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A novel Ethernet based processing system for remote source harmonic detection

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ABSTRACT

This work is carried out to objectively establish a new method to detect harmonics and measure the total harmonic distortion (THD) in a remote source, such as a high voltage transformer. The proposed approach utilized embedded design techniques to construct an embedded processor system with Ethernet intellectual property core to acquire data from a remote harmonics source. The designed system has several notable merits, namely, it is portable that can be applied in the work field, and it avoids workers from being subject to a hazard high voltage shock as well as its simplicity and high accuracy. The harmonics detection and analysis are achieved by inserting a microcontroller system near the high voltage transformer to acquire the necessary data and transmit it to a remote embedded processor system that is used to detect and analyze the harmonics. The microcontroller and the processor systems are connected by a wide-area network (WAN) through Ethernet and transmission control protocol/internet protocol (TCP/IP) protocols. The processor system is accommodated to perform 128 points fast Fourier transform for harmonics detection. Matlab simulations are used to validate the results. It is found that the results match very accurately the simulation results with an error of less than 0.02%.

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1. INTRODUCTION

Harmonics are a combination of infinite sinusoidal signals that have bad effects on the electrical power systems; therefore the harmonics in any power system should be detected and removed. Electrical power systems usually deal with a high electrical voltage that makes any required harmonics measurements very dangerous for humans. The solution forwarded in this article is based on making use of remote sensing techniques. The most viable remote sensing method to avoid high voltage hazards is Ethernet-based embedded systems along with suitable autotransformers. In contrast to other remote sensing systems the embedded systems have the advantages of simplicity, high accuracy, fast response, and portability. Remote measuring and monitoring systems are usually composed of three parts: data acquisition part that is usually laid near the dangerous unit, far analysis, and monitoring part, and a wireless communication link that can be a local area network (LAN) or wide area network (WAN). Microcontroller systems can be used to act as data acquisition unit, embedded processor systems can be used with analysis units.

The data acquisition techniques are envisaged by Soni and Asati [1]. Among different data acquisition systems, microcontroller-based acquisition schemes are widely used [2]-[4]. An Ethernet based data transfer link using an embedded processor system is designed by Khalil *et al.* [5]. Similarly, Kulkarni *et al.* [6] and

Marosan *et al*. [7] used Ethernet techniques with wireless data transfer link construction. The open-source lightweight IP (lwIP) transmission control protocol/internet protocol (TCP/IP) stack is adapted to be applied with embedded processor systems by [8]-[14] to support the networking capability of the communication link. The algorithms and ideas of constructing embedded processor systems are revealed explicitly in [15]-[18].

The fast Fourier transform (FFT) analysis was applied by Parimala *et al.* [19] for power quality monitoring. It can also be utilized to find electrical grid harmonics as shown by Buzachis *et al.* [20]. In addition to the work of Parimala *et al.* [19] and Buzachis *et al.* [20], Das *et al.* [21] used the algorithm to find calibrated non-contact vibrational harmonics.

Based on the results obtained from the above-mentioned previous works, a viable method for remote measurement is suggested. The idea is based on dividing the system into two parts connected by a LAN, the nearby part consists of a microcontroller system to acquire data from a near high voltage unit (transformer) and transmit it via LAN network to a remote embedded processor system that is programmed to perform FFT technique for analyzing and detecting harmonics of any given signal. The key benefit of the proposed system is that the data acquisition unit is designed to improve the performance speed by adding an Ethernet unit to the designed processor system along with Arduino Mega 2560 microcontroller with its sensors (voltage and current). An open-source TCP/IP networking stack, lightweight intellectual property (LWIP), is used to support the networking capability of the designed system. The work is oriented to measure the power system harmonics and total harmonic distortion (THD). A simple client-server application is used for reducing processing time with the TCP/IP protocol for process-to-process communication. Despite the numerous works carried out on the subject, no previous study has investigated the effect of applying the 128 points FFT analysis. Hence this work used 128 points FFT analysis that gives high performance with small resources for harmonic detection.

