DESIGN AND DEVELOPMENT OF A SIMPLE POWER QUALITY MONITOR FOR LOW VOLTAGE DISTRIBUTION SYSTEM

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ABSTRACT

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Power Quality (PQ) is an important issue in the operation of distribution systems. The power delivered to the consumers should be as clean as possible. Quality of power is defined in various standards or regulations such as The Electrical Distribution System Supply Reliability and Quality of Electricity Regulation in Turkey. To comply with these regulations the quality of the electrical power should be monitored and controlled at the consumer side which is at the end of the distribution system. This is achieved by designing and implementing a stand-alone and real-time Power Quality Monitoring device dedicated to the distribution system within the scope of this thesis. The PQ monitoring device, which is named Mini-PQ, processes the power signals in accordance with the international standard IEC 61000-4-30 and sends the data to a PQ monitoring center by using Power Line Communication (PLC). PLC use the existing power lines thus eliminating the need to the existing or a new local area network. Both hardware and software running on the Mini-PQ have been developed in this thesis work. In addition, a graphical user interface (GUI) software is developed to be used in the PQ monitoring center. Performance verification of the designed PQ monitor with field measurements are carried out and the associated results are also presented in the thesis.

Keywords: Power Quality, Power Quality Monitoring, Power Line Communication, Mini-PQ, Signal Processing on Power Quality

ÖZ

DÜŞÜK GERİLİM DAĞITIM SİSTEMLERİNDE BASİT GÜÇ KALİTE MONİTÖRÜ TASARIM VE GELİŞTİRİLMESİ

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Güç Kalitesi, dağıtım sistemlerinin işletiminde önemli bir konudur. Tüketiciye iletilen güç olabildiğince temiz olmalıdır. Gücün kalitesi, Türkiye'de Elektrik Piyasası Dağıtım Sisteminde Elektrik Enerjisinin Tedarik Sürekliliği, Ticari ve Teknik Kalitesi Yönetmeliği gibi çeşitli yönetmelik ve standartlarda tanımlanmaktadır. Güç kalitesi konusundaki standart ve yönetmeliklere uymak için elektrik gücünün kalitesi dağıtım sisteminin son noktası olan tüketici noktasında izlenip kontrol edilebilmelidir. Bu gereksinim, bu tez kapsamında tek başına çalışabilen, gerçek zamanlı, elektrik dağıtım sistemlerine özel tasarlanmış Güç Kalite izleme sistemi tasarımı ve uygulanmasıyla karşılanmıştır. Mini-PQ adıyla tasarlanan cihaz, uluslararası standart olan IEC 61000-4-30'de belirtilen gereksinimleri karşılayacak şekilde, güç sinyallerini işlemekte ve elde ettiği verileri güç kalitesi merkezine güç hattı haberleşme metoduyla göndermektedir. Güç hattı haberleşme metodu var olan güç hatlarını kullanmakta, böylelikle var olan veya yeni yerel ağ kurulumu ihtiyacını ortadan kaldırmaktadır. Sistemin donanım ve üzerinde yüklü yazılımının tasarımı bu tez kapsamında geliştirilmiştir. Bunlara ek olarak, güç kalitesi merkezinde çalıştırılmak üzere bir kullanıcı arayüz programı da geliştirilmiştir. Tasarlanan güç kalitesi monitörünün arazi ölçümleriyle birlikte performans doğrulaması bu çalışmada yapılmış ve elde edilen sonuçlar tezde sunulmuştur.

Anahtar Kelimeler: Güç Kalitesi, Güç Kalitesi İzleme, Güç Kalitesi İzleme Sistemi,
Güç Kalitesi Monitörü, Mini-PQ, Güç Kalitesinde Sinyal İşleme

To my family,
to loving memory of my mother

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LIST OF ABBREVIATIONS

PQ	Power Quality
DSP	Digital Signal Processor
ADSL	Asymmetric Digital Subscriber Line
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
PLC	Power Line Communication
PC	Personal Computer
SQL	Structured Query Language
PCI	Peripheral Component Interconnect
DAQ	Data Acquisition
I/O	Input and Output
GPS	Global Positioning System
DVD	Digital Versatile Disc
IEC	The International Electrotechnical Commission
RMS	Root Mean Square
AC	Alternating Current
DC	Direct Current
CENELEC	European Committee for Electrotechnical Standardization
IEEE	Institute of Electrical and Electronics Engineers
EMC	Electromagnetic Compatibility
FIR	Finite Impulse Response
FFT	Fast Fourier Transform
DFT	Discrete Fourier Transform
PCB	Printed Circuit Board
EVB	Evaluation Board
EVM	Evaluation Module
UART	Universal Asynchronous Receiver/Transmitter
SPI	Serial Peripheral Interface

CHAPTER 1

INTRODUCTION AND MOTIVATION

Electrical power is extremely important raw material that should be available in terms of quality. It is used almost every field in human life, besides in all commercial activities. Essential missions of the organizations which generate, transmit and distribute electrical energy are to provide uninterrupted, cheap and high quality service to the consumers. If a power problem causes a failure or mis-operation in the electrical or electronic equipment, that causes an economical and environmental loss. To detect the problems in the power line and determine solutions to these problems it is necessary to use power quality (PQ) monitor devices in the supply and demand sides. As technology improves PQ becomes very important since new and different electrical and electronics devices are available in the market. Figure 1.1 gives the number of papers in the INSPEC (The Institution of Engineering and Technology) database [4], which use the term "power quality" in the abstract, the list, or the title of keywords. This figure gives an perception to the increasing importance of the PQ monitoring and controlling in the last decades [4]. These new devices are more sensitive to power quality than older ones. In order to improve electric power quality and energy efficiency, the sources and reasons power quality problem must be known by both supply and demand sides. The major objective of PQ monitor system is to analyze the mass of power quality data collected by various monitor sites [15]. Power quality is a big issue not only in the electrical grid but also in vehicles such as ships[16].

Monitoring and controlling the quality of the electrical power at the consumer side, which is at the end of the distribution system, comprise the main reason of this study. The aim of this thesis is to design and implement simple power quality monitoring

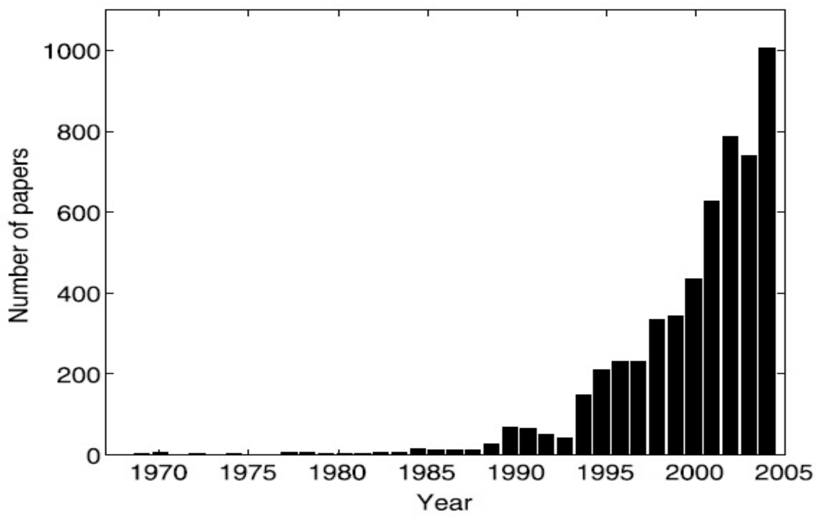


Figure 1.1: Use of term power quality [4]

system for low voltage distribution system level that communicate with a PQ center via a proper communication medium which already exists such as power line communication (PLC).

The design of monitoring system will be implemented with minimum costs and flexible design specifications. The system will be able to analyze the power quality of the connected electrical grid in real time. The existing power quality monitor systems are designed to be able to measure the quality at the transmission systems, therefore they are complex, expensive and big devices [17, 16]. The systems which monitor PQ at the customer level, store the results on-board or send the results via Ethernet, GPRS (General Packet Radio Service) etc., which requires human effort to collect and assess the data afterwards. Moreover, sending data on Ethernet requires building a network. In terms of hardware, the monitoring devices are based on PC (Personal Computer) or DSP (Digital Signal Processor) including high-level commercial software platforms such as MATLAB, Lab-VIEW, C++. These devices only collect raw data from waveforms and process the data by using software platforms. Using these devices at the customer level may cause difficulties in terms of design, price and flexibility. Main motivation of designing such complex, high level monitoring systems is to detect all possible power quality parameters defined by the standards [5] in the transmission system. On the other hand, at the customer level, there is no need to detect all PQ parameters. Because, at this level, more simple events occur and this makes the monitor devices more simple than their counterparts in the transmission system level. So, a monitoring device in the distribution system level requires less computations since all the requirements of IEC-61000-4-30 [5] do not need to be met.

The device in the scope of this thesis, uses power line as the communication environment and hence there is no need to build a new network for communication. Devices in the market use GSM (Global System for Mobile Communications), Ethernet, serial communication or parallel communication for communicating with the power quality centers [15, 17, 18, 19].

There are several PQ monitoring techniques in the field of the power quality measurement. Using data acquisition (DAQ) cards and PCs is one of the most popular method in the field. On the other hand, using DSP technology is another popular methodology [20, 21, 18, 22]. For example, power quality monitoring system in [22] is based on Lab-VIEW, which uses the commercial software platform. Hardware of this system includes two computers, two cases, one modulation card and one DAQ card, which are all commercial. The use of Lab-VIEW requires a PC, which makes the system expensive and inflexible. This system also uses Lab-SQL (Structured Query Language) to generate old data and generate reports for certain periods of time.

Yet another PQ monitoring method is based on DSP and PCI (Peripheral Component Interconnect) technique [23]. This system combines the capabilities of DSPs and resources of the computer together. In this system PCI bus is adopted to PC and DSP to communicate each other and meet the needs of data communication. PLX, TI (Texas Instruments) and Lab-VIEW products are used in this method. Data are processed in the DAQ card and all results are sent to PC via the PC bus which is used as communication medium. An upper computer initializes the DSP by using the PCI bus. Without the PCI bus DSP cannot be initialized, so use of a PC is compulsory here. The upper computer reads the pre-processed data through the PCI bridge. Driver in the upper PC controls all sub-units such as DSP and PCI. By setting up PCI bus, DSP is initialized. Lab-VIEW software is set up on the upper PC and this software processes all the pre-processed data on the PC. DSP only processes the analog signals and sends them to the PC. By using database technology processed data are compared with the standards. Comparison and decision are not made on the DSP, these are achieved on the PC. This monitoring system needs a PC nearby the DSP, and it also uses a commercial software Lab-View that runs on the PC. In addition, using PCI bus and PC reduce the mobility of the device, which also increases the complexity of the system. Every single system needs one PC, one PCI bridge in this method.

