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Elevating Power Quality: Three-Phase Harmonic Analysis using NI myRIO's Synchronous Reference Frame

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ABSTRACT

Harmonics in three-phase electrical networks give rise to significant power losses, necessitating their detection and mitigation to prevent these losses. This research presents the development of a comprehensive system designed to measure harmonic content and extract harmonics, thereby generating a reference signal for an active power filter aimed at harmonics reduction. The methodology leverages the Synchronous Reference Frame - Phase Locked Loop (SRF-PLL) approach to segregate the fundamental order from the harmonic signal, resulting in the isolation of pure harmonic components. The Fast Fourier Transform (FFT) method is concurrently employed to quantify the amplitude of each harmonic order. Both computational processes are executed on the NI myRio controller, programmatically configured through LabVIEW software. The constructed system exhibits remarkable performance, manifesting an average Total Harmonic Distortion (THD) error of 0.47% before and after extraction for non-triple orders, and 99.93% for triplen orders. Consequently, this harmonic extraction system excels particularly in isolating non-triple order harmonics. To optimize its functionality, current or voltage sensors with specifications tenfold the amplitude of the 50Hz AC fundamental order are recommended. Furthermore, the system showcases a remarkable frequency range, capable of accurately discerning AC signal frequencies up to 20kHz or orders as high as 400.

Keywords:
Harmonic analysis; NI myRIO's; power quality; total harmonic distortion

1. Introduction

The presence of harmonics in three-phase electrical networks is a pervasive issue with profound implications, resulting in substantial power losses and a diminished power quality [1, 2]. Harmonic distortions, characterized by deviations from the fundamental sinusoidal waveforms, are primarily generated by non-linear loads such as power electronics, electronic devices, and various industrial equipment [3-5]. These harmonic distortions, when left unattended, can lead to voltage and

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current waveforms that deviate significantly from their ideal sinusoidal counterparts, causing equipment malfunctions, reduced efficiency, and increased energy consumption. Consequently, addressing harmonics in electrical systems has emerged as a critical concern in contemporary power engineering [6-8].

Efforts to mitigate the detrimental effects of harmonics have given rise to various solutions, with active power filters standing as an effective means of harmonic reduction [9-11]. These filters operate by generating compensating currents that actively cancel out harmonic currents, thereby restoring the purity of the electrical supply [1, 12]. However, the success of such active filters hinges on their ability to precisely detect and isolate the harmonic components within the electrical system.

Many literatures studied of the harmonics in three-phase electrical network such as Liserre *et al.,* [13] investigated a new class of hybrid controllers made by PI and resonant controllers implemented in a rotating frame to achieve multiple harmonics compensation. Hansen *et al.,* [14] proposed a method to mix single-phase and three-phase nonlinear loads and reduce the harmonic currents significantly. They found that the adding three-phase rectifier load can improve the power quality at the transformer. Densem *et al.,* [15] proposed three phase modelling of an a.c. transmission system for harmonic penetration studies. They show that the impedances and sequence voltages are presented for selected busbars when the system is subjected to current unbalance and circuit configuration changes. Zare *et al.,* [16] presents the effects of grid-connected three-phase systems with different front-end topologies: conventional, small dc-link capacitor, and electronic inductor.

Subsequently, Carta *et al.,* [17] implementation of digital procedures for the evaluation of the synchronized harmonic phasors in a flexible phasor measurement unit (PMU) based on PXI modular hardware. Davari *et al.,* [18] proposed new cost-effective harmonic mitigation approach for multiple drives and the generated current harmonics by benefiting of the nonlinearity of the drive units and through a novel current modulation scheme. Zhang *et al.,* [19] presented harmonic transfer-function-based impedance modeling of a three-phase VSC for asymmetric AC grid stability analysis. Rodriguez *et al.,* [20] presents a new solution for filtering current harmonics in three-phase four-wire networks and studied characterized by a particular layout of single-phase inductances and capacitors, without using any transformer or special electromagnetic device. De Souza *et al.,* [21] presents a finite-set model predictive control (FS-MPC) applied to the shunt active power filters (SAPF) based on three-phase inverters connected in parallel sharing the same dc-link.

This research endeavors to address this challenge through the development of a comprehensive harmonic extraction system designed to measure harmonic content and produce a reference signal for an active power filter. At the core of this methodology lies the utilization of the Synchronous Reference Frame - Phase Locked Loop (SRF-PLL) approach, which facilitates the accurate segregation of the fundamental order from the harmonic signal. The outcome of this process is the isolation of pure harmonic components, ready for subsequent analysis and filtering.

To quantify the amplitude of each harmonic order, we concurrently employ the Fast Fourier Transform (FFT) method. Both the SRF-PLL and FFT processes are executed seamlessly on the National Instruments (NI) myRio controller, offering a flexible and programmable platform for real-time harmonic analysis. The system's performance is notably impressive, boasting an average Total Harmonic Distortion (THD) error of 0.47% before and after extraction for non-triple orders, and 99.93% for triplen orders. This remarkable performance underscores the system's efficacy in isolating non-triple order harmonics, a critical achievement in the context of harmonics mitigation.

Furthermore, this research provides insights into the optimal specifications for current or voltage sensors used within the harmonic extraction system, advocating for sensor specifications that are tenfold the amplitude of the 50Hz AC fundamental order. Additionally, the system exhibits a remarkable frequency range, capable of accurately discerning AC signal frequencies up to 20kHz or orders as high as 400, enhancing its utility in diverse electrical environments.