The remaining paper is organized as: in section 2, the architecture of the designed system is presented. In section 3, the signal analysis and harmonics detection principles are explained. Results are displayed and discussed in section 4. Finally, the conclusions and recommendations are given in section 5.

2. METHOD

A remote harmonic detection system is designed to be composed of two parts. The first part is the remote source which implies a microcontroller system as a server to acquire signals from a signal source, sample it and transmit it via an Ethernet link to the second part of the designed system. The second part includes an embedded processing system to receive the transmitted signals from the remote source and analyze it to detect harmonics.

2.1. Microprocessor system

Figure 1 shows the block diagram of the designed embedded processor system with Ethernetlite IP core that acts as a media access controller (MAC) operating with interrupt active mode [6]. The designed system uses a processor local bus (PLB) interconnect module that acts as a system bus [22], multi-port memory controller (MPMC) [23] to control a 128 M byte dual data rate memory (DDR-SDRAM) read/ write operations, an interrupt controller (INTC) [15] to deal with the Ethernetlite IP core and timer interrupt signals and timers [17]. The system hardware also includes the necessary peripherals for proper operation.

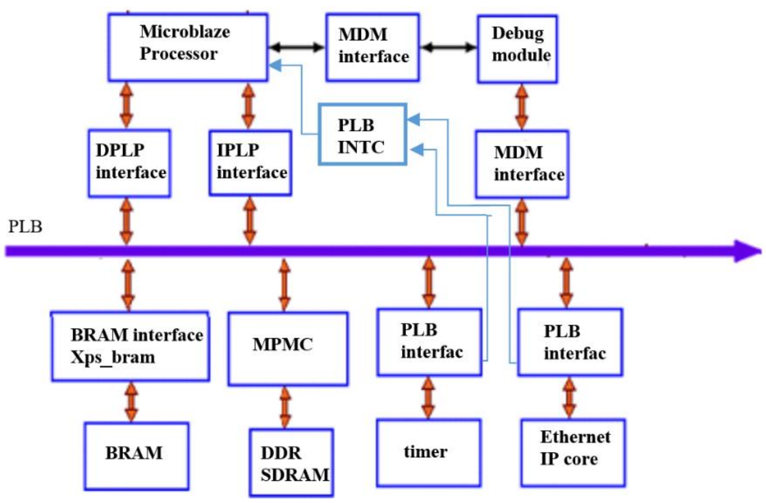


Figure 1. Block diagram of the hardware part of the designed processor system

2.2. Microcontroller system

This work uses the ATmega (8-bit) that is installed in the Arduino Mega 2560 board with the addition of Ethernet Shield 2, the board contains a successive approximation register/analog to digital converter (SAR ADC) (10-bit) with a 10 khz sampling rate [2]-[4], [24]. The Ethernet Shield 2 board is added to the system to provide a wireless data link between the two parts of the network [9], [25]. The microcontroller system used a voltage sensor based on a voltage divider operation instead of the widely used ZMPT101B voltage sensor because the latter yields an inappropriate response for quasi-square voltage as shown in Figure 2 [26]-[28]. The developed voltage sensor shown in Figure 3 is a combination of AC and DC voltage divider to give an analog signal between 0 and 5 V for voltage between -310 and 310.