Another architecture is based on DSP interfaced to a host computer [24]. Although an embedded system architecture appears in this system, all system level requirements are implemented on a PC which is the host computer. While real time tasks are implemented on the DSP chip system user interface, system level requirements such as Interrupt Subroutine are implemented on the host computer. An environment is necessary on the host computer to process some tasks. That means, embedded system cannot work without a PC and for all user-interfaces the device needs a PC alone. Communication between the PC and DSP is made through a parallel interface.

A DSP-based PQ monitoring device is proposed in [25]. This type of device detects and classifies disturbances in real-time. To measure and monitor power quality, device uses an application program in (DSP Starter Kit) DSK using a software platform. There is no record or storage in DSP and the main function of DSP is data processing. A host PC is used to control and obtain output from DSP. The host PC works here as the controller. Similar to mentioned above devices, this device also cannot work without a PC. There is no communication platform, and JTAG (Joint Test Action Group) emulator is used to send the results to the PC.

A monitor based in a PC is proposed in [17]. This monitor consists of voltage and current sensors, signal conditioning board, DAQ card and one PC. All data are processed and stored in the PC. This system uses Lab-VIEW as software development platform. User interface is commercial software by National Instruments, Lab-VIEW.

A system for detecting only disturbances is proposed in [26]. It uses stand-alone DSP that can work by itself. It consists of a multiple sensor boxes, DAQ card and a PC. Communication is implemented via USB between DAQ and PC. Data are recorded on the PC. Therefore it is not suitable to set up it to consumer level.

A nationwide monitoring system for PQ with monitoring devices, installed at the electricity transmission network, and the interface between the transmission and the distribution networks are presented in [27]. The system has been developed through the National Power Quality Project of Turkey. In this proposed system, all monitoring devices, which are installed in the transmission system, both collect and compute real-time PQ parameters in addition to measuring active power, reactive power and power factor [19]. The devices also detect PQ events and faults, and collect raw data of line voltages and currents. The devices use fiber optic cable, ADSL (Asymmetric Digital Subscriber Line) or GPRS network to send the data. The hardware of the device is composed of a mini-ITX motherboard, a DAQ unit, analog signal conditioning unit, digital I/O (Input and Output) functionality circuits, GPS (Global Positioning System)-based synchronization circuitry, various power supplies and human-machine interface circuitry. Despite compactness, robustness and flexibility of the environment, this device is far too equipped and expensive to be installed into a distribution system.

A mobile PQ monitoring device is developed in [28]. In terms of hardware, the device consists of one DAQ Card 6036E, one card for sample and hold purposes, three current probes, three voltage dividers, a laptop computer, an uninterrupted power supply, and an isolation transformer. NT Lab-VIEW is employed as software development platform. The device can perform online data processing, raw data collection and storage and software reporting. The data can be stored in DVDs (Digital Versatile Disc) or data cartridges, but the device has no capability to send the collected data.

Various commercial devices also exist in the market for monitoring PQ in the distribution system level. Fluke 435 is one of them [29]. It requires a memory card to store the PQ data, however, it is not designed to send the data online for signal processing, which requires human effort afterwards. Similar to this device, another commercial device is proposed by Hioki 3196 [30]. It is another device which is able to send the PQ data immediately on Ethernet, however it is extremely expensive to be used in large numbers in the distribution system level.

The outstanding features of the designed and implemented device in the scope of this study are:

1-) Analysis of the simple PQ events and faults;

2-) Power interruption interval and duration detection;

3-) Low power consumption;

4-) Inexpensive unit cost suitable for using in the distribution system level;

5-) Usage of power line as the communication medium;

6-) Centralized control in the distribution system.

This thesis consists of design and implementation of a Power Quality Monitoring device, hardware and software design, and also setting up of the power line communication.

The outline of this thesis can be summarized as follows:

- Chapter 2: This chapter starts with the explanation of the power quality parameters, which are stated in the Standard IEC 61000-4-30 [5]. System block diagram and connections are given in this chapter. Specifications of the designed and implemented system are explained.

- Chapter 3: After designing the processing requirements according to the standard IEC 61000-4-30, the architecture of the algorithms are explained in detail. Simulation results of the algorithm are given in this chapter.

- Chapter 4: Hardware and PLC design of the device are given in this chapter. Architecture of the designed hardware including the DSP and communication medium are discussed.

- Chapter 5: Detailed explanation of the design and implementation of the DSP software and computer interface program are given.

- Chapter 6: System verification in the laboratory environment and later field measurements are provided. Outputs of the designed device are presented for verification.

- Chapter 7: The conclusion of the study with suggestions for the future work are given.

CHAPTER 2

GENERAL SYSTEM DESIGN

The International Electrotechnical Commission (IEC) defines the power quality (PQ) term in IEC 61000-4-30 [158, page 15], as: "Characteristics of the electricity at a given point on an electrical system, evaluated against a set of reference technical parameters." In general, it is a fact that customers always demand information about the quality of the service and the product. It is not different in energy market; customers would like to know everything about the power quality. If something goes wrong with the supply, they want to know what caused this fault and who is responsible. When this power quality problem causes a damage in an electronic equipment, financial responsibility becomes more and more important. In the Netherlands, after a damage in an electronic device, a court stated that the operator of the grid has to prove whether the quality of the power and power parameters were within the limits when the damage occurred [31]. Since there was no evidence, that meant the operator could not prove that quality of the supply was in the range of the normal limits, therefore half of the loss was paid by the operator. Hence, it is always necessary to obtain and collect information about the quality of the power in the network at all levels; generation, transmission and distribution. Considering the power system in the Figure 2.1 there are many customers in the grid at the distribution level. The number of nodes is too high to be compared with those of the generation and transmission levels. Clearly, the power monitoring device in this level should be simple and as cheap as possible. As also mentioned before, a monitoring device in the distribution level requires less computations since all the requirements of IEC-61000-4-30 [5] does not have to be met. So it is possible to sacrifice evaluation of some parameters to make the device simple and cheaper.

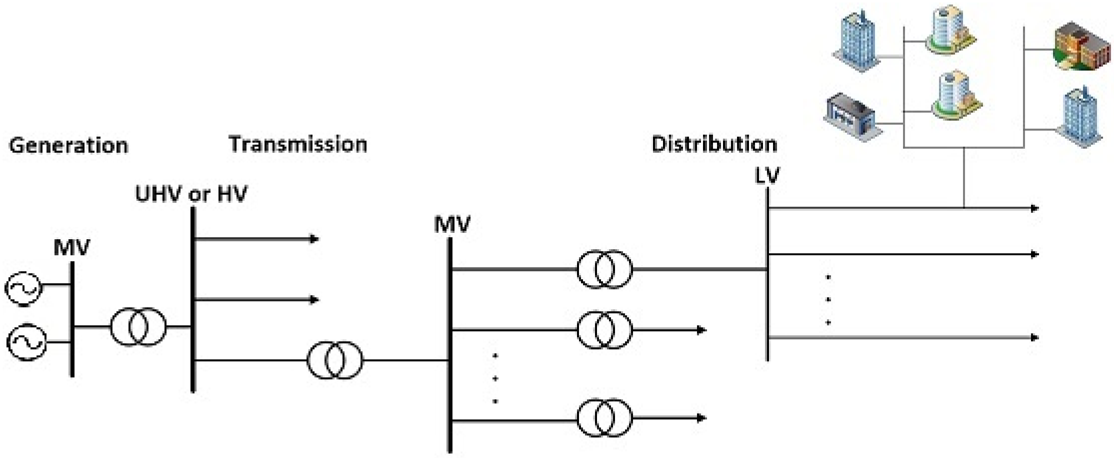


Figure 2.1: Electrical Grid

In this study, main motivation was basically to design and to implement a simple, compact, cheap and flexible power quality monitoring device for low voltage distribution system, which communicates with a Power Quality Center via Power Line Communication. In this case, the power quality center is a device, which had been already designed and implemented by TÜBİTAK UZAY and named PQ++ [32] . All processed PQ parameter logs are sent to this device by using power line as the communication medium, which makes the system cheaper and compact, in terms of network components.

The measurement process is defined in international standard documents such as IEC 61000-4-30 [5] (IEC 61000-4-30: Testing and measurement techniques - Power quality measurements methods. (2008).:IEC, Geneva, Switzerland.) and IEEE 1159-2009 (IEEE Recommended Practice for Monitoring Electric Power Quality). The standard document explains working requirements of PQ instruments in detail. Part 4 of IEC 61000 defines the methods for measurement and interpretation of results for PQ parameters in 50/60 Hz a.c. power supply systems.

The objective of PQ monitoring can be defined as follows [33]:

- The diagnosis of incompatibilities of the power system with the load,
- The evaluation of the electric environment at a part of the system in order to refine modeling techniques or to develop a power quality baseline,
- The prediction of future performance of load equipment or power quality miti-

gating devices.

Electrical power quality may be described by a set of parameters as:

- Continuity of the service,
- Power frequency,
- Voltage magnitude,
- Flicker,
- Supply voltage dips and swells,
- Voltage interruptions,
- Transient voltages,
- Supply voltage unbalance,
- Voltage harmonics.

The designed monitoring device, which we call Mini-PQ, in this thesis obtains continuity of service, voltage and current magnitude, power frequency, voltage dips, swells and interruptions, current harmonics from the above list. In addition, power consumption (active, reactive and apparent power) in the load are also computed.

2.1 Power Quality Parameters Obtained by Mini-PQ

In this section, basic power quality parameters and measurement methods used in this thesis will be described in detail. Definition and theoretical calculations of power frequency, magnitude of the supply voltage, magnitude of the current, supply voltage dips and swells, voltage interruption etc. will be explained. Other parameters in the above list are not crucial for the distribution system levels, therefore Mini-PQ is not designed to obtain them.

