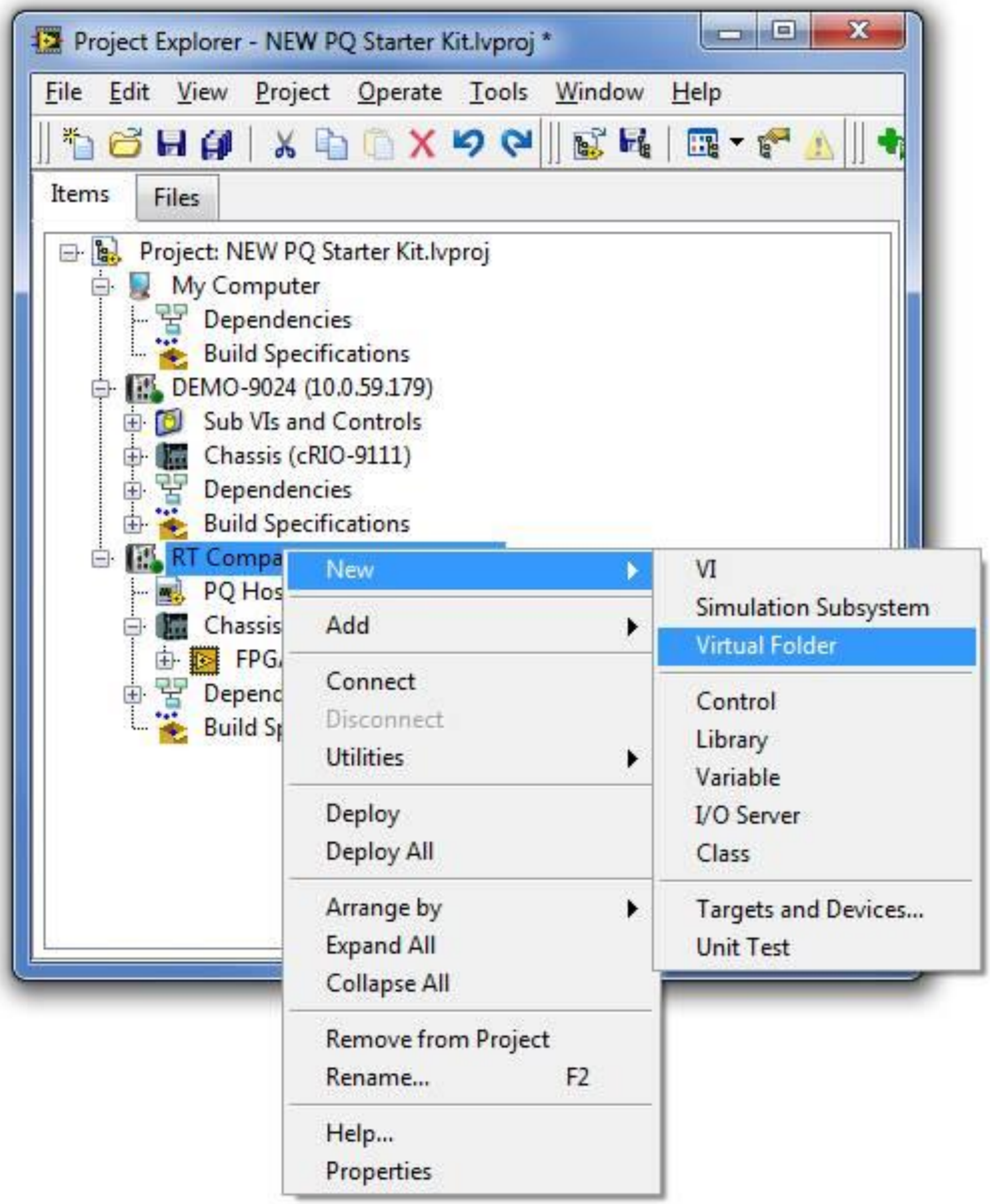


Figure 22: Adding new virtual folder

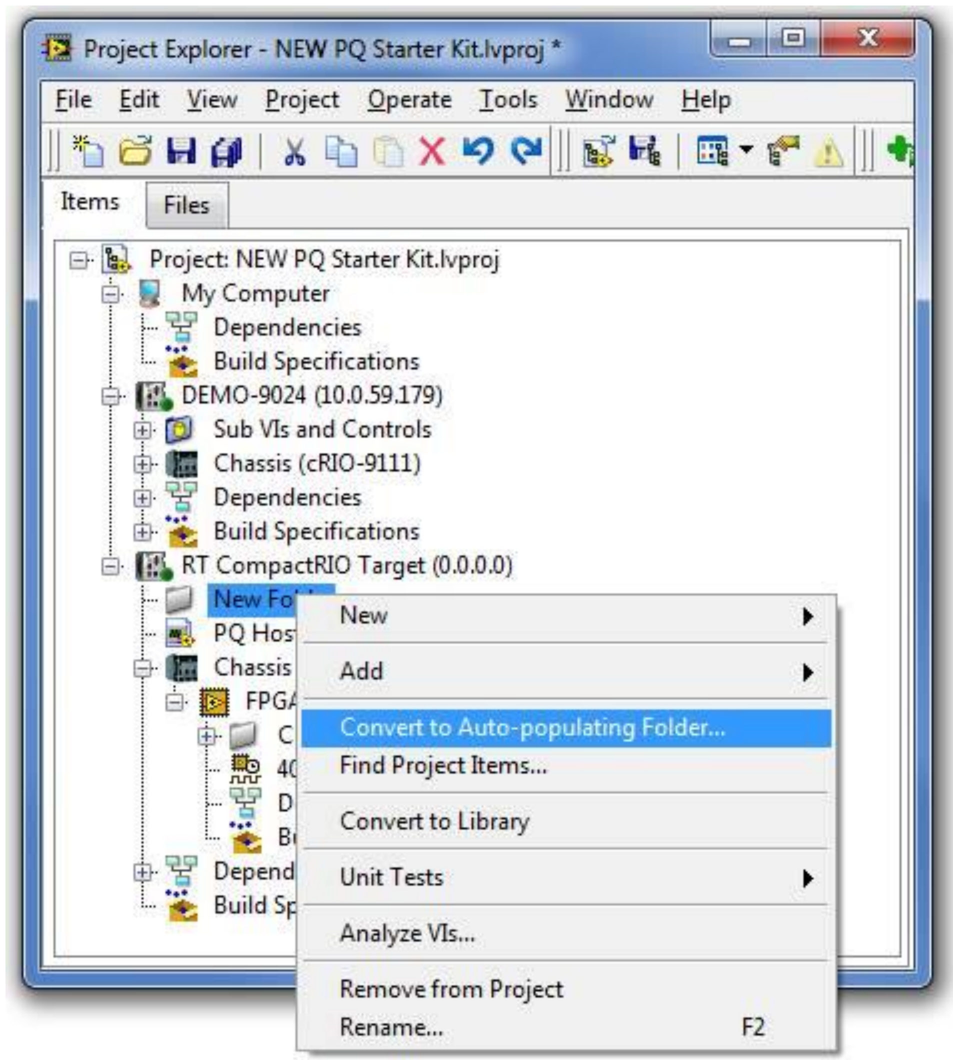


Figure 23: converting the virtual folder to auto-populating

12. Channel address names are important. The easiest way to use similar names is by following these steps:

a. Add "C Series Modules" by right-clicking on the FPGA target

b. Delete the associated folder that is automatically created (usually named "Mod#")