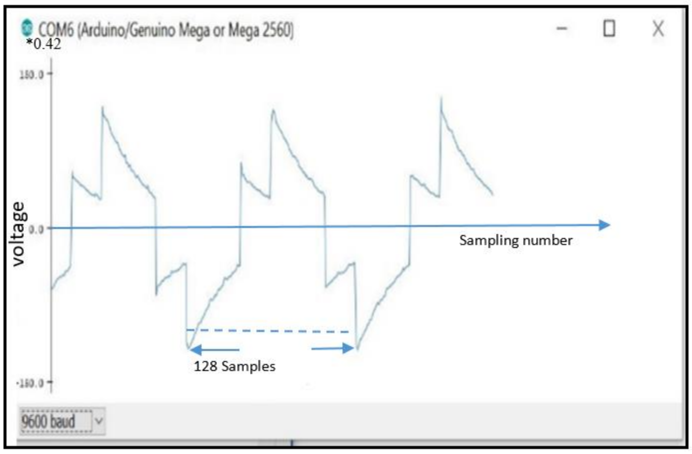


Figure 2. The ZMPT101B voltage result for the quasi-square voltage power signal of the inverter

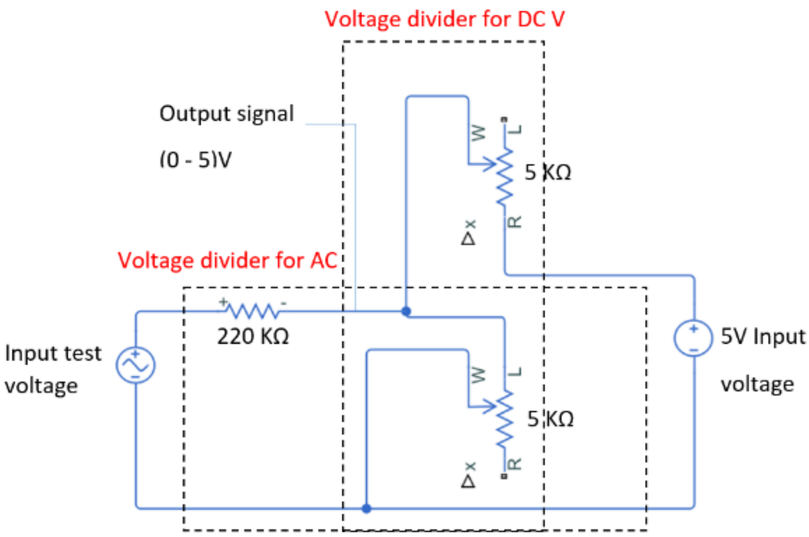


Figure 3. Voltage divider senser

2.3. Data transfer technique

The microprocessor and microcontroller systems use the Ethernet protocol for the WAN network connection under the TCP/IP protocol. On the microcontroller side, the Ethernet library is used to provide TCP/IP protocol [7], while the lightweight intellectual property (lwIP) library is used on the processor side [10]-[14]. The work develops a client-server application for the management and implementation of remote harmonic detection as well as solving different Endean representation problems. The client application is developed in the software development environment of the embedded processor system, and it is depicted in Figure 4 and Figure 5 for receive function and client application respectively. The server application, shown in Figure 6 is developed in the integrated development environment of the microcontroller system.