2.1.1 Power Frequency

The frequency of the system is a measure of the speed with which the electrical machines rotate [4]. If a system is synchronously interconnected, all machines rotate at the same speed. However, we know there are always small speed differences among the machines in an interconnected system. The system frequency is defined as the weighted average of the frequencies of the machines. Voltage frequency is the repetition rate of the waveform of the voltage at a specific location. Therefore, system frequency and voltage frequency are very close to each other and it is possible to assume that voltage frequency is the same as the system frequency.

Variations in the frequency changes depending on the load character and the response of the generator control systems to the change in the loads. In a transmission system, a measured frequency variation during a large disturbance is shown in the Figure 2.2. Changes in the frequency may cause faults in the grid. Therefore, variations in the frequency is limited to a range by national and international standards such as EN50160 [1]. According to the standard [5], the frequency reading shall be obtained maximally every 10 seconds [5]. Measurement method of frequency in IEC 61000-4-30 is defined as the ratio of the number of integral cycles during the measurement interval, divided by the cumulative duration of the integer cycles. The measurement uncertainty is recommended as has a maximum value ±50 mHz over the measuring ranges 42.5Hz - 57.5Hz. If the measurement involves three-phase channel, it is necessary to designate a reference channel and measure frequency in this channel.

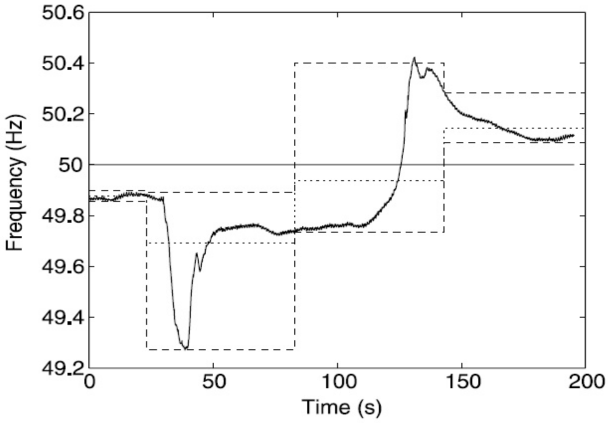


Figure 2.2: Measured Frequency Variation [4]

2.1.2 Magnitude of The Supply Voltage

The RMS (Root Mean Square) value of an AC (Alternating Current) sinusoidal voltage waveform is considered as voltage magnitude. The voltage waveform is:

$$u(t) = \sqrt{2}u \cos 2\pi f t \tag{2.1}$$

where

f : Voltage frequency,
u : RMS voltage.

Change of u in Equation 2.1 causes voltage variations. RMS reduction in the AC voltage defined as a voltage dip, whereas RMS increase in AC voltage is a voltage swell. In an electrical grid, at the transmission system level, to guarantee the system security, voltage RMS control is an important issue. Whereas at the distribution system levels, this is an issue about power quality. Variations in voltage magnitude can effect the performance of electrical-electronic end-user equipment. Therefore, variations in the voltage RMS is limited to a range by international standards. According to the IEC 61000-4-30 the measurement shall be the RMS value of the voltage magnitude over a 10-cycle time interval for 50 Hz power systems. In case of power frequency oscillations, a possible method is using frequency value obtained in compliance with the standard to obtain exact 10-cycle analysis windows. The measurement uncertainty shall not exceed 0.5 % of Udin (value obtained from the declared supply voltage by a transducer ratio), over the range of 20 - 120 % of Udin.

2.1.3 Active, Reactive and Apparent Power

In an AC circuit, voltage and current have sinusoidal waveforms, naturally. So, the amplitude of the voltage and current change over time in an AC circuit, hereby, power is a quantity that will come in different attributes. An electronic circuit have three main components: resistor, capacitor and inductor. Each of these circuit components has different characteristics and effects on a circuit. While a resistor causes no shift between voltage and current, a capacitor and an inductor cause 90 degrees phase shift between voltage and current. Resulting power of a purely resistive load is known as true power, measured in Watts. Another type of power is defined as reactive power, which is the resultant power of an inductive or capacitive load and measured in VA reactive (VAr). In a capacitive load, the voltage lags the current waveform by 90 degrees and this will produce negative reactive power. In an inductive load, positive reactive power is produced because the voltage leads the current waveform by 90 degree. This negative and positive power occurs because inductors consume reactive power, capacitors generate reactive power. Any AC system have a composition of true and reactive power, whose angle varies between voltage and current as shown in the Figure 2.3. The combination of active and reactive power is known as apparent power, measured in volt amps (VA).

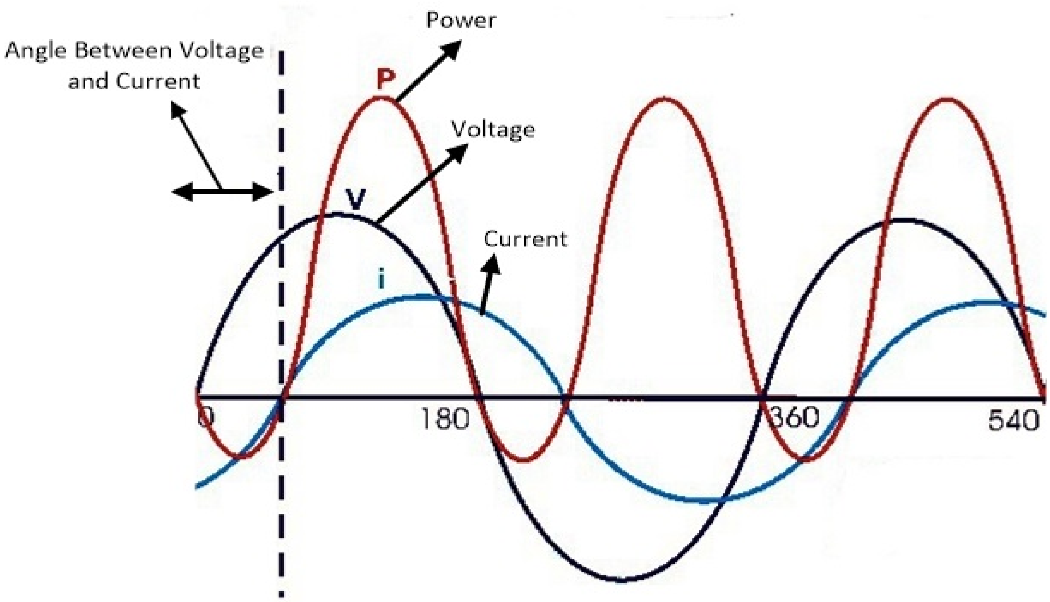


Figure 2.3: Active and Reactive Power

The formulas for the active, reactive and apparent power are defined as:

$$P = VI\cos\theta \tag{2.2}$$

$$Q = VI\sin\theta \tag{2.3}$$

$$S = VI \tag{2.4}$$

where

P : Active power,

Q : Reactive power,

S : Apparent power,

V : RMS value of the line to neutral voltage,

I : RMS value of the line current,

θ : Angle between voltage and current waveforms.

These power quantities are trigonometrically related to each other. This relation is shown in the Figure 2.4. The relation is formulized as:

$$ReactivePower = \sqrt{(ApparentPower^2) - (RealPower^2)} \tag{2.5}$$

$$RealPower = \sqrt{(ApparentPower^2) - (ReactivePower^2)} \tag{2.6}$$

$$ApparentPower = \sqrt{(RealPower^2) + (ReactivePower^2)} \tag{2.7}$$

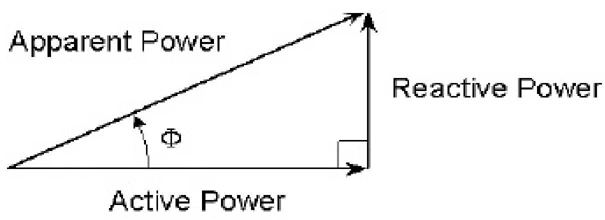


Figure 2.4: Power Triangle

Although the above power parameters are not included in PQ parameters in the IEC 61000-4-30 standard, they are computed in the Mini-PQ. Because in the distribution system level, especially reactive power is a very important issue.

2.1.4 Supply Voltage Dips and Swells

A short-duration reduction of the RMS voltage is defined as voltage dip. During the event, the RMS voltage may be any value that is between zero and nominal voltage values. Reduction in the RMS value causing short-duration increases in the magnitude of the load current. Generally, a PQ monitoring device is triggered for a voltage-dip logging, when the actual RMS voltage is below its 90 % of its nominal RMS values. The residual voltage is the lowest input RMS value measured on any channel during the dip. Voltage dip is stated for poly phase systems in IEC 61000-4-30 as:

"a voltage dip begins when the RMS input voltage of the channels are below the dip threshold and ends when the URMS (value of the RMS voltage measured over one cycle) voltage on all the channels are equal to or above the voltage dip threshold plus the hysteresis voltage." Hysteresis is difference in magnitude between the start and end thresholds. The duration of a voltage dip is the time difference between the start time and the end time of the voltage dip.

A short-duration increase in the RMS voltage is defined as voltage swell. The voltage swell threshold is a percentage of the line RMS voltage. Voltage swell is stated in IEC 61000-4-30 as :"a voltage swell begins when the input supply voltage of the channels are above the swell threshold and ends when the URMS voltage on all measured channels are equal to or below the swell threshold minus the hysteresis voltage." The start time of a swell shall be time stamped with the time of the end of the input supply of the channel that initiated the event and the end time of the swell shall be time stamped with the time of the end of the input supply voltage that ended the event, as defined by the threshold minus the hysteresis.

Voltage dip and swell are shown in Figure 2.5 and Figure 2.6 [34].