c. Change the name of the module to match the name in the PQ Starter Kit project (for example, I or V for current or voltage)

d. Right-click on the newly named module and select N**ew » FPGA I/O**

e. Channels are now addressed based on the module name

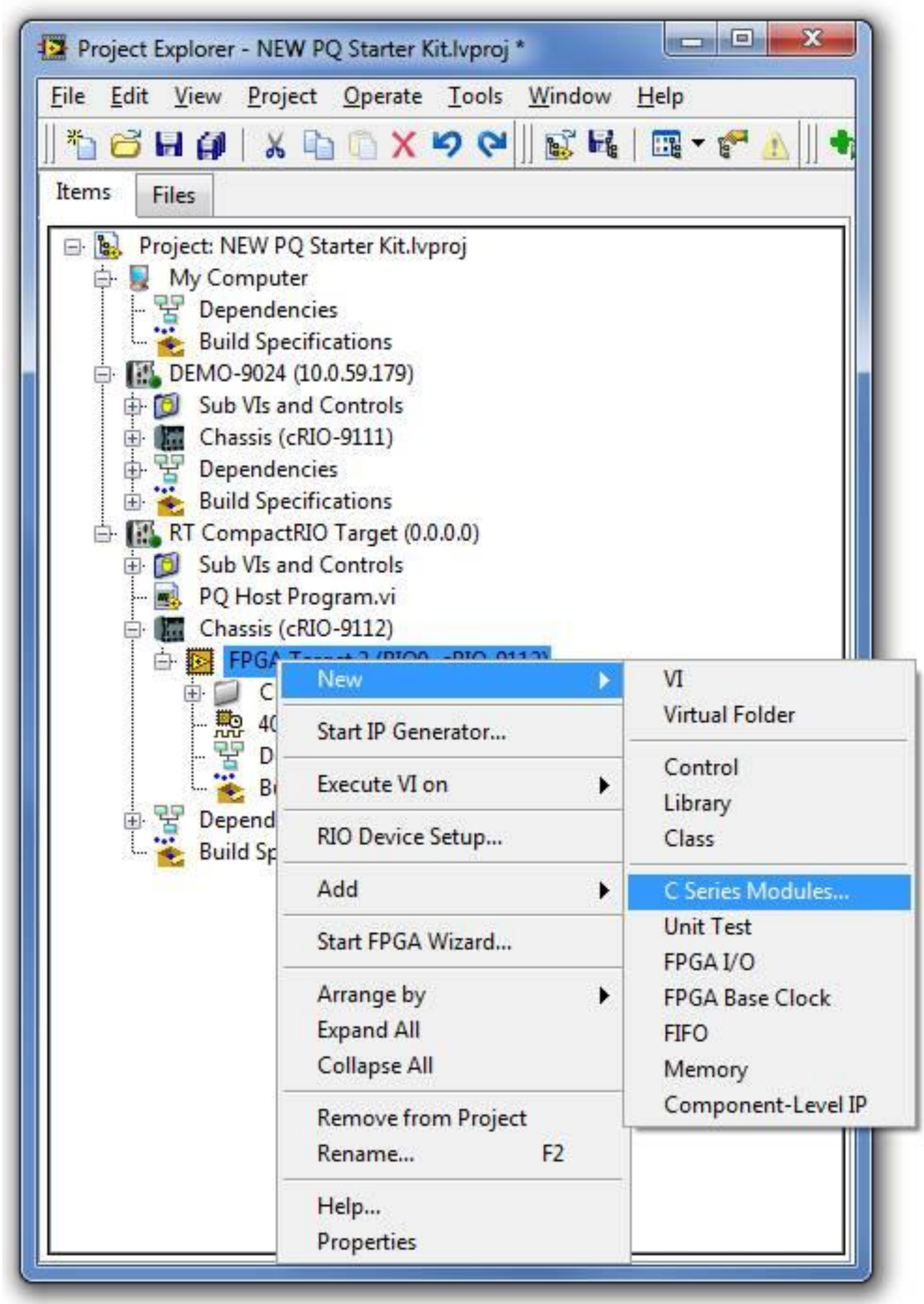


Figure 24: adding cRIO modules

13. After you have created folders, moved VIs, and discovered modules, you can remove the old system from the project by right-clicking it and selecting **Remove from Project.**

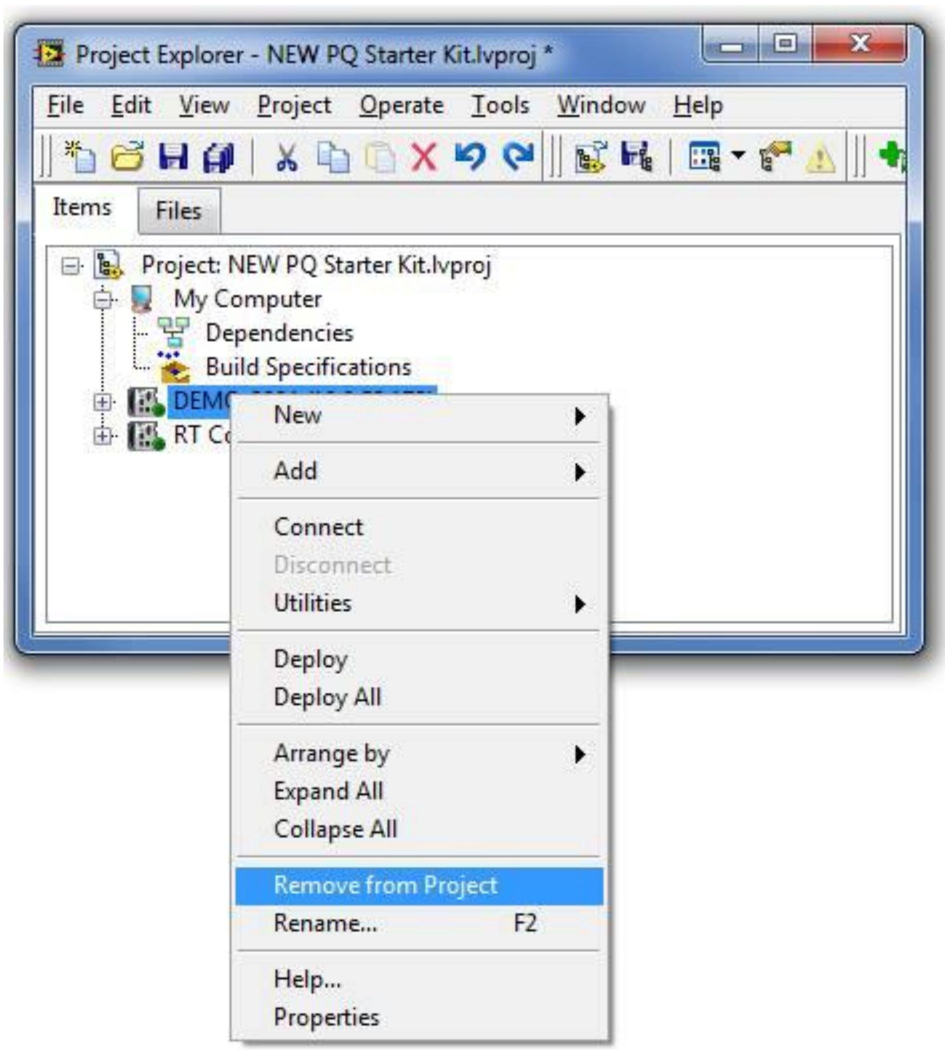


Figure 25: Deleting Demo project

14. Open the [FPGA] Main program and note that the run arrow is broken. This is normal. You need to make a few adjustments before the program can execute on your new target.

a. Synchronize the NI 9225 and NI 9227 modules by right-clicking one of them, going to Properties, and checking "Export Onboard Clock."

b. On the other module, go to Properties and use the "Master Time base Source" pull-down to select the module for which you just exported the onboard clock. The modules can now synchronize within the chassis.

c. Check for broken wires. If the channel address names are not correct, there may be a broken wire on the I/O nodes. Channel order is important, so note the V0, I0, V1, I1… pattern (see image below).

d. Once all the broken wires are gone, save and close the VI.