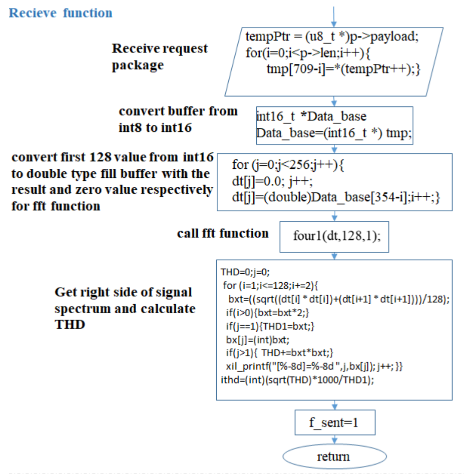


Figure 4. Flow chart of receive function in client application

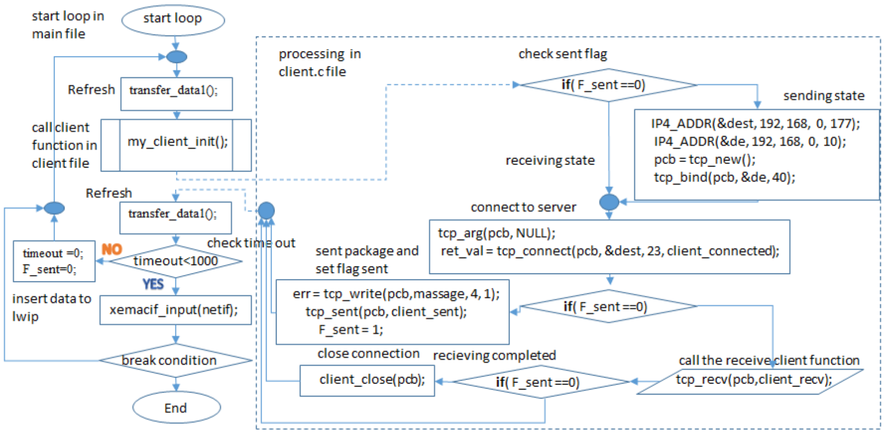


Figure 5. Client application in microprocessor system side

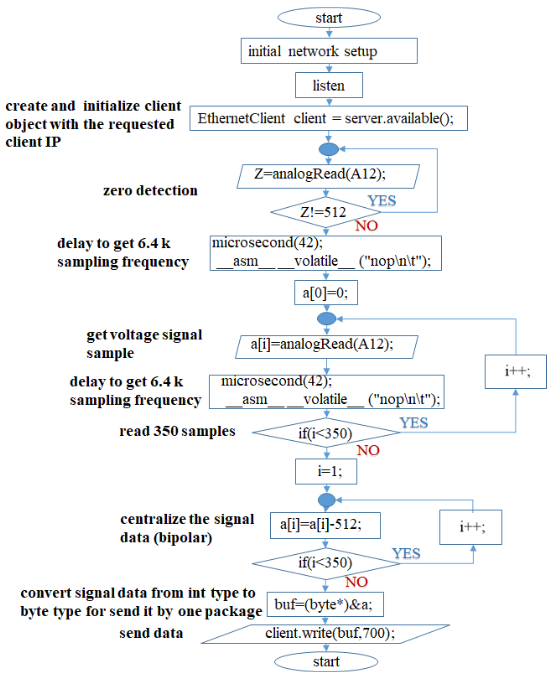


Figure 6. The server application was developed on the microcontroller system side

2.4. Data representation

The Endean representation difference between the microcontroller system and the microblaze processor system is solved by using stack and heap memories [29], [30]. The received data is stored in the heap part of the memory in a stack mode. Heap-stack combination is shown explicitly in Figure 7.

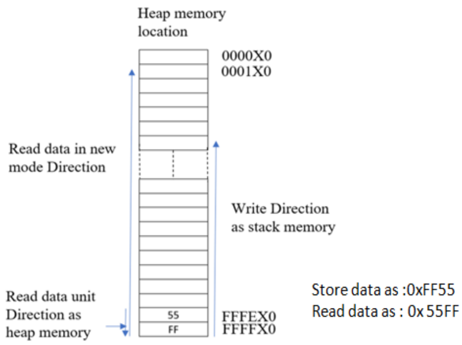


Figure 7. Heap-stack combination

2.5. Signal analysis and harmonic detection

The processor system is programmed to analyze the acquired signal with fast Fourier transform type-128-point FFT to achieve high-quality performance in harmonic detection. Cooley–Tukey algorithm (CT) with a rectangular window is adopted to calculate the FFT [31]-[32]. The Cooley–Tukey algorithm (CT) is a widely used algorithm to perform FFT/IFFT as it reduces the calculation steps of the discrete Fourier transform DFT to a great extent. The algorithm implies a bit reversal with Danielson-Lanczos lemma techniques as shown in Figure 8. The total harmonic distortion (THD) is computed by (1) [33]. Zero detection mode is used during the sampling operation to obtain high accuracy computation [34].