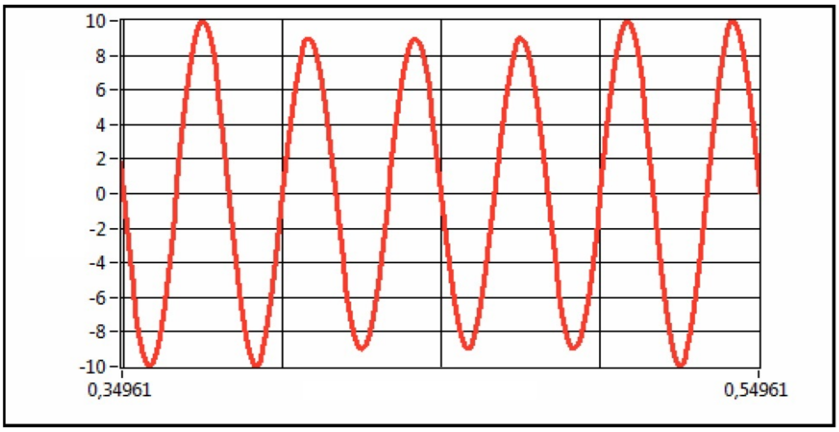


Figure 2.5: A Voltage Dip

2.1.5 Voltage Interruption

In general, PQ monitors compare the measured supply voltage magnitude with a pre-defined threshold level. When the measured supply voltage pass this threshold for longer than a certain time, the monitor detects a voltage interruption. The monitor

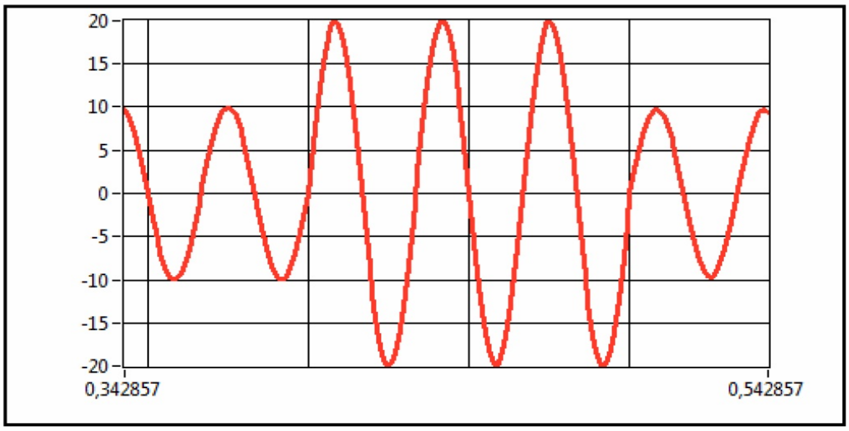


Figure 2.6: A Voltage Swelll

continues to record the time duration until the supply voltage magnitude rises above the threshold. The time interval between the beginning and end of the event is logged as voltage interruption duration.

2.1.6 Current Harmonics

Harmonics refers to the amount of distortion to the sine wave. In a distribution system, harmonics are any non-linear current or voltage. A typical distorted waveform is shown in Figure 2.7. Harmonics is generally referred to as electrical noise. At customer level, harmonics can be caused by several sources, such as fluorescent light ballasts, speed control devices, halogen lights, electric arc furnaces, battery chargers, AC to DC (Direct Current) rectifiers and power supplies which are used in most of the electronic devices. When any electrical device draws unbalanced current from the supply, that causes a vibration harmonic, the current is not drawn as a smooth sine wave. Resonance, exist at integer multiples of the main frequency. These integer multiples of the main frequency define harmonic order of magnitude.

In the electrical distribution system, odd number of harmonics (3^{rd}, 5^{th}, 7^{th}, etc.) have the greatest importance. Because, the sinusoidal wave distortion is symmetrical below and above the average center line of the waveform. Even number of harmonics are usually given less importance (2^{nd}, 4^{th}, 6^{th}, etc.) because of their equal swinging in both the positive and negative directions.

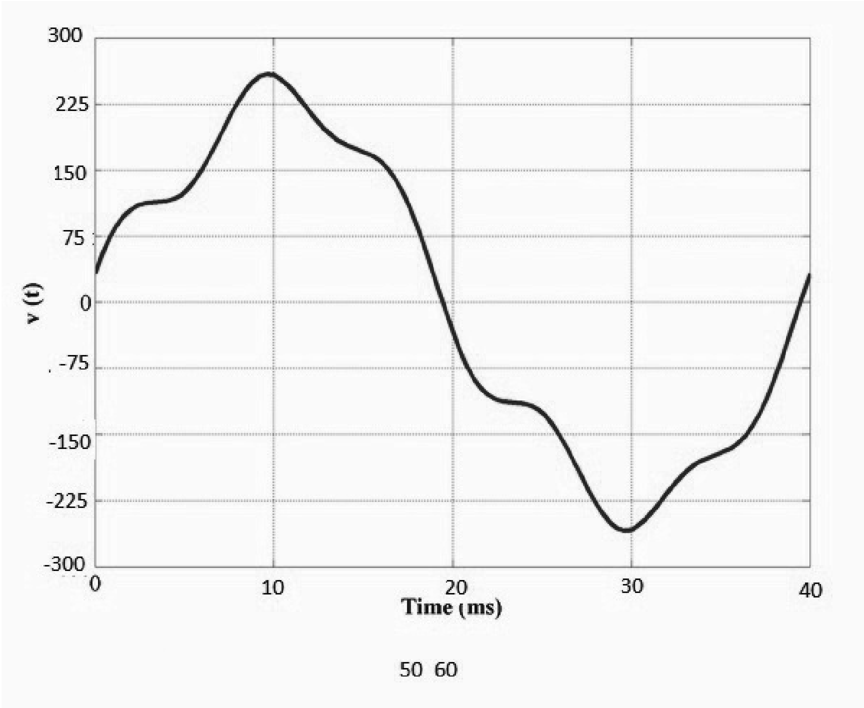


Figure 2.7: A Typical Distorted Waveform

Harmonic current distortion is only a power quality issue if it affects sensitive equipment. Some effects of harmonic currents are in the distribution system level are:

- Additional heating in transformer,
- Increase in power loss,
- Noise in communication and telephone lines,
- Overloaded capacitors.

2.2 Power Quality Standards

Measurement techniques and limits of the power quality parameters described above are standardized according to the national and international standards.

A norm called EN 50160 [1] is created by the CENELEC (European Committee for Electrotechnical Standardization) in Europe. The norm designates in the point of delivery to the customer (PCC - Point of Common Coupling), the power quality parameters of a distribution system. Some European countries have already adopted to this norm. International Electrotechnical Commission (IEC) and the Institute of Electrical and Electronics Engineers (IEEE) have also published norms which aim to limit the harmonic contents in the voltages, named IEEE-519 and IEC 61000.

The main set of international standards on power quality is found in the IEC documents on EMC (Electromagnetic Compatibility). The IEC EMC standards consist of six parts, each of which consists of one or more sections [4]:

- Part 1-General: This part of the standard contains for the time being only a section in which the basic definitions are described and explained.
- Part2-Environment: Quantification of various disturbance levels sections are contained in this part. This part also contains environment description, classification and methods for quantifying the environment.
- Part 3-Limits: This part is the basis of the EMC standards where the several emission and immunity limits for equipment are given. Standards IEC 61000-3-2 and IEC 61000-3-4 give the limits for emission for harmonic currents; IEC 61000-3-3 and IEC 61000-3-5 give emission limits for voltage fluctuations.
- Part 4-Testing and Measurement Techniques: Definition of immunity and emission limits are not enough for such a standard. The standard also must define standard ways of measuring techniques for the emission and of testing the immunity of equipment. This is taken care of in part 4 of the EMC standards.
- Part 5-Installation and Mitigation Guidelines: This part gives background information on how to avoid electromagnetic interference at the design and installation stage.
- Part 6-Generic Standards: Immunity and emission are defined for many types of equipment in specific product standards. For those devices that are not covered by any of the product standards, the generic standards apply.

EN 50160 is the most important non-IEC standard defining voltage characteristics, which have been created by CENELEC, defining voltage characteristics. Several countries have created power quality documents of their own. The IEEE has published a significant number of standard documents on PQ, with the harmonics standard IEEE 519 probably being the most widely used outside of the United States. A more recent document that has become a global standard is IEEE 1366 defining distribution reliability induces. Other IEEE power quality standard documents worth mentioning are IEEE 1346, IEEE 1100 (power and grounding of sensitive equipment), IEEE 1159 (monitoring electric power quality), and IEEE 1250 (service to sensitive equipment) [4].

The main measurement ranges and uncertainties of the measured signals according to the EN 50160 are presented in the Table 2.1.

2.3 Installation of Mini-PQs in the Distribution System

The device described in this thesis, the Mini-PQ, is designed for the low voltage distribution system levels. In the beginning of this chapter, electric grid scheme has been given in the Figure 2.1. The electrical connection of the installed power quality monitoring devices in the Turkish Power System is shown in Figure 2.9. In this figure, PQ+ and PQ++ devices are designed implemented by TÜBİTAK UZAY. The PQ+ analyzer is specifically designed for multipurpose usage such as event recording and raw data collection, in addition to the usual PQ analysis functions [27].

These devices communicate with each other and National Monitoring Center for Power Quality (NMCPQ) via Asymmetric Digital Subscriber Line (ADSL) or fiber optic lines. The PQ+ analyzers are continuously communicate with NMCPQ to send obtained data or result. The exported data by the analyzers are stored in the PQ database of the NMCPQ and they are also displayed on the country map on the digital light processing technology based screen for the PQ operators of TEIAS to do the analysis and take necessary actions [27]. The PQ++ also uses ADSL or fiber optic cable as the communication medium. A PQ++ is setup into the distribution system and it can measure and collect data from up to ten feeders.