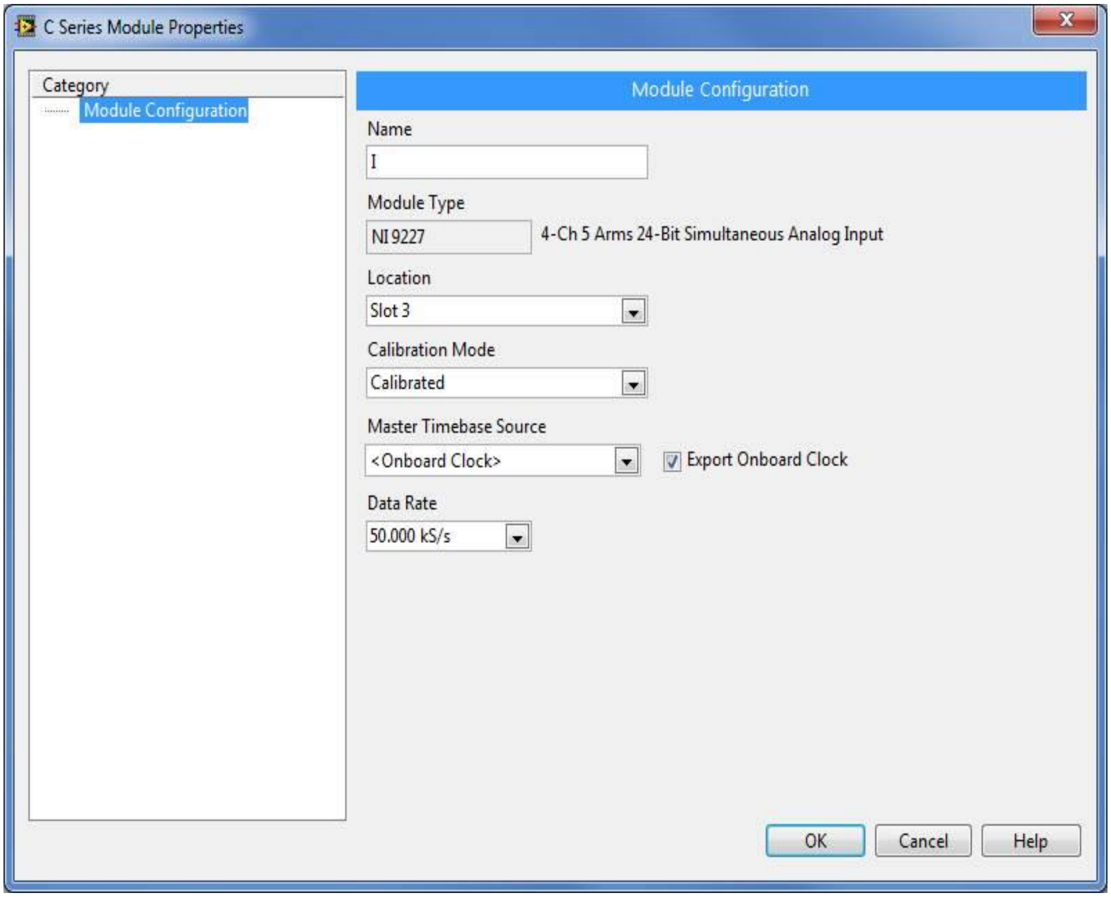


Figure 26: synchronizing all on board clocks

15. Open the “PQ Host Program” and press the Run button on the front panel. Before the example runs, you are prompted to compile the FPGA VI. Once you have completed this compilation, the example runs automatically. Compilation is system-dependent but should take around 20 minutes.

4.1 Configuring Remote Front panels on a Real-time system.

To host a Remote Front Panel on a real-time (RT) target so that we can view the front panel of the application running in a web browser following steps are implemented.

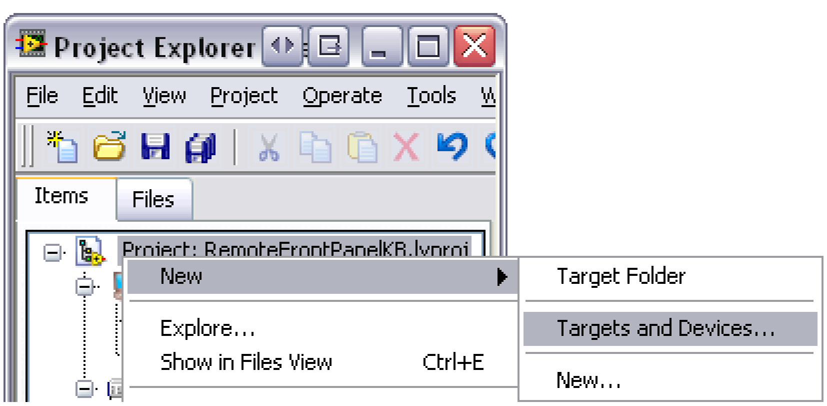
Once we have checked to make sure you have an active Remote Panel License, we can proceed with the following steps:

1. In LabVIEW RT 8.6 and later, you must explicitly install the Web Server for LabVIEW RT to the RT target to host a Remote Front Panel on it. In LabVIEW RT 2014, this component is called the Remote Panel Server for LabVIEW RT. Refer to the Remote Systems Help in Measurement & Automation Explorer (MAX) for information on how to do this. [13]

2. Open a project and add an RT target to the project:

    a. In the Project Explorer, right-click LabVIEW.lvproj file and select **New »Targets & Devices...**.

    b. From the Add Targets and Devices window, select or create your RT target.



3. Enable the web server on the RT target:

   a. Right-click the target in the project and select **Properties**.

   b. Select the **Web Server** category from the left pane.