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} \times 100 \tag{1}$$

Where V_1 is the fundamental output voltage, V_n is the output voltage of the n^{th} harmonic.

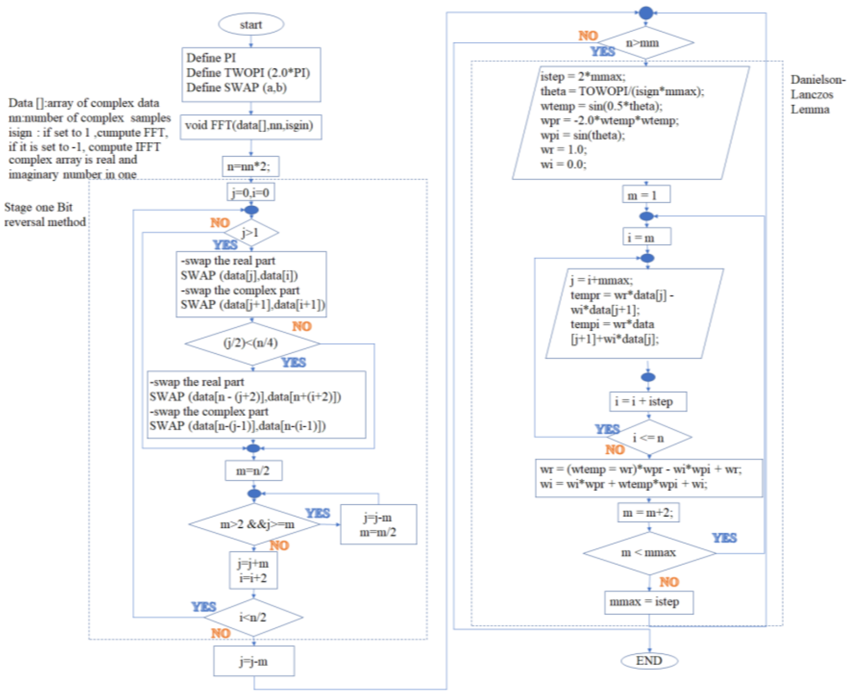
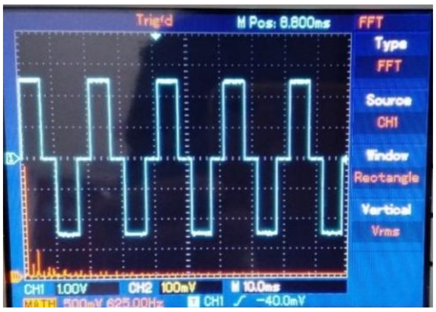


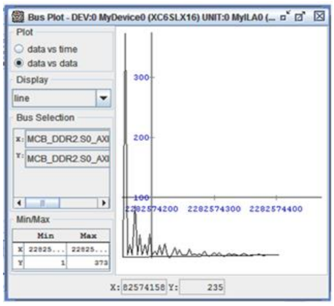
Figure 8. FFT calculation flow chart

3. RESULTS AND DISCUSSION

The designed system performance is tested in two stages. The first stage implies applying a square wave with known harmonics to the inverter circuit, the resultant quasi-square waveform at the inverter output is sampled and transmitted by the remote server microcontroller system to the client embedded processor system to analyze it and calculate harmonics. The obtained results were compared with the results obtained using mat lab analysis. Figure 9(a) displays the output of the inverter circuit with its harmonics shown on the oscilloscope screen while Figure 9(b) shows the harmonics analysis performed by the processor system, and finally, Figure 9(c) and Figure 9(d) show the harmonics analysis and THD calculation results performed by the Matlab respectively. The result of calculating the THD by Matlab is 33.347%, while the result obtained by the designed processor system is 33.3% with an error of less than 1%. The difference between the theoretical and practical values of THD is due to the dead-time, the duration is placed between two transistors in one leg to prevent a short circuit on the dc source.