The Mini-PQ is designed to be integrated to these devices. The Mini-PQ is installed to the customer level, which is the end of the low voltage distribution system of the power system. It sends the power quality logs to the PQ++ via power line. As stated before, PQ++, PQ+ and NCMPQ communicate with each other via an ADSL modem

Table 2.1: EN50160 limits for characteristics of supply voltage [1]

Characteristic	**nominal value**	**ip**	**variation min/max**	**meas. period**	**note**
Power frequency	*50Hz*	*10s*	*-1% / +1% @ 99.5% of a year* *-6% / +4% @ 100% of a year*	*1 week*	
	50Hz	*10s*	*-2%/+2% @ 95% of a week* *-15%/+15%@ 100 % of a time*	*1 week*	*for systems isolated systems*
Magnitude of supply voltage	*LV: 230V* *MV: Uc*				*until 2003 LV Un may be according natonal HD 472 S1*
Supply voltage variation	*LV: Un* *MV: Uc*	*10min* *10min*	*-10% / +10% @ 95% of a week* *-15% / +10% @ 100% of a week* *-10% / +10% @ 95% of a week*	*1 week* *1 week*	
Rapid voltage changes	*LV: Un* *MV: Uc*		*generally ±5%* *max ±10% several time a day* *generally ±4%* *max ±6% several time a day*	*1 day*	*indicative*
Flicker severity			*Plt < 1 @ 95% of a week*	*1 week*	*Pst is not used*
Supply voltage dips	*LV* *MV*		*10-1000 / year, <1s,depth< 60% caused by large loads* *10-1000 / year, <1s,depth< 60% caused by large loads and faults*	*1 year*	*indicative* *depth% of Un (Uc)*
Short interruptions			*10 to several hundreds , 70%<1s*	*1 year*	*indicative; duration < 3 min*
Long interruptions			*10-50*	*1 year*	*indicative; prearranged are not counted in*
Temporary overvoltages	*LV* *MV*		*<1.5 kV rms up to 5s* *< 2.0 Uc; failures* *< 3 Uc; ferroresonance*		*indicative*
Transient overvoltages	*LV* *MV*		*< 6 kV*		*indicative*
Supply voltage unbalance		*10min*	*<2% @ 95% of the week, occasionally up to 3%*	*1 week*	
Harmonics		*10min*	*table 4 @ 95% of the week*	*1 week*	
Inter-harmonics		*10min*	*limits under consideration*	*1 week*	
Mains signalling		*3s*	*less then EN50160 curve on figure 16 @ 99% of a day*	*1 day*	

and the internet or fiber optic cable. PQ++ sends the collected data from the Mini-PQ to the PQ+ or to the NCMPQ by using one of these communication networks. The communication diagram of the devices is shown in Figure 2.10. In the figure the gray colored lines indicate communication lines between the devices and NCMPQ. By looking at these lines we can see that; whereas it is necessary to set up a new communication network for PQ+ and PQ++, this is not necessary for the Mini-PQ since power lines can be used as communication network. As stated in Chapter 1, this network is already installed for power systems with PQ+ devices [27, 19]. The Mini-PQ is designed to use this network to send the data to a PQ++.

2.4 Measurement Setup and Hardware Structure for the Mini-PQ

Hardware description for a power quality monitor is provided in IEC 61000-4-30 [5]. This measurement setup for power quality monitors is shown in Figure 2.8. The electrical quantity to be measured may be either directly accessible, as is generally the case in low-voltage systems, or accessible via measurement transducers. The first step in a power quality monitor is transformation of the input signals to a level so that these signals can be measured in the measurement unit. Next step is the signal conversion, signal is converted from analog domain to digital domain to be processed in a processing system. Final step is the evaluation, where the measured and processed signal is evaluated according to the requirements of the international standards [5, 34].

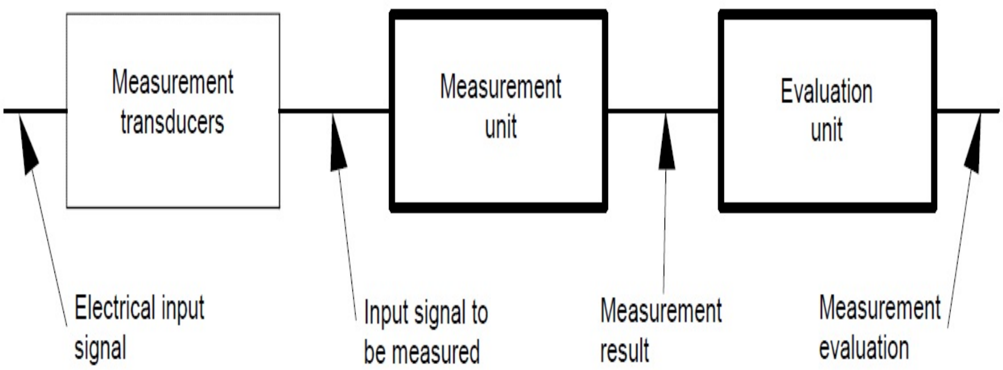


Figure 2.8: Measurement Chain [5]

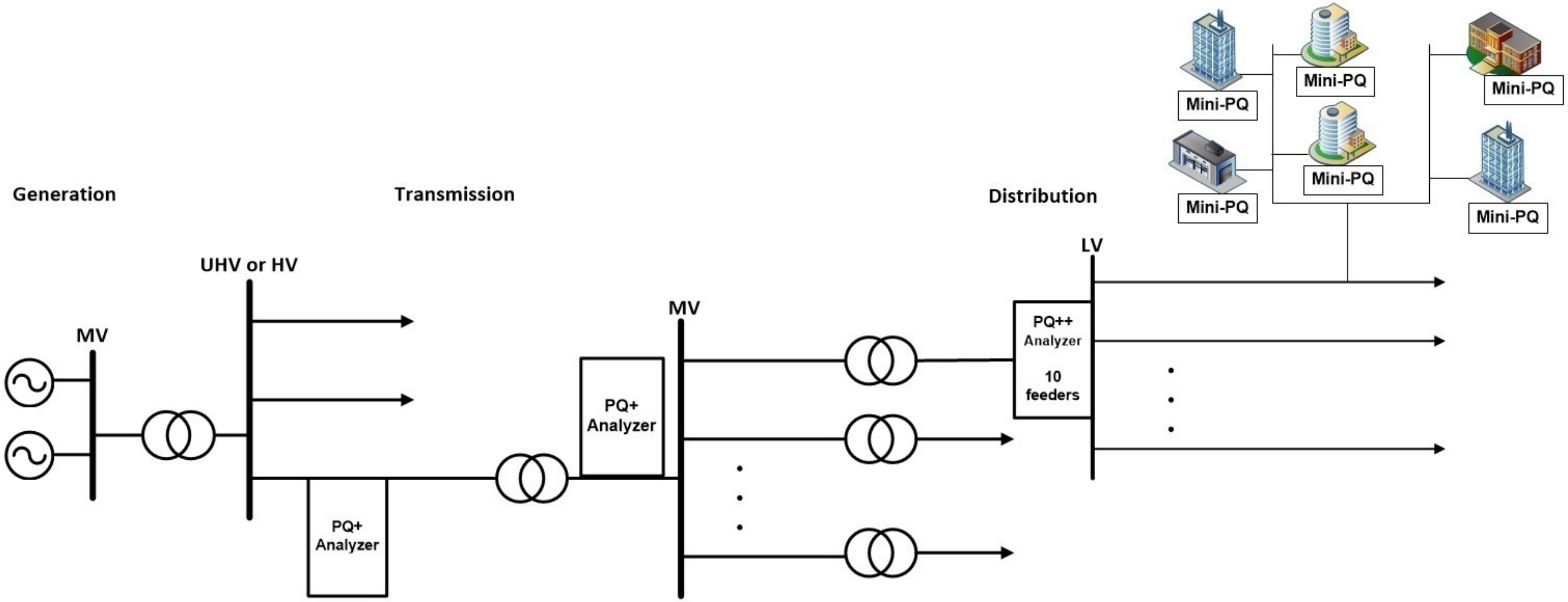


Figure 2.9: Conceptual illustration of the installed PQ monitoring devices in the Turkish electrical grid with multiple Mini-PQs

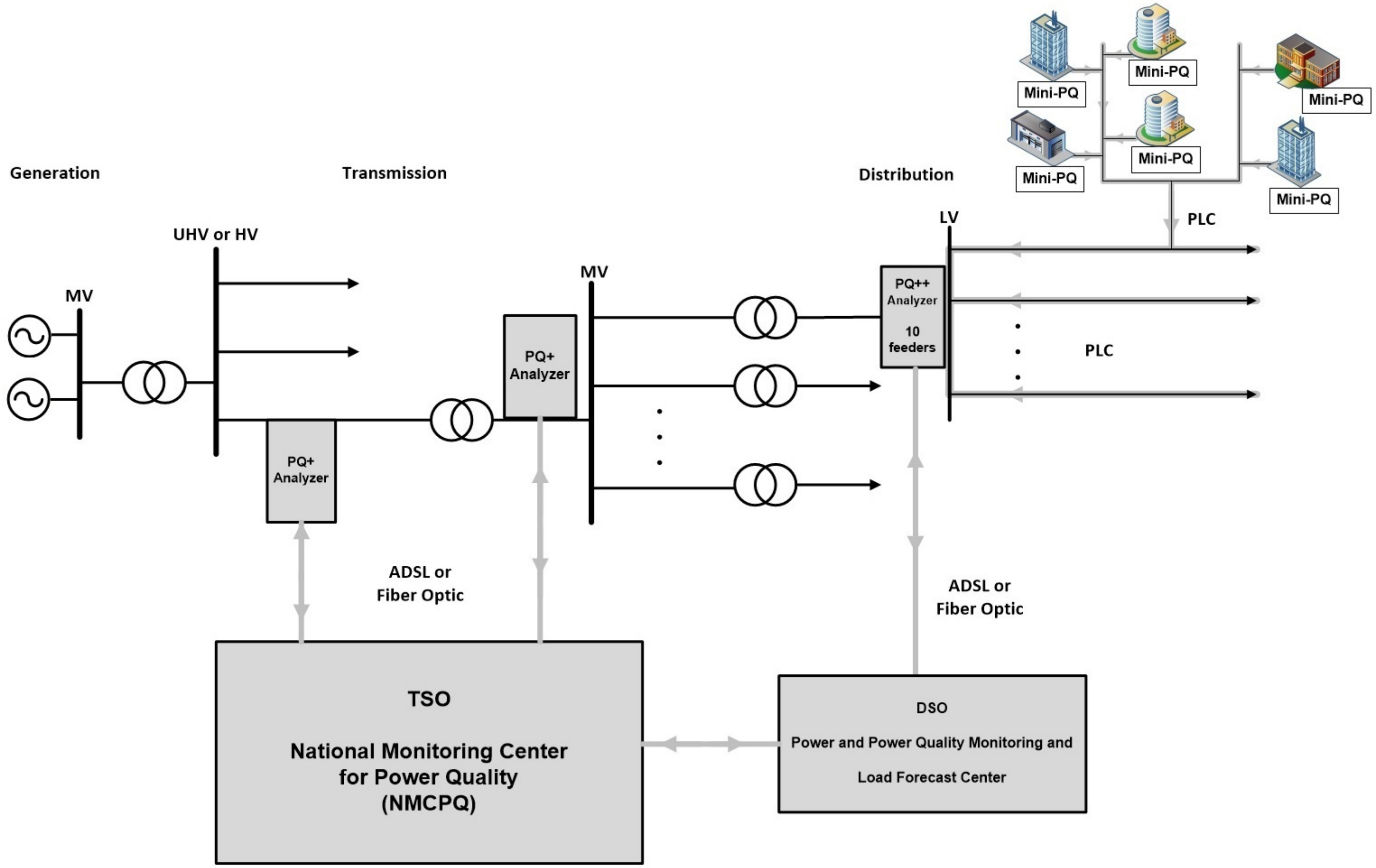


Figure 2.10: Conceptual illustration for the operation of the monitoring and control center together with multiple Mini-PQs and possible other monitoring and control centers. The gray lines indicate communication network between the monitors. The Mini-PQs use power line as the communication medium. TSO:Transmission System Operator, DSO:Distribution System Operator

The requirements of IEC 61000-4-30 are only ensured by the usage of a powerful hardware, since time aggregations of parameters have to be made and certain level of uncertainties have to be satisfied. The hardware of the designed device was implemented with satisfactory capacity for its performance and for possible performance upgrades. A simplified measurement setup block diagram of the device is presented in the Figure 2.11.