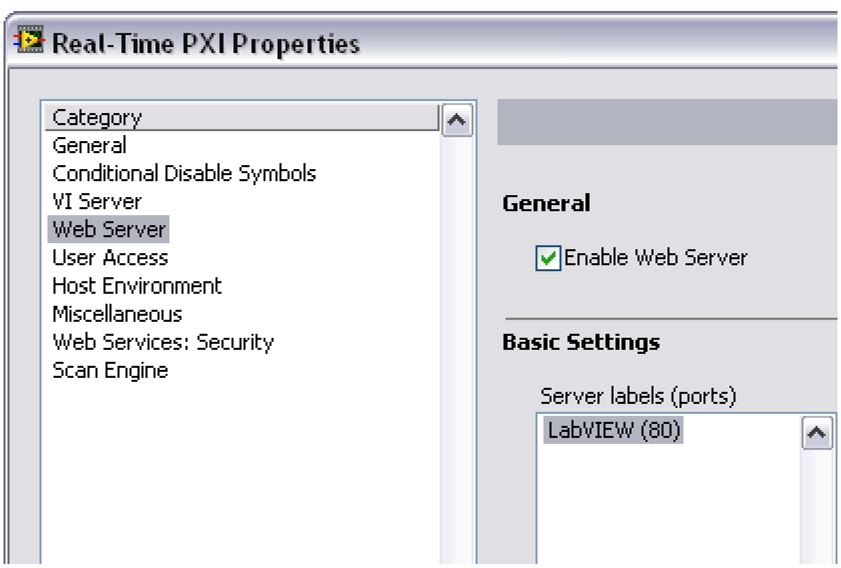
   c. Make sure that the **Enable Web Server** checkbox is checked. Also, verify that **Visible VIs** and **Browser Access** have the correct permissions setup (* can be entered to allow access to all VIs or IP addresses).

   d. Click **OK**.

   e. Right-click the target again, and select **Deploy**. This will deploy the settings to the target.

   f. These settings will not take effect until the next time the target boots. We can reboot the target now or wait until later.

   Note: In LabVIEW 2010, the default port is Port 8000. In versions prior to LabVIEW 2010, the default port is Port 80.



4. Generate the HTML file for the Remote Front Panel:

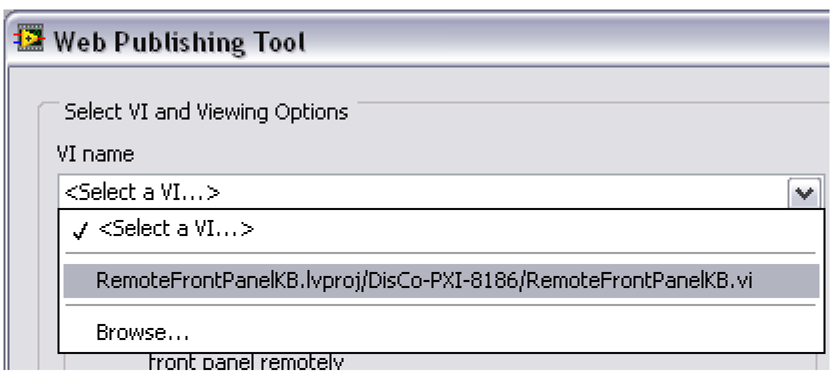
a. Open the VI if it is not already open.

b. Open the Web Publishing Tool by going to **Tools»Web Publishing Tool...**.

c. In the **VI Name** drop-down box, select your VI. You will notice that the **Snapshot** and **Monitor** Viewing Modes become grayed out. This is because those modes are not supported on RT targets.

d. Proceed through the Web Publishing Tool wizard and customize as desired. On the final screen, it is recommended to change the **Filename** of the HTML file to something short and meaningful.

e. Click **Save to Disk**. This will save the HTML to the destination directory and add it to your project under your target.



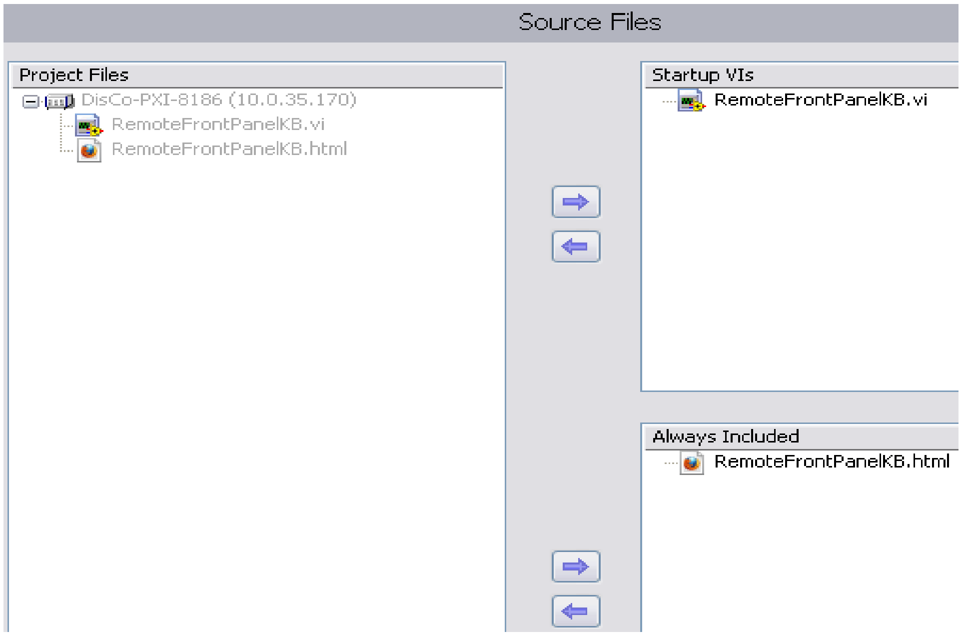
5. Build your RT application:

a. Right-click **Build Specifications** under the target and select **New » Real-Time Application**.

b. Select the **Source Files** category from the left pane.

c. Select your VI and click the arrow to add it to **Startup VIs**.

d. Select your HTML file and click the arrow to add it to **Always Included**.

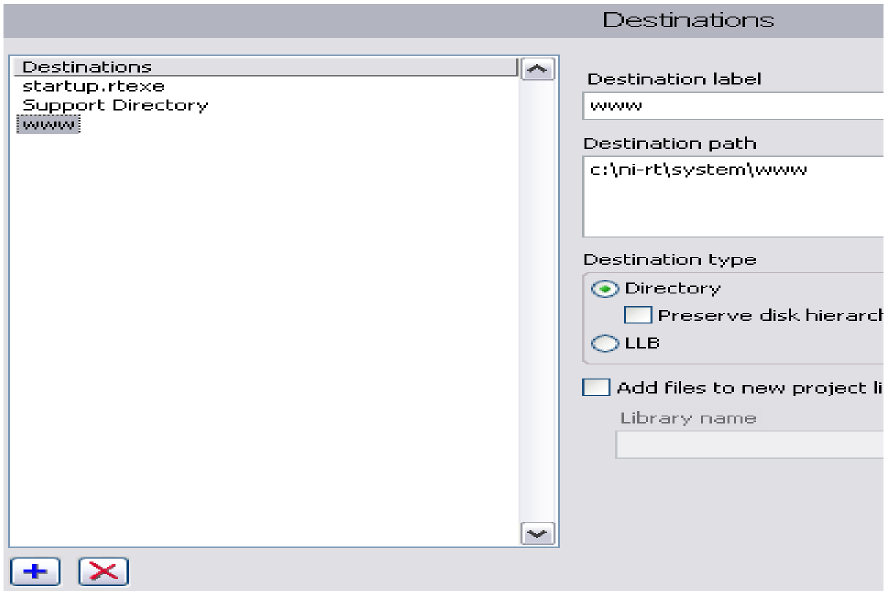


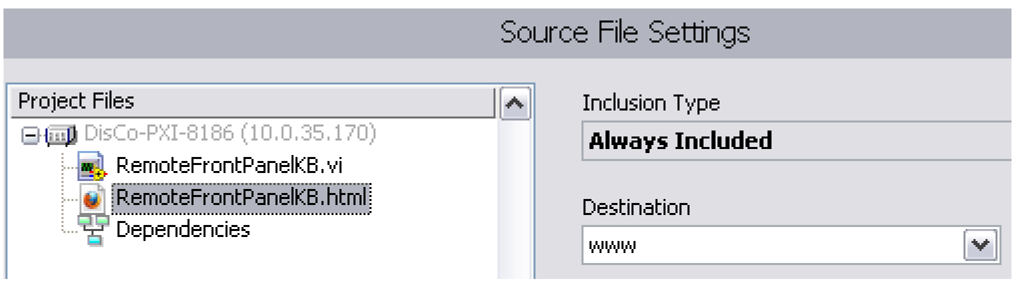
e. Select the **Destinations** category from the left pane.

f. Click the **blue plus sign (+)** to add a new destination.