In summary, this research contributes a robust and efficient solution for addressing harmonics in three-phase electrical networks, offering not only precise harmonic detection but also effective harmonics reduction through active power filtering. The subsequent sections of this paper delve into the methodology, experimental setup, results, and implications of this innovative harmonic extraction system, providing a comprehensive understanding of its capabilities and potential applications in modern power engineering scenarios.

2. Methodology

2.1 Data Acquisition

The first phase of our methodology involves the acquisition of electrical data from the three-phase network under examination. To accomplish this, a set of high-precision current and voltage sensors is strategically placed within the electrical system. These sensors are selected based on the recommended specifications, ensuring that their amplitude range is tenfold greater than the 50Hz AC fundamental order. The acquired data, comprising current and voltage waveforms, is then transmitted to the NI myRio controller for real-time processing.

2.2 Synchronous Reference Frame - Phase Locked Loop (SRF-PLL) Implementation

The heart of our harmonic extraction system lies in the application of the Synchronous Reference Frame - Phase Locked Loop (SRF-PLL) methodology. This technique plays a pivotal role in isolating the fundamental order from the harmonic signal, effectively distinguishing between the desired sinusoidal waveform and the unwanted harmonic distortions.

The SRF-PLL algorithm operates as follows:

i. Signal synchronization: The acquired current and voltage waveforms are initially synchronized with the system's reference voltage. This synchronization process ensures that the system operates in phase with the fundamental frequency, thereby enhancing accuracy.
ii. Angle calculation: The phase angle between the synchronized current and voltage signals is calculated using the arctangent function. This angle serves as the reference for subsequent harmonic extraction.
iii. Phase Locking: The SRF-PLL continuously adjusts the phase angle of the voltage signal to match the calculated angle. This phase-locking mechanism guarantees that the extracted harmonics remain synchronized with the fundamental frequency.

3.3 Fast Fourier Transform (FFT) Analysis

Concurrently, the Fast Fourier Transform (FFT) method is applied to the synchronized data to quantify the amplitude of each harmonic order present in the electrical system [22-26]. The FFT algorithm converts the time-domain waveforms into the frequency domain, revealing the spectral composition of the signal. By examining the magnitudes of the spectral components, we can precisely determine the amplitude of each harmonic order.

3.4 Harmonic Extraction and Filtering

With the fundamental order isolated using the SRF-PLL and the amplitudes of the harmonics obtained through FFT analysis, our system proceeds to extract the harmonic components. This involves the subtraction of the fundamental order from the synchronized current and voltage waveforms, resulting in a pure harmonic signal ready for further processing. The extracted harmonic components are then utilized as input for an active power filter, which generates compensating currents to counteract the effects of the harmonics in the electrical system. This filtering action effectively reduces harmonic distortions and enhances power quality.

3.5 Performance Evaluation

To assess the system's performance, we calculate the Total Harmonic Distortion (THD) error before and after harmonic extraction. This metric provides a comprehensive measure of the harmonic content in the electrical system and quantifies the system's ability to isolate non-triple order and triplen order harmonics.

3.6 Frequency Range Analysis

Finally, the system's frequency range capability is evaluated by subjecting it to AC signal frequencies spanning from the fundamental order up to 20kHz or orders as high as 400. This analysis ensures the system's adaptability to a wide range of electrical environments and applications. In summary, our methodology combines the precision of the SRF-PLL approach with the spectral analysis power of FFT to effectively extract harmonics from three-phase electrical networks. The extracted harmonics are subsequently utilized for active power filtering, enhancing power quality, and minimizing energy losses. Performance evaluation metrics, including THD error and frequency range analysis, validate the system's robustness and suitability for diverse electrical scenarios.

3. Results

3.1 System Planning

In this work, we started by turning on the system which consists of two myRio and one computer that has run the LabVIEW application, then the system samples the current or voltage signals that are read by the analog pins. This sampling process is the concept of analog to digital conversion. The results of sample data are stored and forwarded for the extraction process of harmonics with plots of harmonic waves before being extracted and harmonics after being extracted.

At this stage, the system is considered to have completed adding one sampling. If the system is still on, this process is repeated and will go through checking when the sample reaches 5120 samples. When the sampling number is met, an FFT analysis is carried out and the results are forwarded to be plotted on a graph. Then the amplitude of each harmonic order can be known, so the system can calculate the RMS and THD values. After going through the FFT process, the sample is then emptied and replaced with a new sample obtained from a repeated sampling process as shown in Figure 1.

In the hardware assembly process, a wiring diagram image is needed as a reference. Figure 2 is the overall system wiring scheme with the HIL (Hardware in Loop) concept. There is no difference between the designed block diagram and the proposed wiring diagram, where myRio B represents part of the input, namely the signal source in the form of a signal generator. Meanwhile, myRio A represents as part of the process and the laptop as part of the output.