As shown in the figure, the device involves a signal-conditioning module, a high-speed multi-channel ADC, a powerful DSP, and a power line communication modem. The objective of the proposed device is to calculate power quality parameters and classify disturbances and events in real-time. It uses data processing capability of embedded DSP with high speed bipolar, 16-bit ADC. The device also has a battery and storage ability to detect the duration of voltage interruption. The real-time logs are send to a PC via power line communication modem. Furthermore, a user-friendly interface which is designed to run in PQ++ devices and can be set up into any PC is developed to access the outputs of Mini-PQ obtained from the modem.

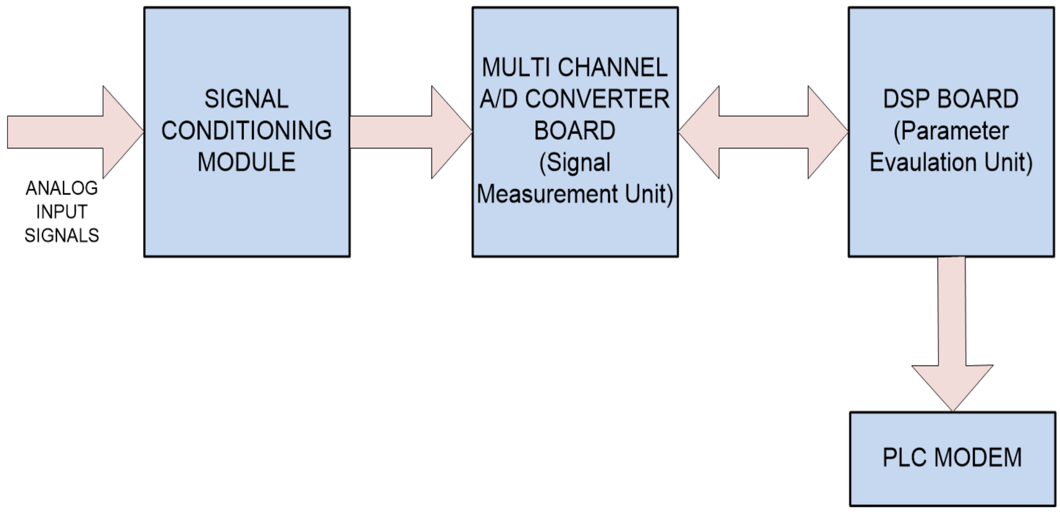


Figure 2.11: Simplified Measurement Setup of the Mini-PQ

CHAPTER 3

SIGNAL PROCESSING ALGORITHMS OF THE MINI-PQ

In this chapter, designed algorithms to calculate PQ (power quality) parameters, which are described in Chapter 2, are explained. First, general information about the algorithms are shared and they are supplied with simulation results. Then, individual algorithm for each parameter is described in detail, as well.

3.1 An Overview of Algorithm Design

All signal processing algorithms are implemented in MATLAB signal processing environment. Therefore, they can easily be adopted to the C environment in which the DSP (Digital Signal Processor) operates. The designed system is capable of sampling both voltage and current data generated of three phases of the power system, simultaneously. As a result, there are six independent input channels on the Mini-PQ. Sampling frequency in which the analog data is converted to digital is chosen as 1.5 KHz, therefore the Mini-PQ can compute current harmonics up to 13^{th} order, which is good enough for the distribution system level. However, the sampling rate and hence the maximum harmonic order is upgradable up to 40 if required.

As defined in IEC 61000 4-30, the frequency measurement is required to be realized every 10 sec at most. In this study, the period of frequency measurement is chosen as nine sec. Calculation of voltage RMS values are done at each period of three sec. Therefore, each nine sec-length raw data-segment is used to calculate one power frequency, three voltage RMS, and the rest of PQ parameters for each phase.

As recommended in the [5], unwanted harmonics and interharmonics are filtered out from the raw data by using a low-pass filter at the beginning of each calculation period. In addition, zero-crossings are used to determine integer cycles. The low-pass filter which is used to eliminate harmonics on the voltage waveform is a linear phased Finite Impulse Response (FIR) filter. The cut-off frequency of this filter is chosen as 2 KHz for harmonic calculations and 60 Hz for the rest of the parameter calculations.

All data are sampled at 1.5 KHz; therefore, in a data segment for one channel there are:

N = 9 s x 1500 (samples/second) x 1 channel = 13500 samples/channel.

Performances of all the designed signal processing algorithms satisfy the aggregation and measurement requirements described in the [5].

General signal processing flow diagram is provided in Figure 3.1

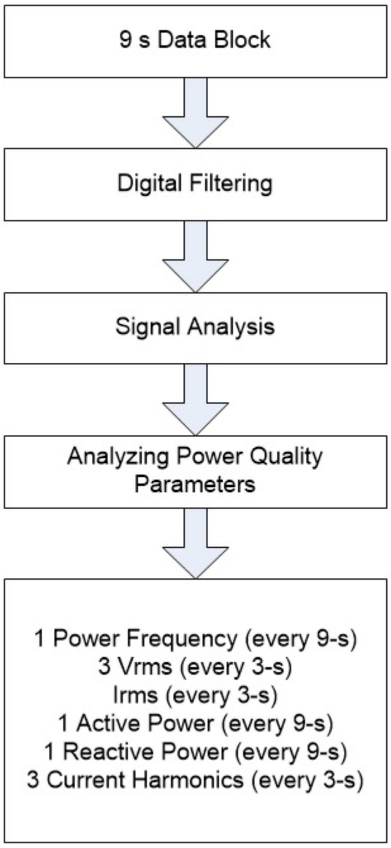


Figure 3.1: General flow diagram of data processing

3.2 Power Frequency Calculation

As stated before, line voltage contains odd and even harmonics and these harmonics affect the sensitivity of frequency calculations. Therefore, a low pass filter is designed to attenuate these harmonics. At frequency calculations, cut-off frequency of the low-pass filter is chosen 60 Hz. As discussed in Chapter 2, the frequency measurement range for a 50 Hz system is between 42.5 Hz and 57.5 Hz. Therefore, the chosen cut-off frequency is beyond this range and suitable for this application.

FIR low pass filter can be designed by using equation [35]:

$$y_n = \sum_{i=0}^{N-1} c_i x_{n-i} \tag{3.1}$$

$$c_i = \frac{1}{N} \tag{3.2}$$

where

N : Degree of the filter,
X_n : Input signal samples,
C_i : Filter coefficients.

In the above equation, *N* = 10 for the designed filter. As given in 3.2, filter coefficients are constant and equal to each other. In addition, the filter creates *N* point linear phase shift. In order to eliminate phase shift effect, filtered signal is shifted by N points. Frequency response of the designed filter is shown in Figure 3.2 and phase response is shared in Figure 3.3.

Counting of zero crossings is one of the most commonly used method to calculate the power frequency. IEC 61000-4-30 clearly defines the method of the frequency calculation as: “the ratio of the number of integral cycles counted during the maximally 10 sec time clock interval, divided by the cumulative duration of the integer cycles.” In this study, frequency measurement is based on zero-crossing method, calculating the number of samples between the consecutive positive to negative transitions.

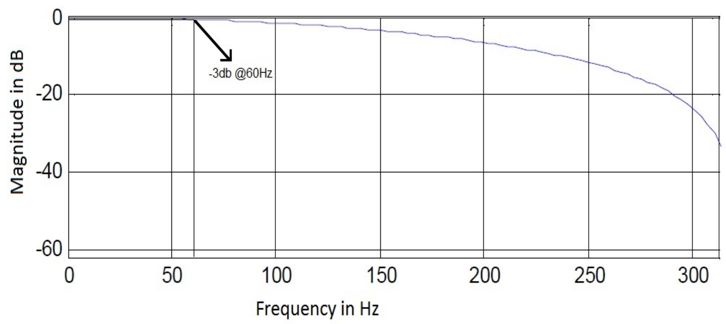


Figure 3.2: Frequency response of the LP FIR filter

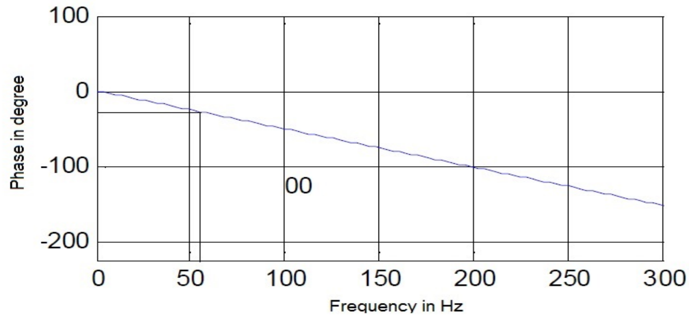


Figure 3.3: Phase response of the LP FIR filter

For an exact 50 Hz frequency, there are 450 cycles in a 9-s interval. If the frequency raises to 50.01 Hz, there are more than 450 cycles during a 9-s interval. In order to achieve high frequency measurement accuracy, exact time interval containing integer number of cycles should be used. When analyzing PQ events (e.g., estimating the phase-angle jump with voltage dips), the frequency is assumed constant, therefore a voltage dip or another event causing a change in phase angle shows up as a large frequency variation [4]. Hence during these events, frequency data is flagged to remove corrupted such frequency values from the statistics.