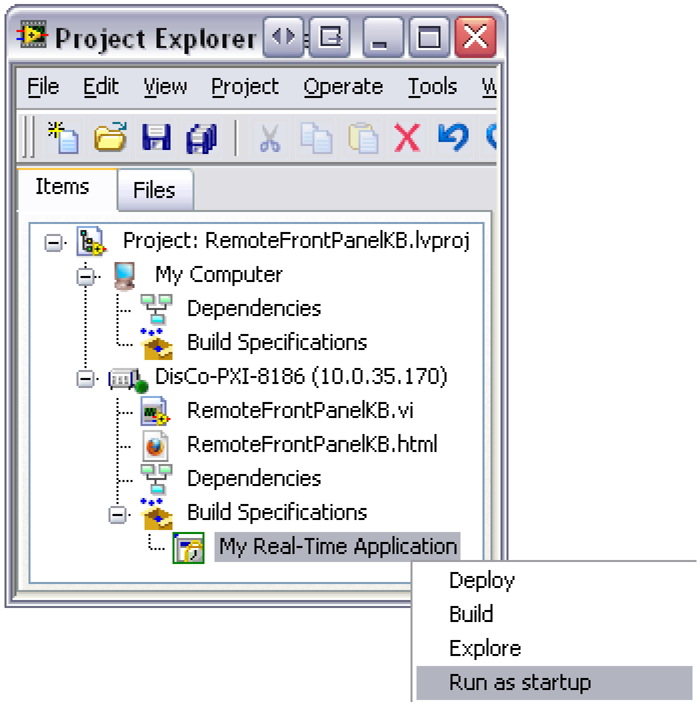
g. Change the **Destination label** to something more meaningful, such as www.

h. Change the **Destination path** to c:\ni-rt\system\www on a PharLap or VxWorks Target or /var/local/natinst/labview/www on a Linux RT target. This corresponds to the web server directory on the target.





6. Select the **Source File Settings** category from the left pane.
    a. Select your HTML from the **Project Files** list and change the **Destination** drop-down box to the destination you created (i.e. www).
    b. Customize the rest of the build specification as desired. Click **Build**.
7. When the build is finished, right-click the application and select **Run as startup**. This will set the application as a startup application, deploy the application to the target, and then prompt you to reboot the target. When you are prompted to reboot the target, click **Yes**.



8. When the target comes up after the reboot, your application should be running, and the Remote Front Panel should be accessible. To verify this, open a web browser and navigate tohttp://xxx.xxx.xxx.xxx:yyyy/<file name>.html, where xxx.xxx.xxx.xxx is the IP address of the target, yyyy is the port assigned to host the Web Server in step 3, and<file name> is the name of the HTML file that was generated from the Web Publishing Tool.