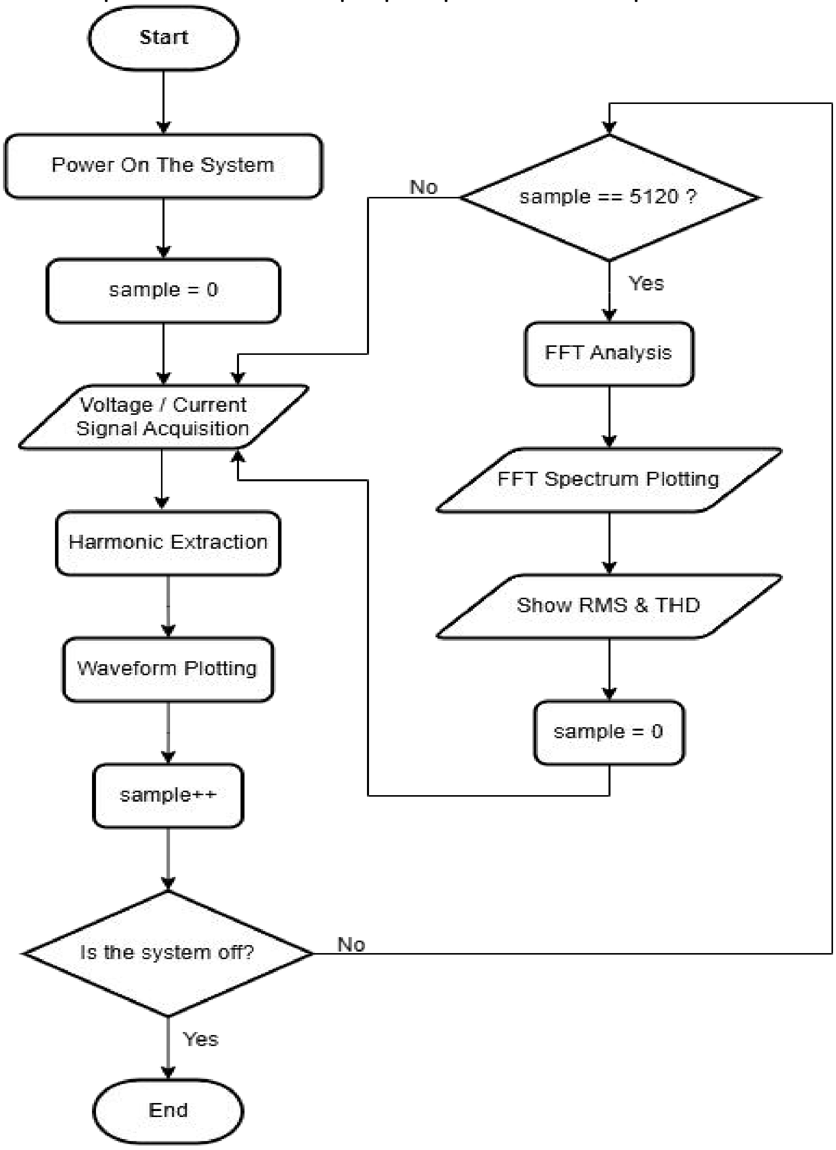


Fig. 1. Flow chart of the system

The use of myRio B as a three-phase harmonic signal generator replaces the use of current or voltage sensors in a three-phase network. Thus, the harmonic extractor (myRio A) receives harmonic signals through its three analog input pins from the three analog output pins of the harmonic signal generator (myRio B). Thus, the shape of the incoming signal to the harmonic extractor can be controlled, so that tests can be carried out with various harmonic wave configurations. In this study, this research requires several components to realize it both hardware and software as in Table 1.

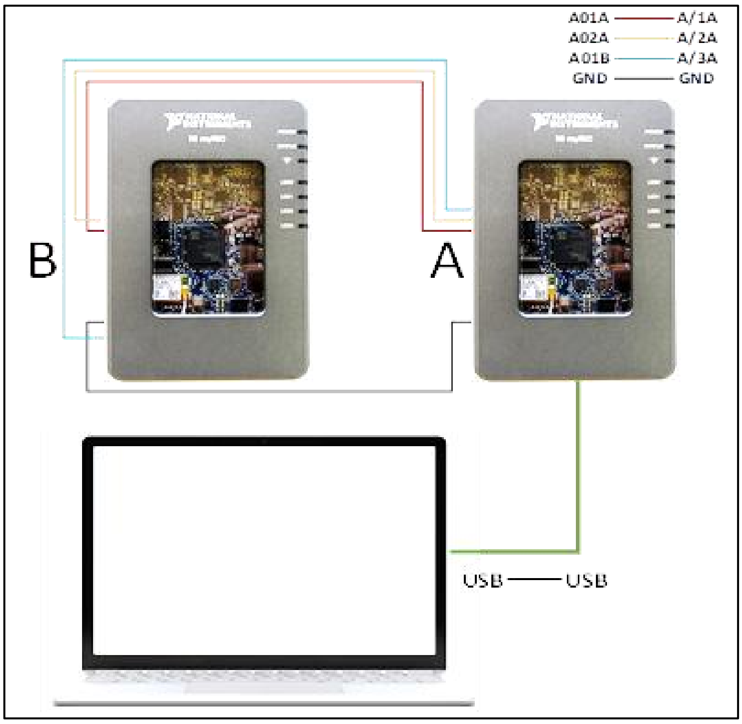


Fig. 2. Wiring diagrams system

Table 1
Research components

No	Components	Total
1	NI myRio	2 pieces
2	Laptop/PC	1 piece
3	Jumper cables	12 pieces
4	myRio adapter	2 pieces
5	Data cable	2 pieces
6	Labview 2016	1 piece

3.2. Software and Hardware Implementation
3.2.1 Human Machine Interface (HMI)

A Human-Machine Interface (HMI) is a technology or system that allows humans to interact with and control machines, devices, or software applications. HMIs are essential components in various fields, including manufacturing, automation, computer systems, and consumer electronics. Figure 3 is the result of the harmonic extraction HMI display which contains some information related to the harmonic signal being extracted. Part (a) is a graph of the waves that the user can choose from. Part (b) is the harmonics before extraction (L1, L2 and L3), the output of the park transformation (*D*, *Q*), the harmonics after extraction (L1, L2 and L3). Part (c) is a graph of the pre-extracted and post-extracted FFT analysis. Meanwhile, part (d) is information in the form of numbers including fundamental rms values, overall rms and THD.