An example of voltage waveform which is used in zero-crossing detection algorithm is shared in Figure 3.4. x[n] and x[n+1] represents two consequtive samples. If multiplication of these two sequential signal samples equal to or smaller than zero;

$$x[n] \times x[n+1] \leq 0 \tag{3.3}$$

that means a zero-crossing is detected.

The most important point which affects the overall performance of the algorithm is

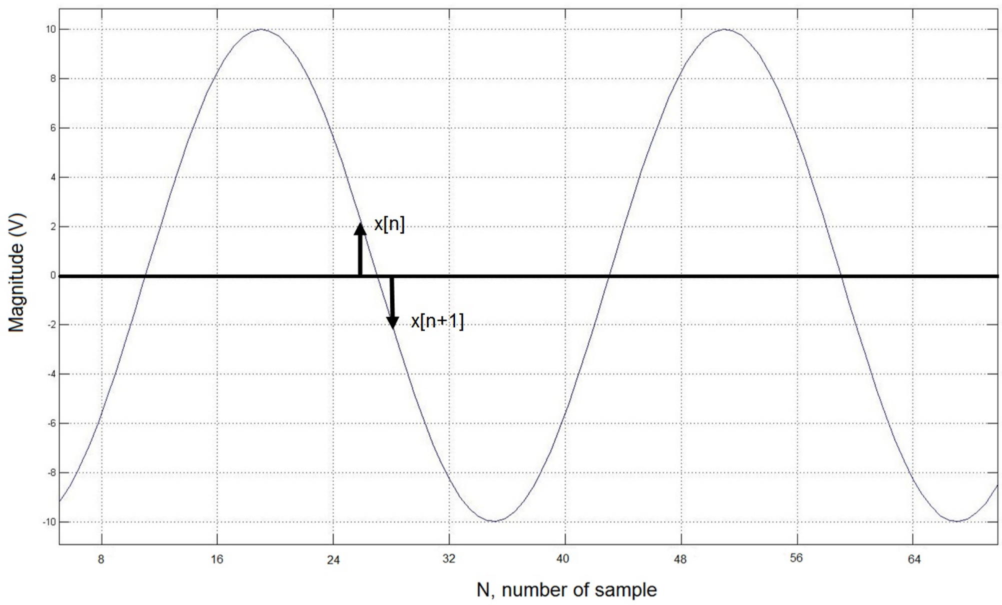


Figure 3.4: An example voltage signal for detecting zero crossing

that, the determination of exact time at which the zero-crossing occurred. Choosing x[n] or x[n+1] as zero crossing point directly affects the accuracy of the calculated frequency. A closer view of Figure 3.4 around the zero-crossing is shown in Figure 3.5. This figure shows, a zero-crossing point can be represented by two triangles assuming that signal changes linearly from one sample to the next. ABC and EDC triangles are similar triangles. So, the lengths of corresponding sides should have the same ratio. By using basic similarity theorem, point C can be found exactly. Using point C as the zero-crossing point provides more accurate frequency computation, when compared to using points B or D.

At every nine seconds, frequency is calculated once in real time. So, contents of index and counter should be reset at the beginning of the each nine seconds period. After initialization of the index and the counter, the sampled data is stored in a vector. Process begins with the occurrence of the first zero-crossing and ends with the last zero-crossing point. The time interval falling between these two zero-crossing points is used for calculation instead of constant time interval of nine sec. Zero crossing points are determined for every voltage cycle (AC voltage cycle). In equation 3.4 frequency calculation for a cycle is given. Finally, an average of the determined frequencies is calculated in order to get line voltage frequency.

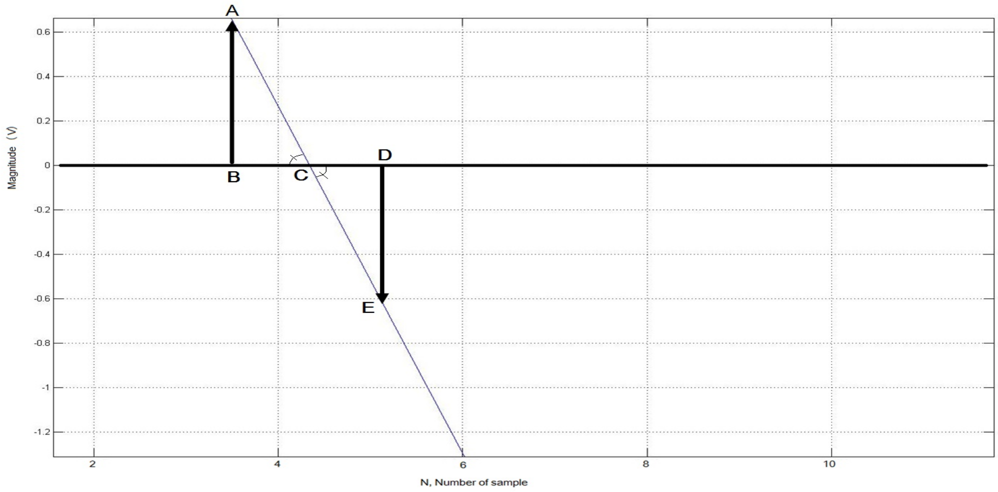


Figure 3.5: A closer view to the zero-crossing point

$$f_n = \frac{fs}{zi[n+1] - zi[n]} \tag{3.4}$$

where

n : Number of loop,

f_n : Frequency of nth loop,

f : Sampling frequency,

$zi[n]$: The index of the nth zero-crossing point.

Flow diagram for the frequency calculation is given in Figure 3.6

3.3 Voltage and Current Magnitude Calculation

RMS value of the line voltage is calculated from equation 3.5

$$V_{rms} = \sqrt{\frac{1}{T}\int_{t=0}^{T}(A\sin(2\pi ft + \theta))^2 dt} \tag{3.5}$$

where

t : Time,

f : Frequency,

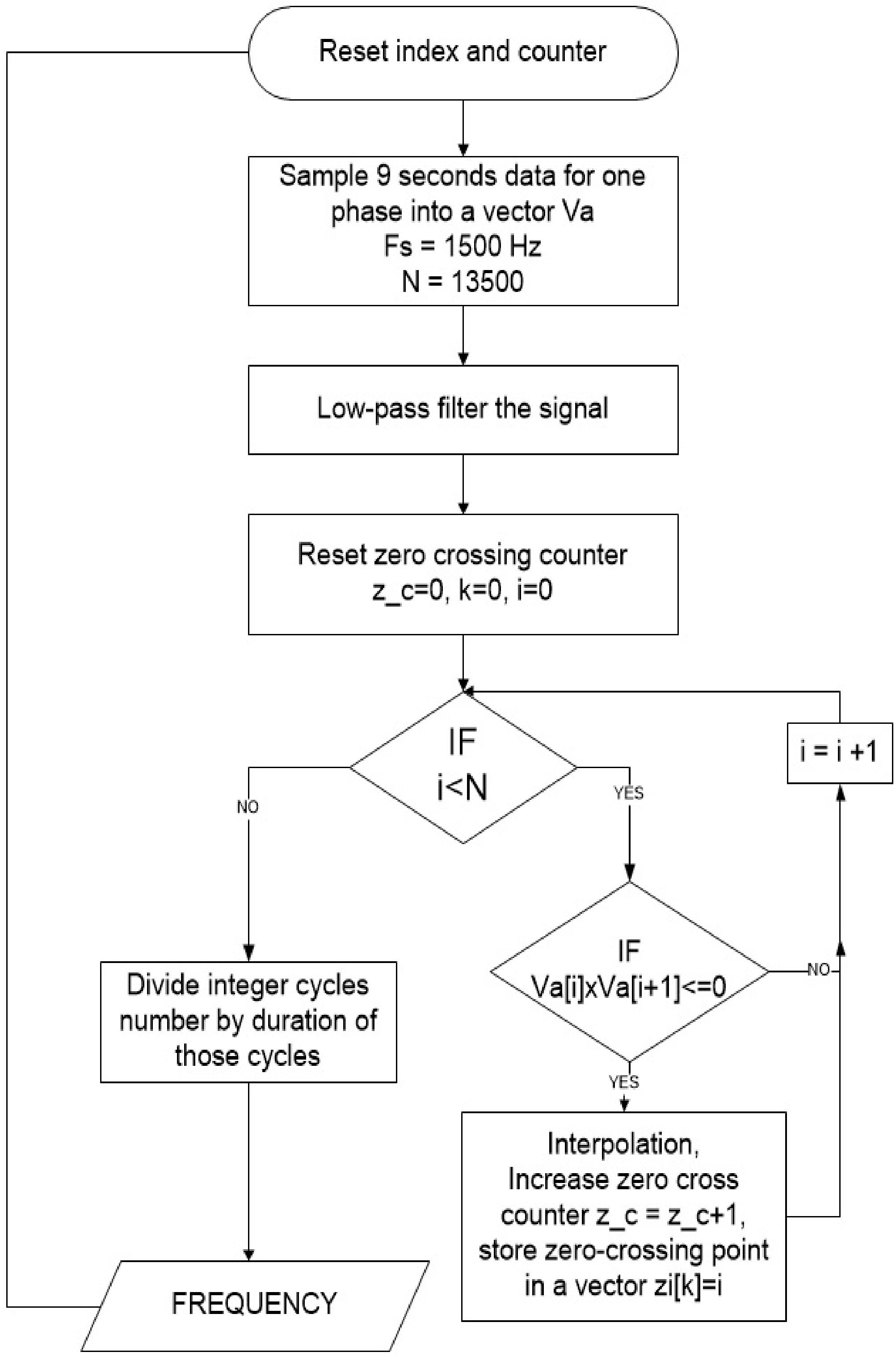


Figure 3.6: Frequency algorithm flow chart

A : Amplitude,

T : Period of the waveform.

Integral calculation is a time consuming process for a processor; therefore, if equation is converted to discrete domain, RMS value can be calculated using summation easily. The voltage magnitude V is obtained from the sampled waveform by using equation [36]:

$$V_{rms} = \sqrt{\frac{\sum_{k=1}^{N}(v_k)^2}{N}} \tag{3.6}$$

where *N* is an integer multiple of the number of samples in one half-cycle of the waveform and *k* represents kth sampled data.

The standard [5] does not state the determination of the length of a cycle. The frequency calculated from a 9-s raw data may be used to determine cycle length determination in accordance with the standard. Using a short time window to calculate RMS Voltage causes noisy appearance. Applying a longer window gives a more smooth function of time [4]. Effect of window length on RMS voltage calculation is provided in Figure 3.7.