   http://192.168.1.111:8000/PQ_starterkit.html

4.2 LabVIEW project and panel diagrams

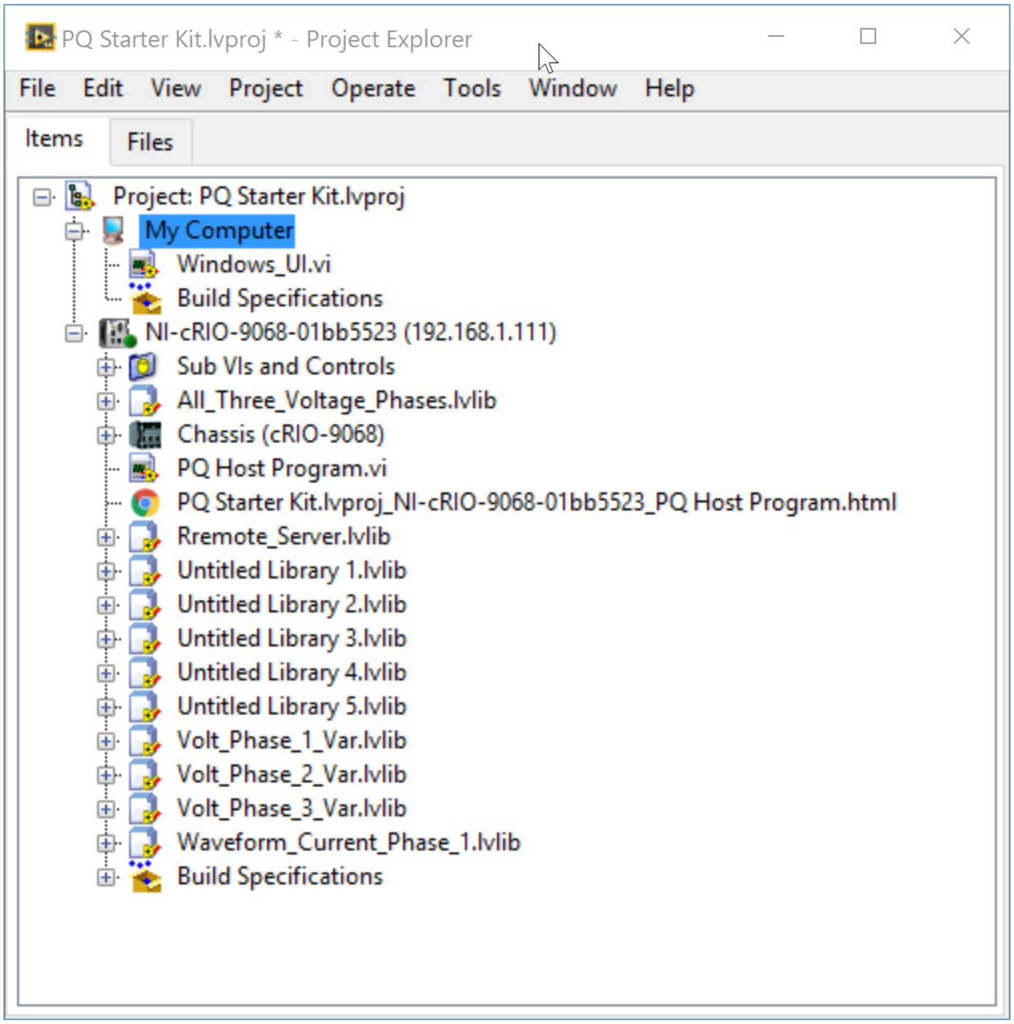


Figure 27:Power Quality LabVIEW project

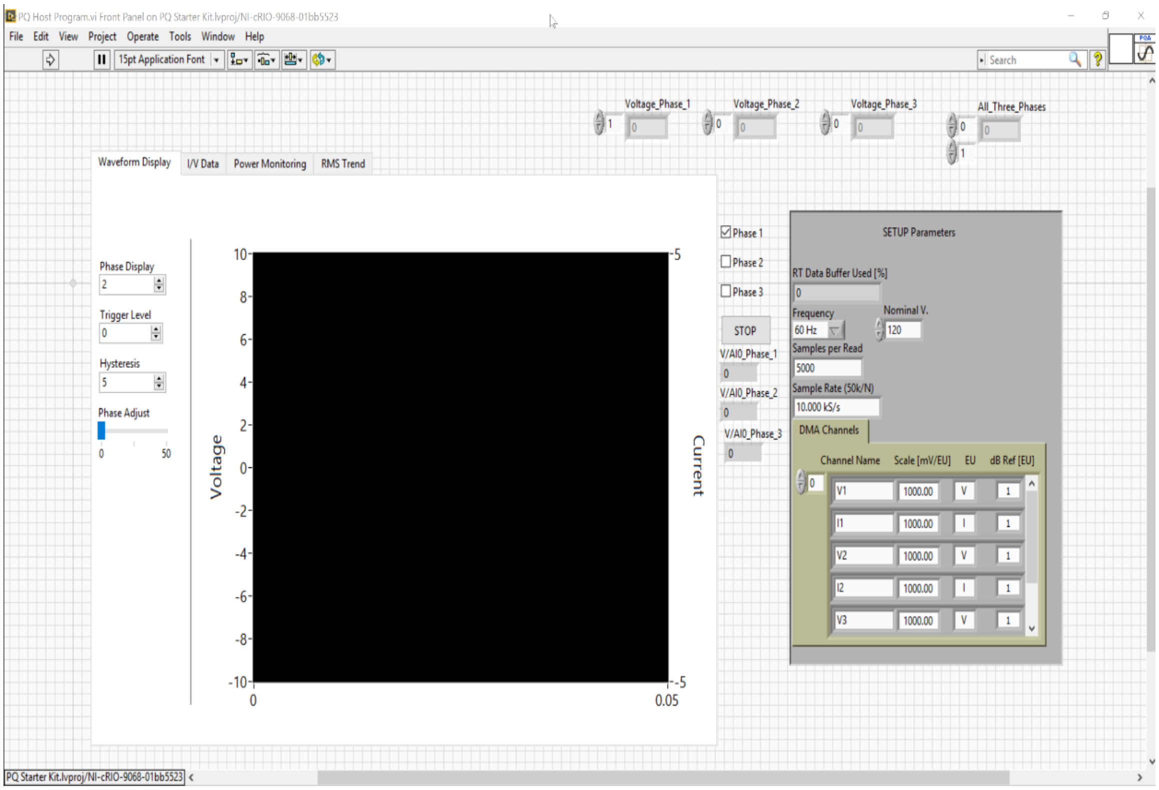


Figure 28: Front Panel of PQ_Host VI

4.2 Block diagrams

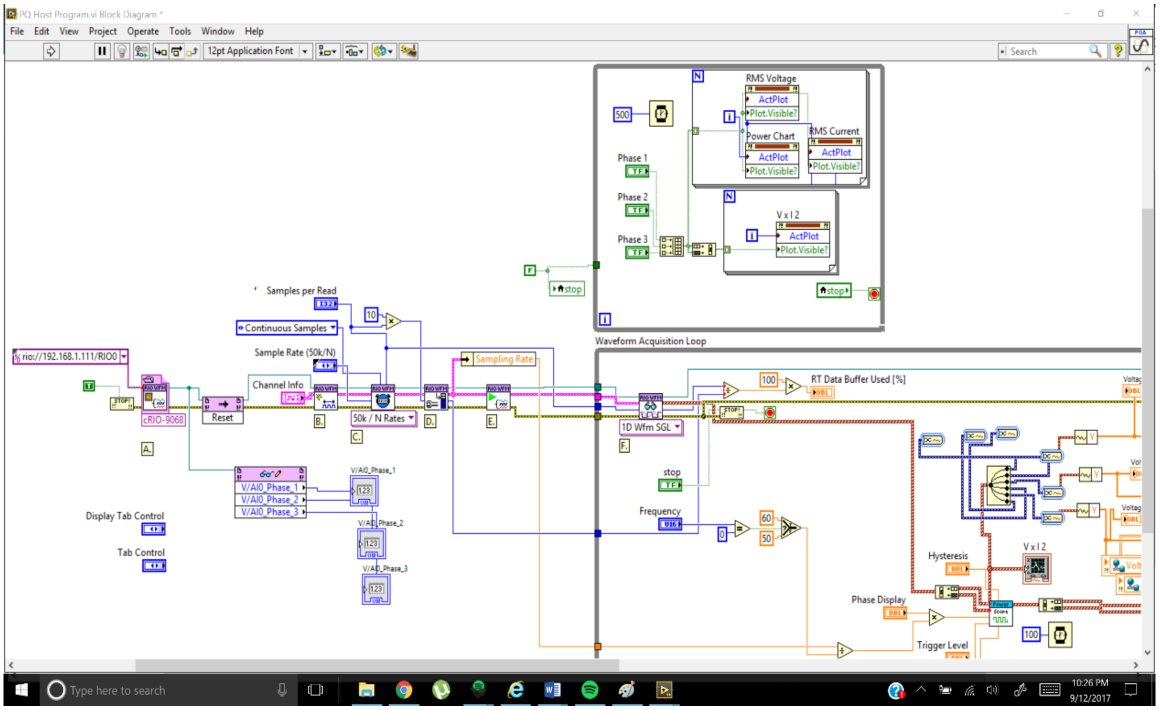


Figure 29: Block diagram of Host VI part1

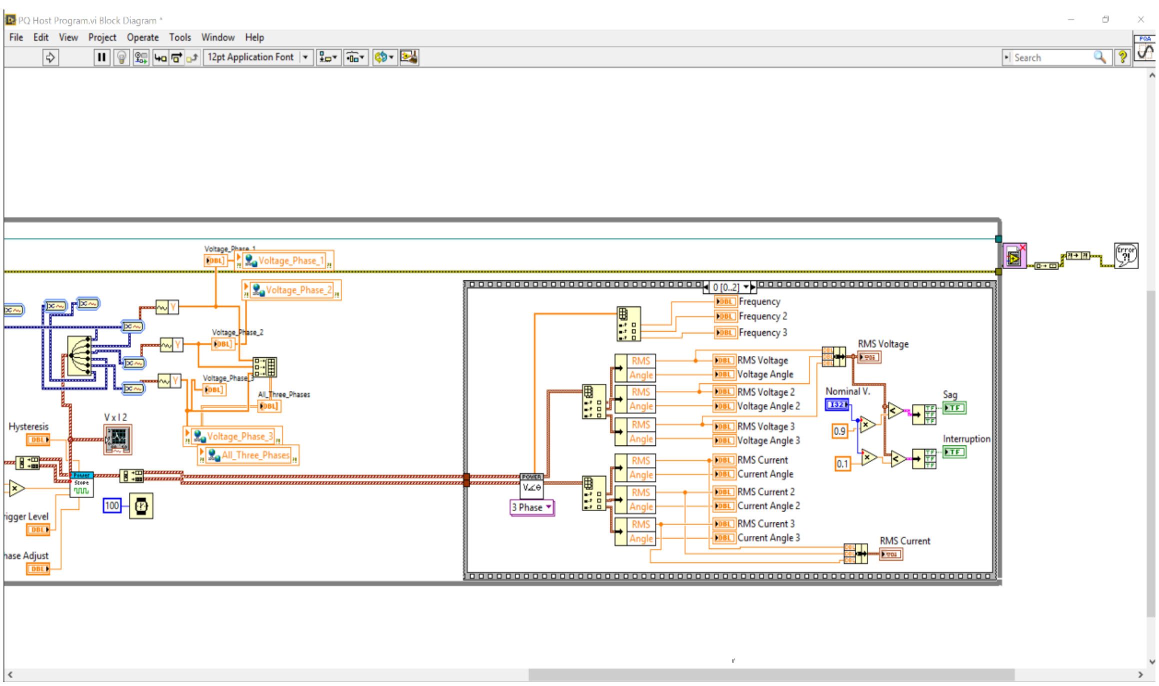


Figure 30: Block diagram of Host VI part2

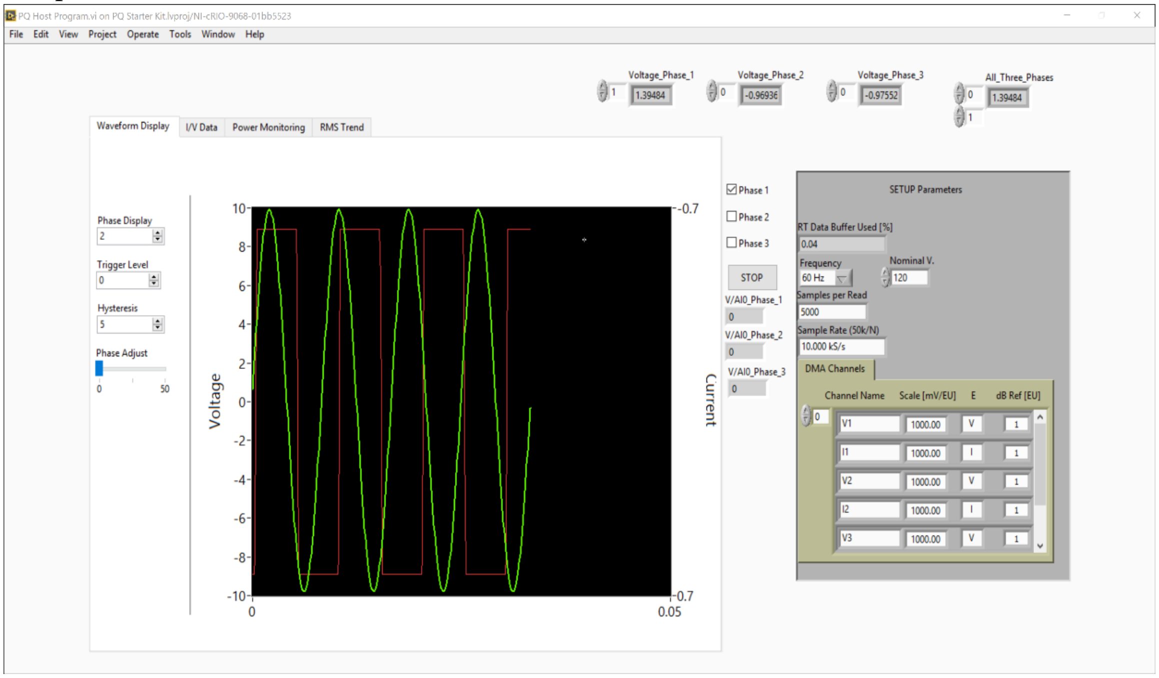


Figure 31: Voltage and Current waveforms

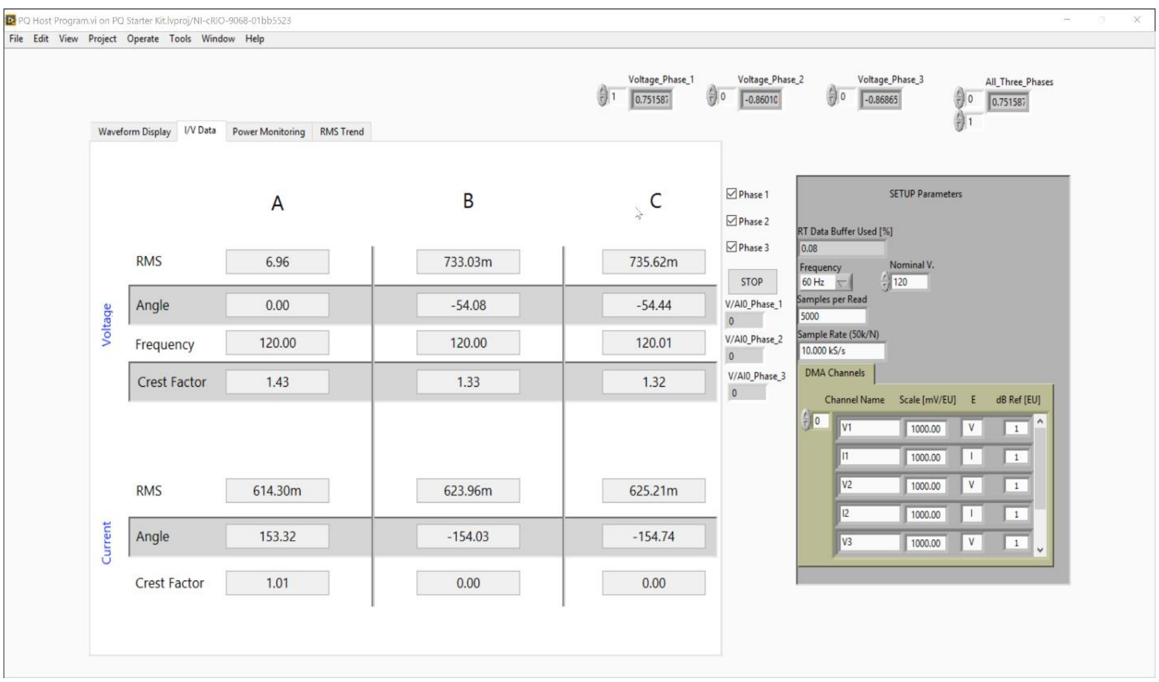


Figure 32: Phase angle and Frequency of waveforms

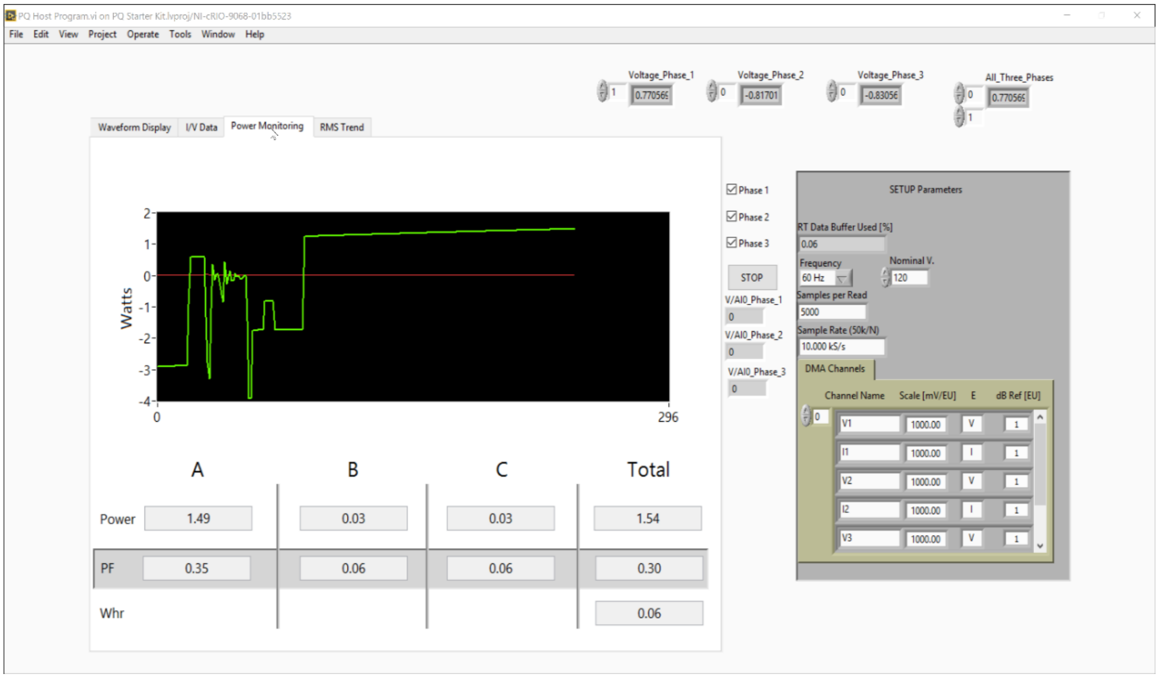


Figure 33: Power characteristics

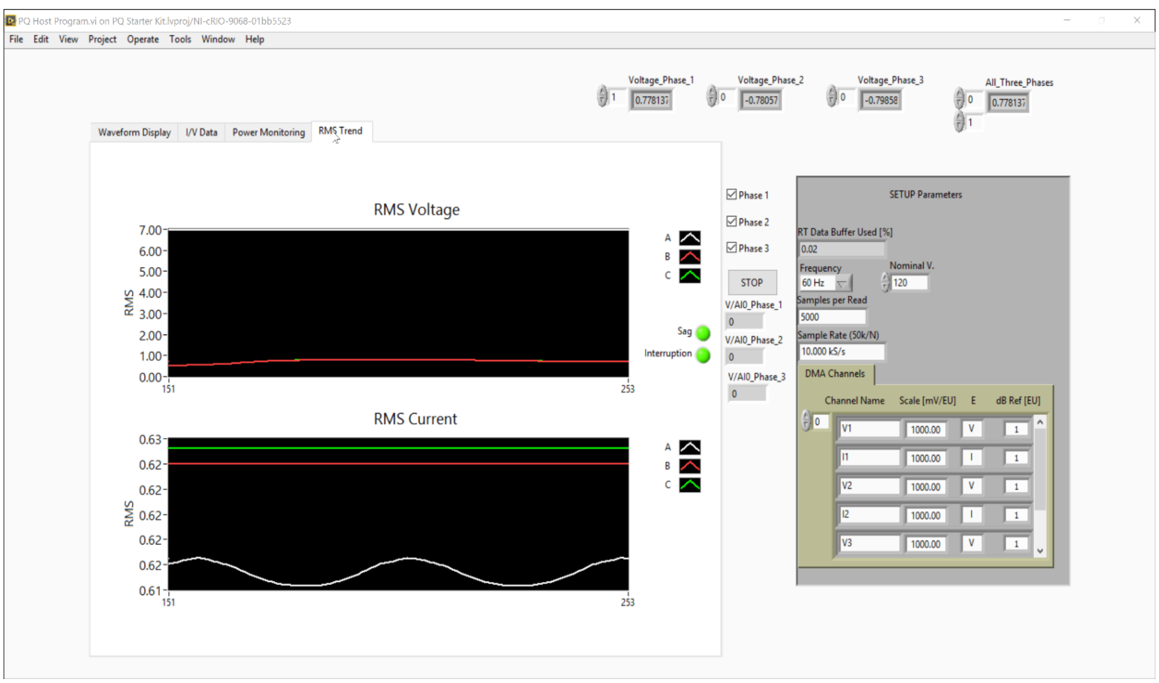


Figure 34: RMS waveforms

Chapter 6: Conclusion

The developed micro PMU can be used to monitor voltages, current and power usage in a system. The micro PMU is a prototype that works for nominal voltage of 120 volts and 15 amps current. The analog input channels that are designed for potential transformer and current transformer inputs use high-speed, high-resolution converters that sample at up to 1,000 samples per cycle with 24 bits of resolution.