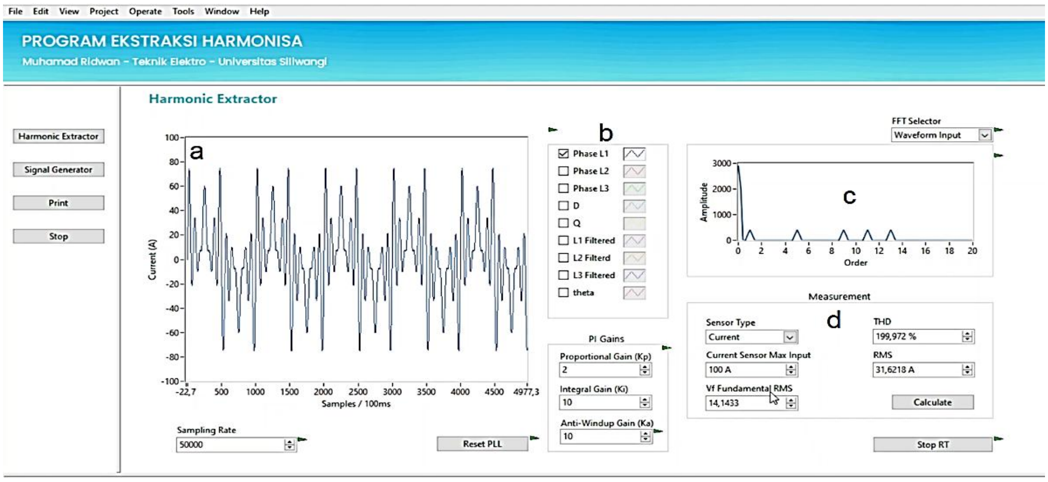
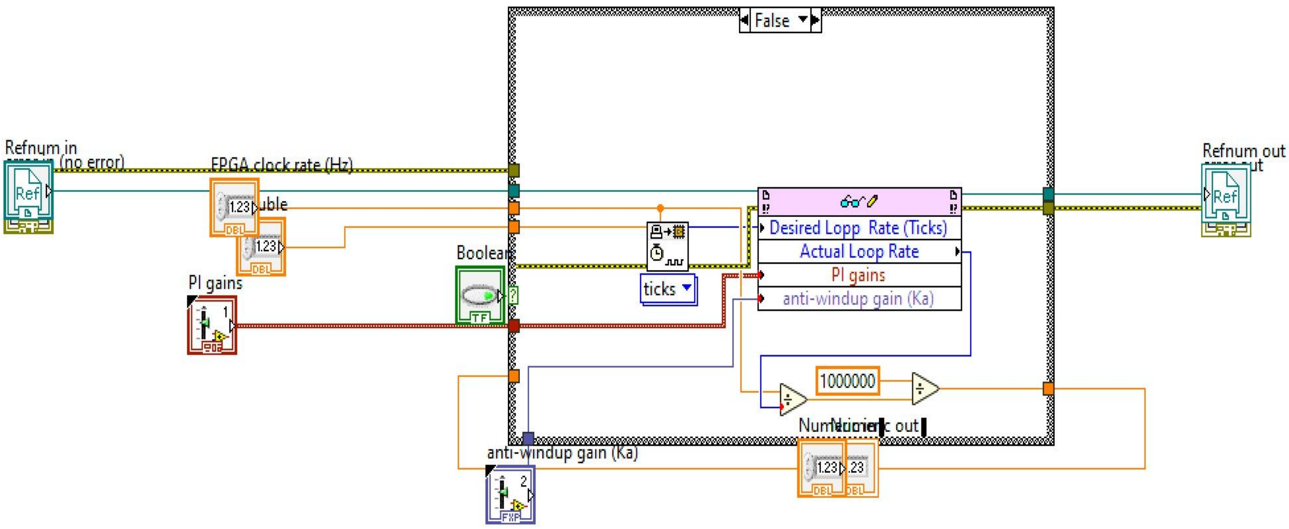


Fig. 3. Harmonic extraction HMI display

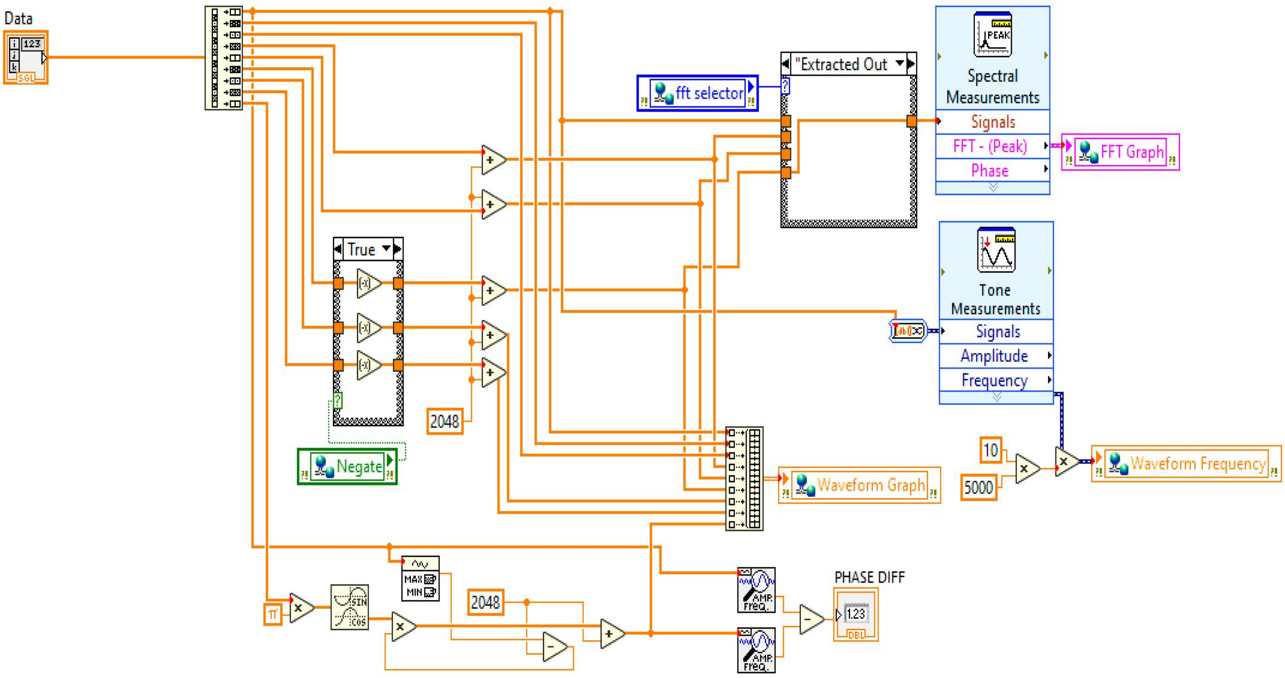
In this HMI program, there is a data binding term which allows desktops to share the same variable with myRio. So that variables that implement data binding in the HMI program make it possible from a block diagram perspective to not have a process. This is because the process occurs on the myRio side and the variables in the HMI program only hold the process results and then display them. Using one variable together is possible, because there is data exchange between the computer and myRio via the TCP/IP communication protocol. Variables that apply this data binding can be easily distinguished from ordinary variables which in appearance or interface are marked with a small flag.