(a)



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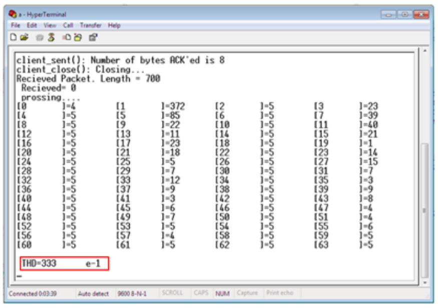
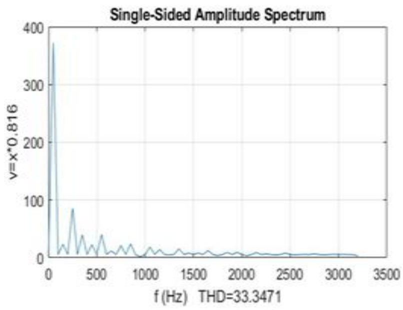


(c)



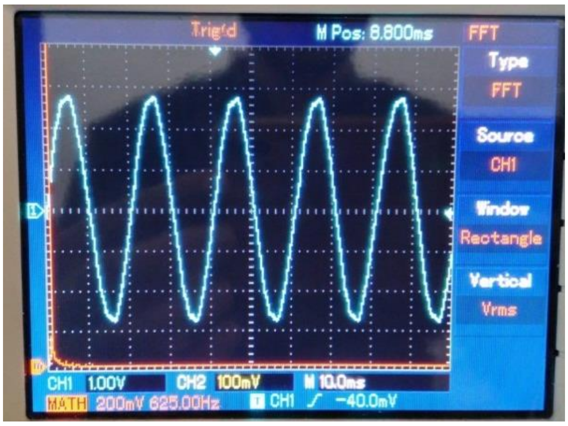
(d)

Figure 9. Inverter voltage and its harmonics analysis of (a) harmonic results obtained from the processor system are shown on the oscilloscope window; (b) harmonic results obtained from the processor system are shown on-chip scope window; (c) harmonic results and THD calculated by the processor system are shown on the HyperTerminal window; and (d) harmonic result and THD obtained from Matlab analysis

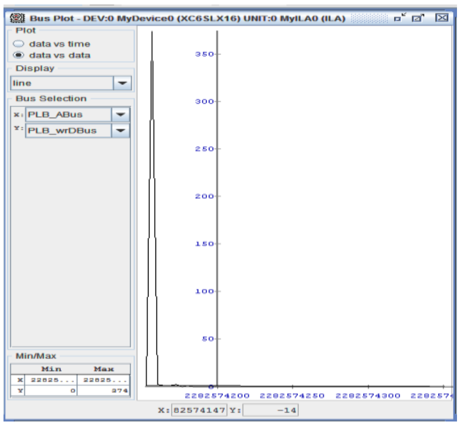
The second stage implies applying a (220 V – 50 Hz) sine wave voltage signal to a remote (220 V – 50 Hz) transformer. The transformer output is shown in Figure 10(a). It is sampled and transmitted by the remote server microcontroller system to the client embedded processor system to analyze it and calculate harmonics. The obtained results were compared with the results obtained using mat lab analysis. Figure 10(b) displays the transformer output waveform with its harmonics shown on the chiposcope screen; it also shows the harmonics analysis performed by the processor system as in Figure 10(c) and finally Figure 10(d) displays the harmonics analysis results performed by the Matlab. The result of calculating the THD by Matlab is 1.9738%, while the result obtained by the designed processor system is 1.8%. The difference between the calculated values of THD is due to both systems running in real-time and the microcontroller updating the reading signal for each request.

Figure 11 shows the laboratory environment of the designed system. Figure 11(a) exhibits the remote part of the designed system acting as a server for both test stages with a microcontroller system. Figure 11(b) shows the client part of the system that includes the designed processor system configured on Spartan 6E field-programmable gate arrays (FPGAs) slice available on SP601 Xilinx board with Ethernet router.