Although the micro PMU works for nominal voltage and current, it needs to be tested for different scenarios and test case before it is market deployable. Some of the standard test conducted on PMU analysis are as follows,

- Power and Energy Calculations (IEC 61000-4-30)
- Unbalance (IEC 61000-4-30)
- Flicker (IEC 61000-4-15)
- Event detection and aggregation (IEC 61000-4-30)
- Harmonic Analysis (IEC 61000-4-7)
- Phasor Measurements (C37.118.1a-2014 PMU)

References

[1] A. G. Phadke and J. S. Thorp, “History and applications of phasor measurements,” *2006 IEEE PES Power Syst. Conf. Expo. PSCE 2006 - Proc.*, pp. 331–335, 2006.

[2] L. K. and F. S. Nesrine MEKKI, Faouzi DERBEL, “PMU deployment for state estimation in smart grid,” pp. 82–88.

[3] A. S. Rana and M. S. Thomas, “Exploring IEEE Standard for Synchrophasor C37 . 118 with Practical Implementation,” pp. 1–6, 2015.

[4] H. P. Das, “Development of a Micro- Phasor Measurement Unit for Distribution System Applications,” 2016.

[5] M. E. Moustafa and M. E.-S. Masoud, “A Novel Wide Area Protection Classification Technique for Interconnected Power Grids Based on MATLAB Simulation,” E. P. B. T.-S. and E. A. U. M. Leite, Ed. Rijeka: InTech, 2011, p. Ch. 08.

[6] M. Penshanwar, M. Gavande, and M. F. A R Satarkar, “Phasor Measurement Unit Technology and its Applications – A Review,” no. Icesa, pp. 318–323, 2015.