3.2.2 myRio processor program

FFT analysis requires more than one sample of waveform data, so the system cannot perform FFT analysis if the data being processed is single data resulting from ADC data acquisition. Because myRio has an FPGA which is very good at analog signal data acquisition, the myRio processor is programmed to only carry out FFT analysis of the data array sent by the FPGA, then sends the data processing results to the computer. The program for the myRio processor is listed in Figure 4.



(a)



(b)

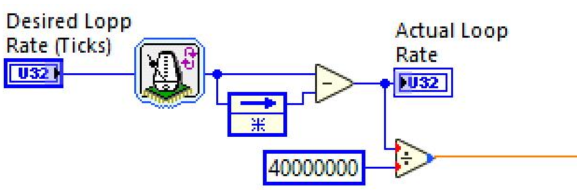
Fig. 4. MyRio processor overall program (a) Block A (b) Block B

The myRio processor program algorithm can be presented as follows:

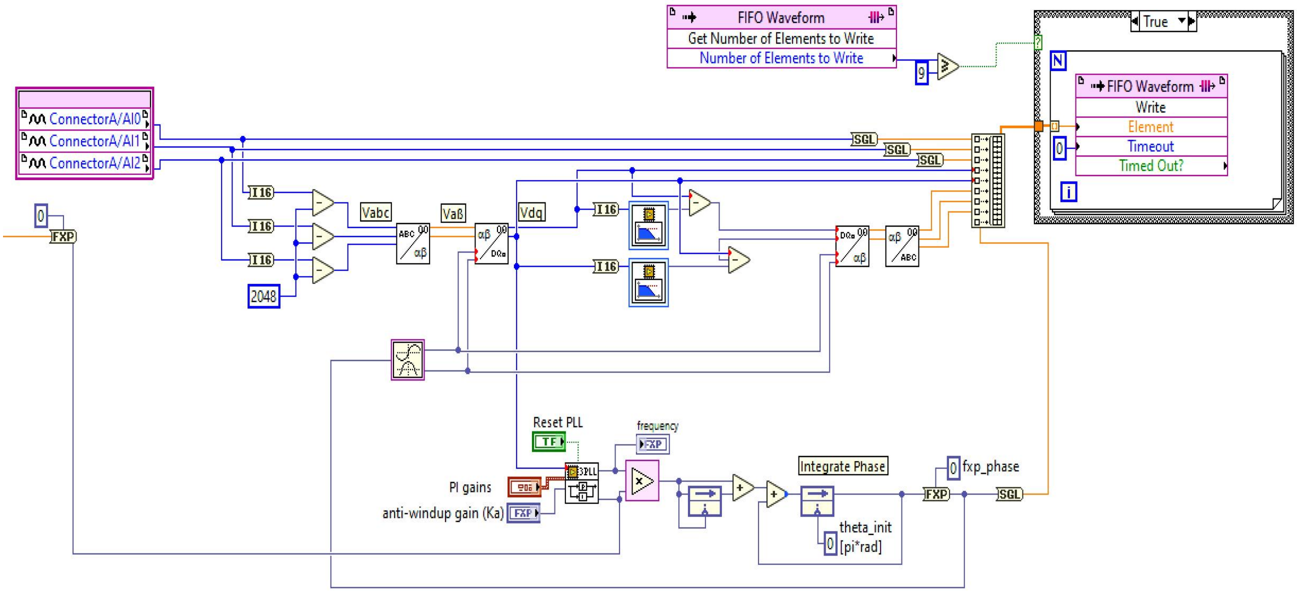
i. FIFO DMA initialization.
ii. Initialization of FPGA parameters.
iii. Initialization of variables.
iv. Set the loop period.
v. Setting parameters on FPGA.
vi. Retrieving data from FPGA.
vii. Negation
viii. FFT.

3.2.3 myRio FPGA program

The program for the myRio FPGA in Figure 5 focuses on data acquisition from the three analog inputs and extraction of harmonics using the SRF-PLL method. The acquisition and extraction data is then sent to the processor using the DMA FIFO feature which is then analyzed using FFT and forwarded to the Desktop for the information to be displayed.