In a practical system, the obtained results translate to a lower hazard as well as highly precise analysis results. The obtained results are expected considering that the designed system is based on embedded design techniques. The results are in agreement with the planned targets.



(a)



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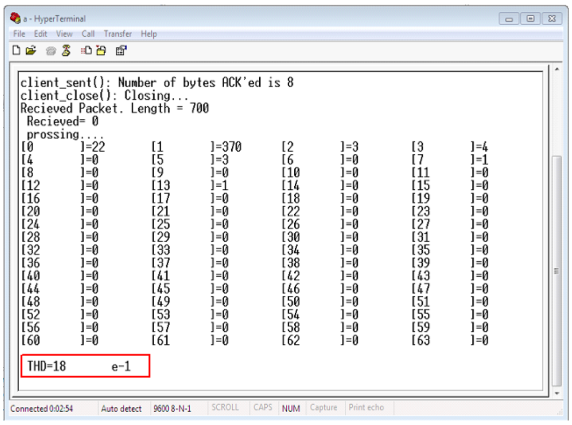

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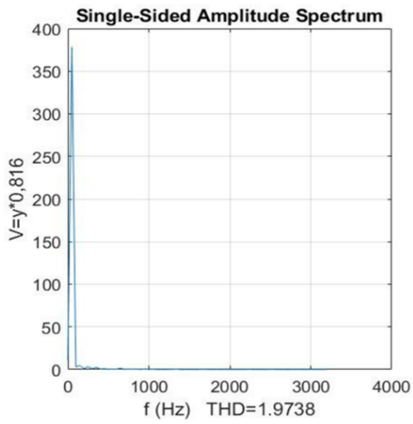
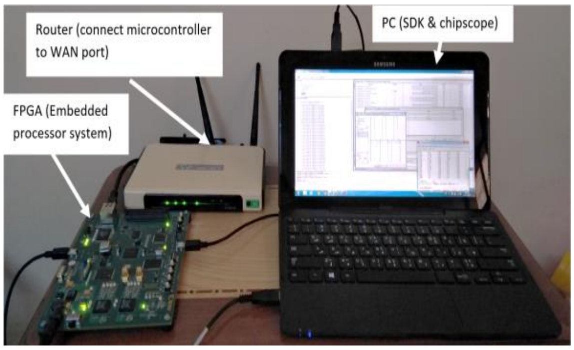


(d)

Figure 10. Practical waveform and its harmonic analysis of (a) the output voltage waveform of a remote transformer with its harmonic; (b) harmonic results were obtained by the processor system on the chip scope window; (c) harmonic results and THD are calculated by the processor system on the HyperTerminal window; and (d) harmonic results and THD were obtained in Matlab

(a)



(b)

Figure 11. Practical environment laboratory of (a) remote part of the designed system acting as a server for both test stages with a microcontroller systemn and (b) analyzer system client at the remote power system server

4. CONCLUSION

The main goal of the current research is to establish a highly precise harmonics detection algorithm that can be applied with high voltage systems to avoid hazardous shock. The algorithm was undertaken to design the system with embedded design techniques to achieve portability and high precise results. A set of digital signals acquired from audio or power sensors by a remote microcontroller media are transmitted to the designed embedded processor system configured on FPGA through a WAN network using an Ethernet core. The received signals are processed by the processor system to detect their harmonics using FFT analysis. The system was validated by two remote signals. The first signal comes from a remote dc to ac converter with well-known THD (31%), its practical measurements showed a small difference with the converter THD (practical THD = 33.3%). The result difference is caused by the dead-time operation in the inverter. The second signal comes from the remote transformer, the practical detection and measurements of transformer output voltage THD indicate the high efficiency and accuracy of the designed system and evaluate how effective are the used algorithms. In summary, the current research reveals that the developed algorithm can be conveniently and safely used with high voltage systems with high precision results.

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