[7] J. Zhang and Y. Dong, “Preventing false trips of zone 3 protection relays in Smart Grid,” *Tsinghua Science and Technology*, vol. 20, no. 2. pp. 142–154, 2015.

[8] J. E. Tate and T. J. Overbye, “Phasor Angle Measurements,” *IEEE Trans. Power Syst.*, vol. 23, no. 4, pp. 1644–1652, 2008.

[9] S. Sarri, M. Pignati, P. Romano, L. Zanni, and M. Paolone, “A Hardware-in-the-Loop test platform for the performance assessment of a PMU-based Real-Time State Estimator for Active Distribution Networks,” *2015 IEEE Eindhoven*

PowerTech, PowerTech 2015, 2015.

[10] W. Yu, W. Kai, and Y. Chen, "A single-phase Phasor Measurement Unit for smart distribution systems," pp. 3559–3565, 2016.

[10] http://www.ni.com/white-paper/52251/en/

[11] http://www.ni.com/en-us/shop/select/c-series-voltage-input-module?modelId=122193

[12] http://www.ni.com/en-us/shop/select/c-series-voltage-input-module?modelId=122191

[13] https://www.smartgrid.gov/recovery_act/program_impacts/applications_synchrophasor_technology.html

[14] http://www.ni.com/tutorial/11336/en/

[15] http://digital.ni.com/public.nsf/allkb/AB6C6841486E84EA862576C8005A0C26

[16] http://www.phasor-rtdms.com/phaserconcepts/phasor_adv_faq.html