(a)



(b)

Fig. 5. myRio FPGA program (a) Block A (b) Block B

The myRio FPGA program algorithm can be presented as follows:

i. Setting the FPGA loop period
ii. Reading analog values
iii. ABC to DQ transformation
iv. Phase Locked Loop (PLL)
v. Filter
vi. DQ to ABC transformation
vii. Sending data from FPGA

3.2.4 Hardware

From the wiring diagram in Figure 2, it is realized by assembling the hardware as in Figure 6. MyRio B as a harmonic signal generator transmits a three-phase harmonic signal connected to Y via three analog outputs, namely connector A AO0, connector A AO1 and connector B AO0. Meanwhile, myRio A as a harmonic extractor system receives harmonic signals via three analog inputs, namely connector A AI0, AI1 and AI2. To display information on harmonic content and extracted waves, myRio A is connected to a laptop via a USB cable with TCP/IP protocol.

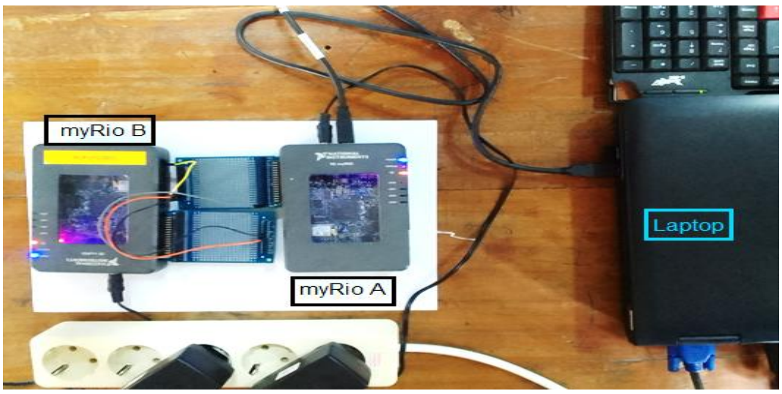


Fig. 6. Hardware of myRio

3.3 Extraction Results
3.3.1 System testing for extracting triplen order harmonics

Based on Figure 7, the test begins by determining the amplitude ranging from 10% to 100% at orders 3, 9 and 15 to be generated at the signal source. The system reads the harmonic signal then extracts it and performs an FFT computation on the read harmonics. The harmonics that have been extracted are then plotted in waves, as well as the FFT results are plotted into a harmonic spectrum. The success of this test is measured from the fundamental order removed in the harmonics that have been extracted. Table 2 is the test result of the system for extracting triplen order harmonics.

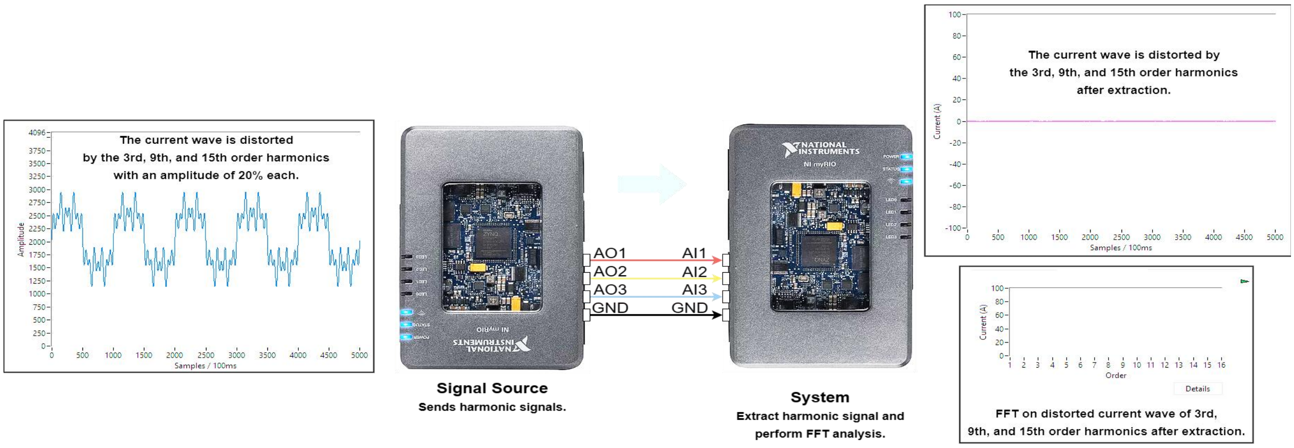


Fig. 7. Extraction of triplen order harmonics

Table 2
System test results for the extracting triplen order harmonics

No	Harmonics %	Harmonic signal before extraction (A)				Harmonic signal after extraction (A)				THD (%)		Error (%)
		1st order	3rd order	9th order	15th order	1st order	3rd order	9th order	15th order	Before extraction	After extraction	
1	10.00	10.00	1.00	1.00	1.00	0.02	0.00	0.00	0.00	17.32	0.05	99.74
2	20.00	10.00	2.00	2.00	2.00	0.02	0.00	0.00	0.00	34.64	0.05	99.84
3	30.00	10.00	3.00	3.00	3.00	0.02	0.00	0.00	0.00	51.96	0.04	99.92
4	40.00	10.00	4.00	4.00	4.00	0.02	0.00	0.00	0.00	69.28	0.03	99.96
5	50.00	10.00	5.00	5.00	5.00	0.02	0.00	0.00	0.00	86.60	0.03	99.96
6	60.00	10.00	6.00	6,00	6.00	0.02	0.00	0.00	0.00	103.92	0.05	99.96
7	70.00	10.00	7.00	7.00	7.00	0.02	0.00	0.00	0.00	121.24	0.04	99.97
8	80.00	10.00	8.00	8.00	8.00	0.02	0.00	0.00	0.00	138.57	0.03	99.98
9	90.00	10.00	9.00	9.00	9.00	0.02	0.00	0.00	0.00	155.89	0.03	99.98
10	100.00	10.00	1.,00	10.00	10.00	0.02	0.00	0.00	0.00	173.21	0.06	99.97

Table 2 is the results of harmonic extraction tests on odd order harmonic waves of multiples of three (orders 3, 9 and 15). The test is divided into 10 parts based on amplitude values of triple order starting from 10% to 100%. If we observe the amplitude values of the 3rd, 9th, and 15th order harmonics after extraction they are reduced to almost zero. This is different from the aim of harmonic extraction in this research, namely reducing the fundamental order amplitude and maintaining the harmonic order amplitude value to produce a pure harmonic signal wave without fundamental order. Thus, harmonic extraction using the SRF-PLL method can be said to have limitations in extracting harmonics of order multiples of three because it cannot maintain the amplitude value of the harmonics. However, the fundamental order can be reduced to close to 0. It can also be observed that the THD values before extraction and after extraction have an error difference of more than 99%.

3.3.2 System testing for extracting of non-triplen order harmonics

Based on Figure 8, the test begins by determining the amplitude ranging from 10% to 100%, at 5, 7, 11, 13, 17 and 19 to be generated at the signal source. The system reads the harmonic signal then extracts it and performs an FFT computation of the read harmonics. The harmonics that have been extracted are then plotted in waves as well as the FFT results are plotted into a harmonic spectrum. The success of this test is measured by the removed fundamental order in the extracted harmonics. Table 3 is the test result of the system for extracting non-triple order harmonics.

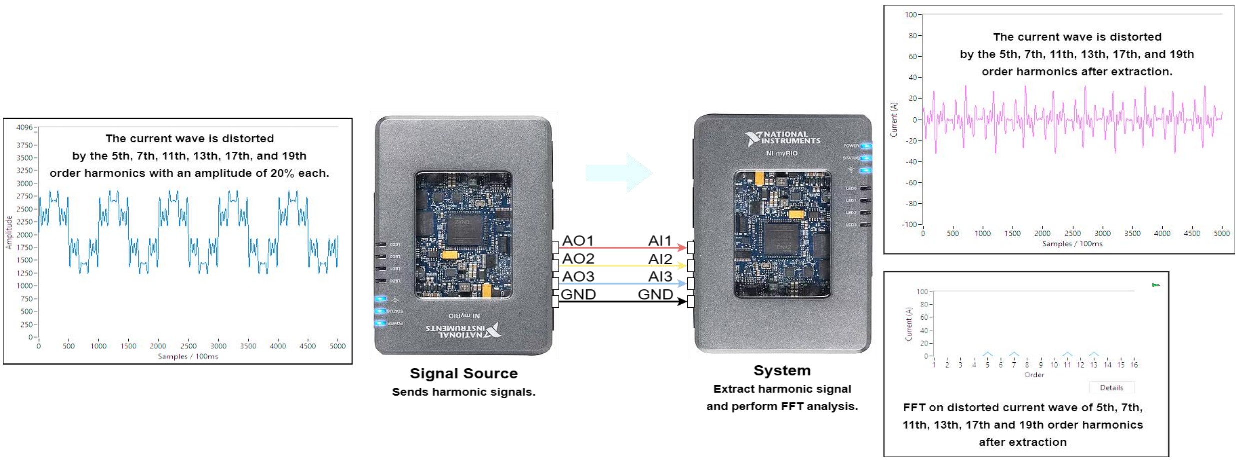


Fig. 8. Extraction of non-triplen order harmonic

Table 3 is the results of harmonic extraction tests on non-multiples of three order odd-order harmonic waves (orders 5, 7, 11, 13, 17 and 19). The test is divided into 10 parts based on the amplitude value of non-multiples of three harmonic orders starting from 10% to 100%. If observed from the amplitude value of the harmonic order after extraction there is a decrease and increase in the amplitude value in several harmonic orders. However, it can be seen from the THD value, the error difference before extraction and after extraction is less than 1%. Meanwhile, the fundamental order amplitude value can be reduced to close to 0. Thus, the SRF-PLL harmonic extraction method can reduce the fundamental order and maintain the harmonic amplitude value, thereby producing a pure harmonic signal wave without fundamental order.

Table 3
System test results for the extracting non-triplen order harmonics

No	Harmonics %	Harmonic signal before extraction (A)							Harmonic signal after extraction (A)							THD (%)		Error (%)
		1st Oder	5th Oder	7th Oder	11th Oder	13th Oder	17th Oder	19th Oder	1st Oder	5th Oder	7th Oder	11th Oder	13th Oder	17th Oder	19th Oder	Before extraction	After extraction	
1	10	10.00	1.00	1.00	1.00	1.00	1.00	1.00	0.03	0.99	0.99	1.02	1.00	0.99	0.99	24.49	24.36	0.54
2	20	10.00	2.00	2.00	2.00	2.00	2.00	2.00	0.05	1.97	1.98	2.01	1.99	1.99	2.00	48.97	48.78	0.39
3	30	10.00	3.00	3.00	3.00	3.00	3.00	3.00	0.07	2.97	2.97	3.01	2.98	3.00	3.00	73.49	73.21	0.37
4	40	10.00	4.00	4.00	4.00	4.00	4.00	4.00	0.09	3.95	3.96	4.01	3.98	4.00	4.00	97.99	97.58	0.42
5	50	10.00	5.00	5.00	5.00	5.00	5.00	5.00	0.10	4,.93	4.95	5.02	4.97	5.00	5.01	122.49	121.97	0.43
6	60	10.00	6.00	6.00	6.00	6.00	6.00	6.00	0.12	5.92	5.93	6.01	5.96	5.99	6.01	146.97	146.26	0.48
7	70	10.00	7.00	7.00	7.00	7.00	7.00	7.00	0.13	6.90	6.92	6.95	7.01	6.99	7.01	171.46	170.62	0.49
8	80	10.00	8.00	8.00	8.00	8.00	8.00	8.00	0.15	7.89	7.91	8.01	7.94	7.99	8.00	195.94	194.95	0.51
9	90	10.00	9.00	9.00	9.00	9.00	9.00	9.00	0.16	8.87	8.90	9.01	8.93	8.99	9.01	220.46	219.31	0.52
10	100	10.00	9.99	9.99	9.98	9.98	9.98	9.99	0.18	9.85	9.87	9.99	9.91	9.96	9.99	244.65	243.25	0.57

3.3.3 Harmonic extractor system validation

Validation of the system extraction results was carried out using Simulink. In the Simulink application, pure harmonic signals without fundamental order can be generated with order configurations 5, 7, 11, 13, 17 and 19 with the same amplitude, then compare the shape with the results of harmonic extraction by the system on harmonic signals with the same harmonic order configuration.

The extraction results show that the extracted harmonic waves in Figure 9 and the pure harmonic waves plotted using Simulink in Figure 10 have identical similarities. Although of course the pure harmonic waves produced by Simulink are ideal because they do not go through an extraction process but are generated directly, while the waves resulting from harmonic extraction by the system as shown in Table 3 have an error in the amplitude of each harmonic order with a value below 5%. The SRF-PLL method used has deficiencies in detecting triplen order harmonics. So, because of the shortcomings of this method the system cannot extract harmonics with a triplen order according to the test results in Table 2.

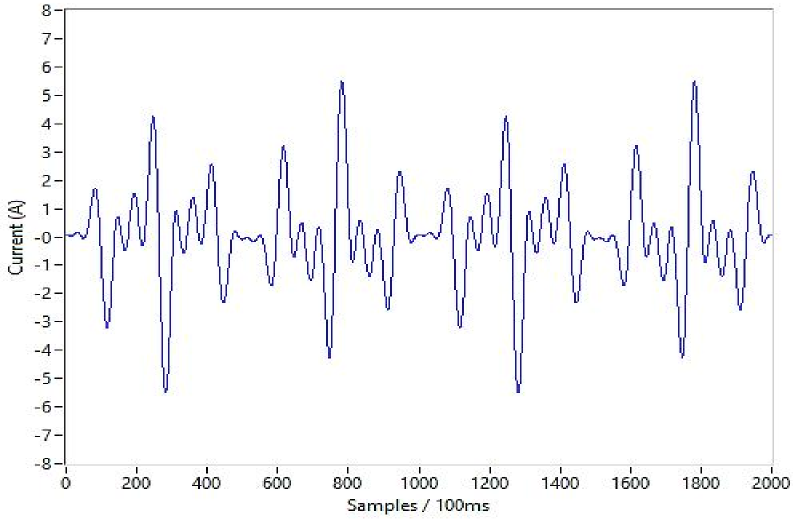


Fig. 9. Extracted of harmonic wave

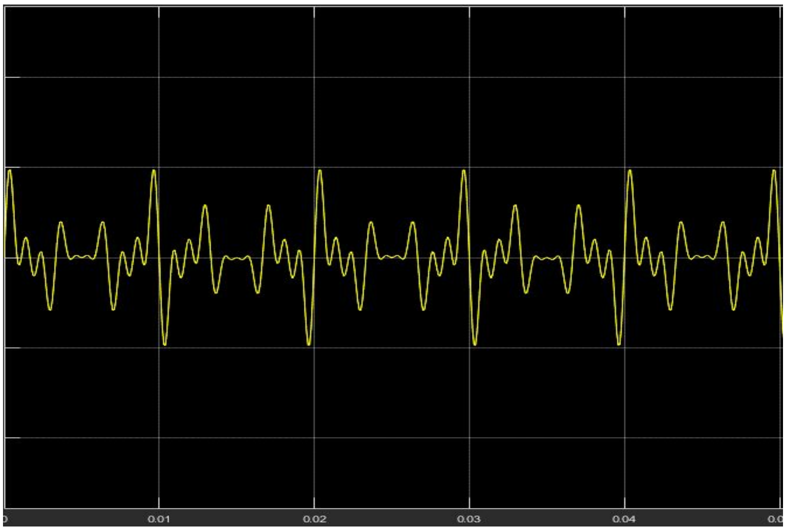


Fig. 10. Pure harmonics wave by Simulink

4. Conclusions

The three-phase harmonic extraction system using NI myRio can extract non-triple order harmonics with an average THD error before and after extraction of 0.47%. Meanwhile, due to the shortcomings of the SRF-PLL method, the three-phase harmonic extraction system cannot extract triplen order harmonics with an average THD error result before and after extraction of 99.93%. In this research, the use of a 5A sensor to read an AC amplitude of 0.5A had a reading error of 0%. Meanwhile, the use of a sensor with a larger maximum reading specification with the same measured AC amplitude of 0.5A increases the reading error. This means that to get an accurate AC amplitude reading, the sensor specifications used are a maximum of 10 times the size of the AC amplitude being measured. However, on the other hand, for the system to read harmonic signals completely, the sensor specifications used are at least 10 times the amplitude of the 50Hz AC fundamental order. Thus, the optimal sensor specification used is 10 times the amplitude of the fundamental order of 50Hz AC. When reading AC signal frequencies, the system can read up to a frequency of 20kHz or order 400.

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