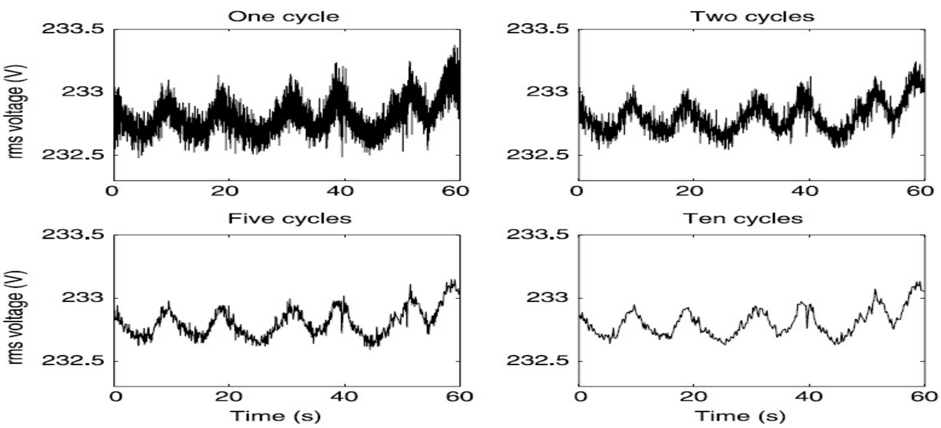


Figure 3.7: Effect of window length on RMS voltage versus time [4]

Voltage magnitude is calculated at each 3-s segments in a 9-s data block. Number of samples in a 9-s data block is already known, and by dividing this data block into three equal parts, three data blocks are obtained which represent 3-s data segments. Therefore, after processing a 9-s data block, three voltage magnitude is calculated for each channel. Eventually, for 3-s data segment, voltage magnitudes of all cycles are calculated. First, the sum of the squares of samples in a cycle is obtained. Then, this sum is divided by the number of samples and; finally, square root of the result of the division comes out as the RMS value of the voltage waveform. All RMS values obtained for 3-s data segments are averaged to calculate one RMS value. Flowchart for voltage magnitude calculation is given in Figure 3.8. Similarly, current magnitudes for three current channels are calculated by using the same algorithm.

3.4 Active, Reactive and Apparent Power Calculation

The parameters needed for power calculation have already been given in Chapter 2 with equations 2.2,2.3 and 2.4.

For the calculation of symmetrical components, the angular difference between voltage and current is needed [4]. The power is obtained by multiplying values of the voltage and the current using a function of phase angle between them. Voltage and current amplitudes are defined and calculated in the previous sections of this chapter. When voltage and current are out of phase, the active power is always less than the maximum power. To calculate active, reactive and apparent power, phase angle between voltage and current should obtained, which is θ in equations 2.2,2.3. In Figure 3.9 two out of phase waveforms are shown.

Zero cross indices for each channel are obtained using the frequency determination algorithm whose flow-chart is shown in Figure 3.6. The indices are stored for phase angle calculations. Index difference between two zero-crossing points, represented by "d", is shown in Figure 3.9. Then, index difference is converted to seconds by multiplying it with the sampling period (1/sampling frequency). Finally, time difference between two zero crossing points is converted to radian to obtain the phase angle. All phase angles obtained for a 9-s data block are averaged to calculate one phase angle for the corresponding data block. Flow chart for power calculation is shown in Figure 3.10.

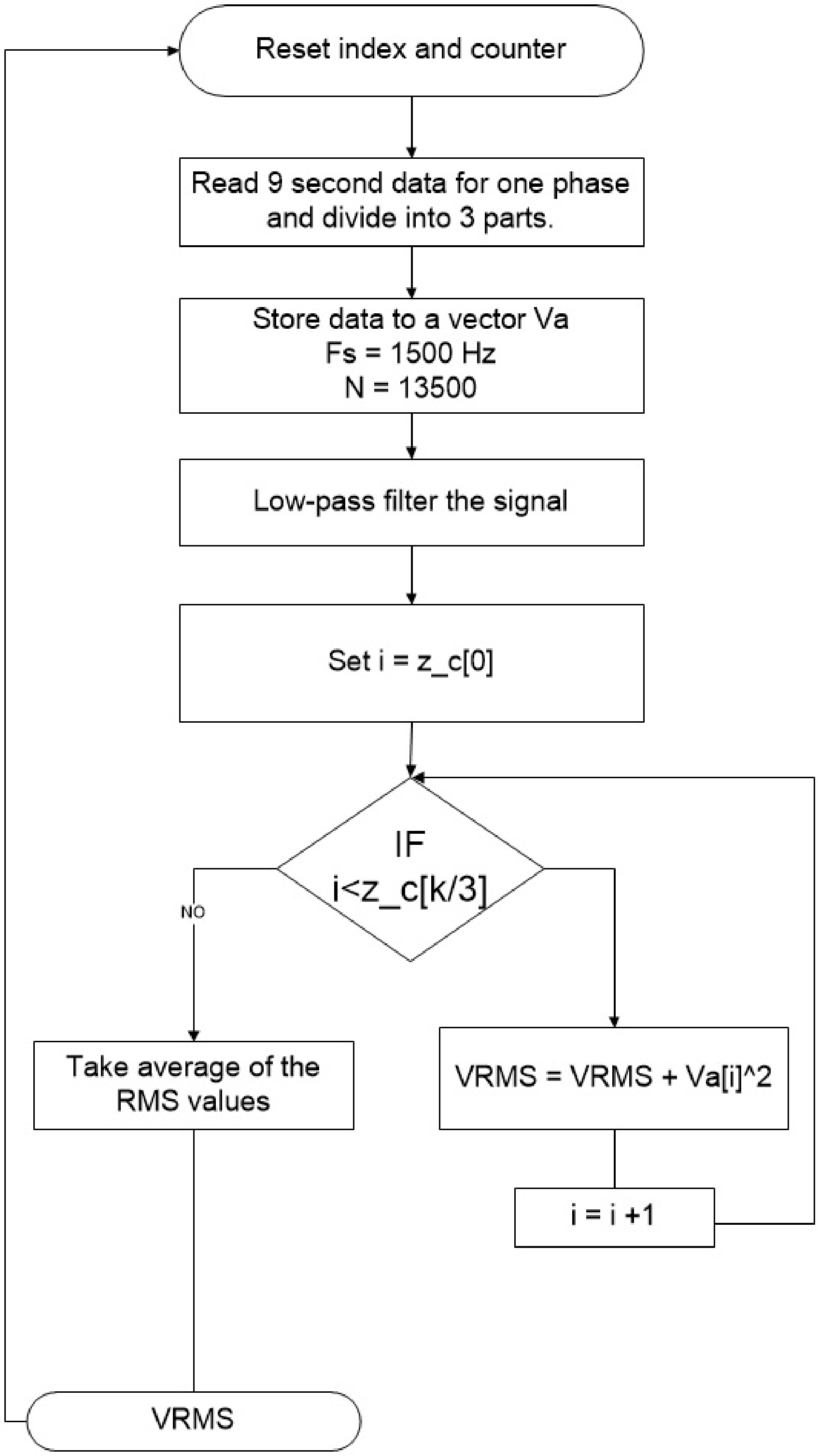


Figure 3.8: Flow chart for RMS calculation algorithm

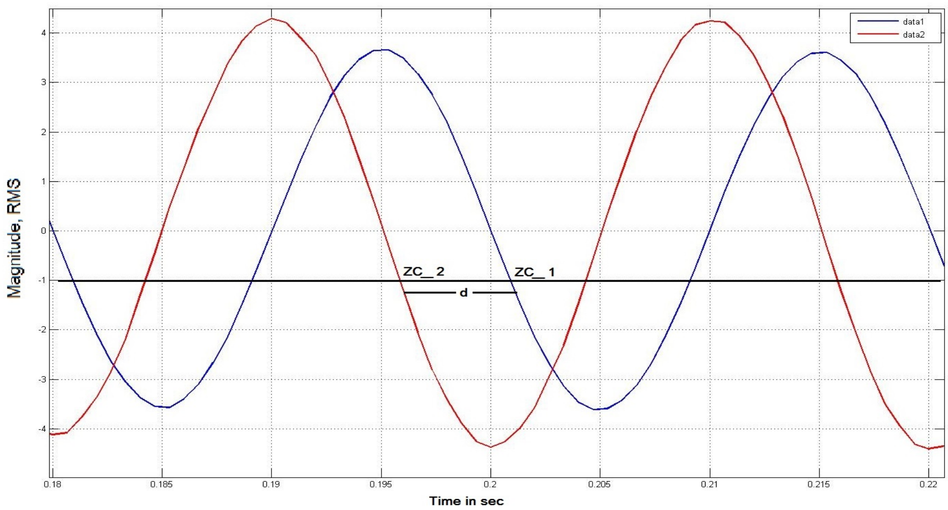


Figure 3.9: Voltage and current waveform which are out of phase

3.5 Current Harmonics Calculation

The Fast Fourier Transform (FFT) is one of the most commonly used operations in digital signal processing to provide a frequency spectrum analysis [37]. Spectrum analysis is the process of determining the frequency domain representation of a time domain signal and most commonly employs the Fourier transform [38]. An FFT can be computed in two ways: the decimation-in-frequency and the decimation-in-time. The FFT is an efficient algorithm that is used to calculate frequency domain representation of a time-domain signal, based on the Discrete Fourier Transform (DFT).

The standard IEC 61000-4-7 [34], defines the measurement of harmonic distortion. The way in which harmonic current distortion shall be measured when comparing equipment emission with the emission limit is described in this standard.

Mini-PQ is capable of measuring harmonics up to 13^{th} order. The harmonic calculation is repeated every hour by using one 9-s data block of that hour. In the previous section, we stated that the sampling frequency for the Mini-PQ is 1.5 KHz. The choice of this sampling frequency is important because of the aliasing issues. Illustration of the phenomenon of frequency aliasing is shown in Figure 3.11. In a 50 Hz system, 13^{th} harmonic of a waveform corresponds to the 650-Hz frequency component. According to Nyquist theorem, in order to avoid aliasing, sampling frequency should be chosen more than 2xf, where f is the frequency of 13^{th} harmonic compo-

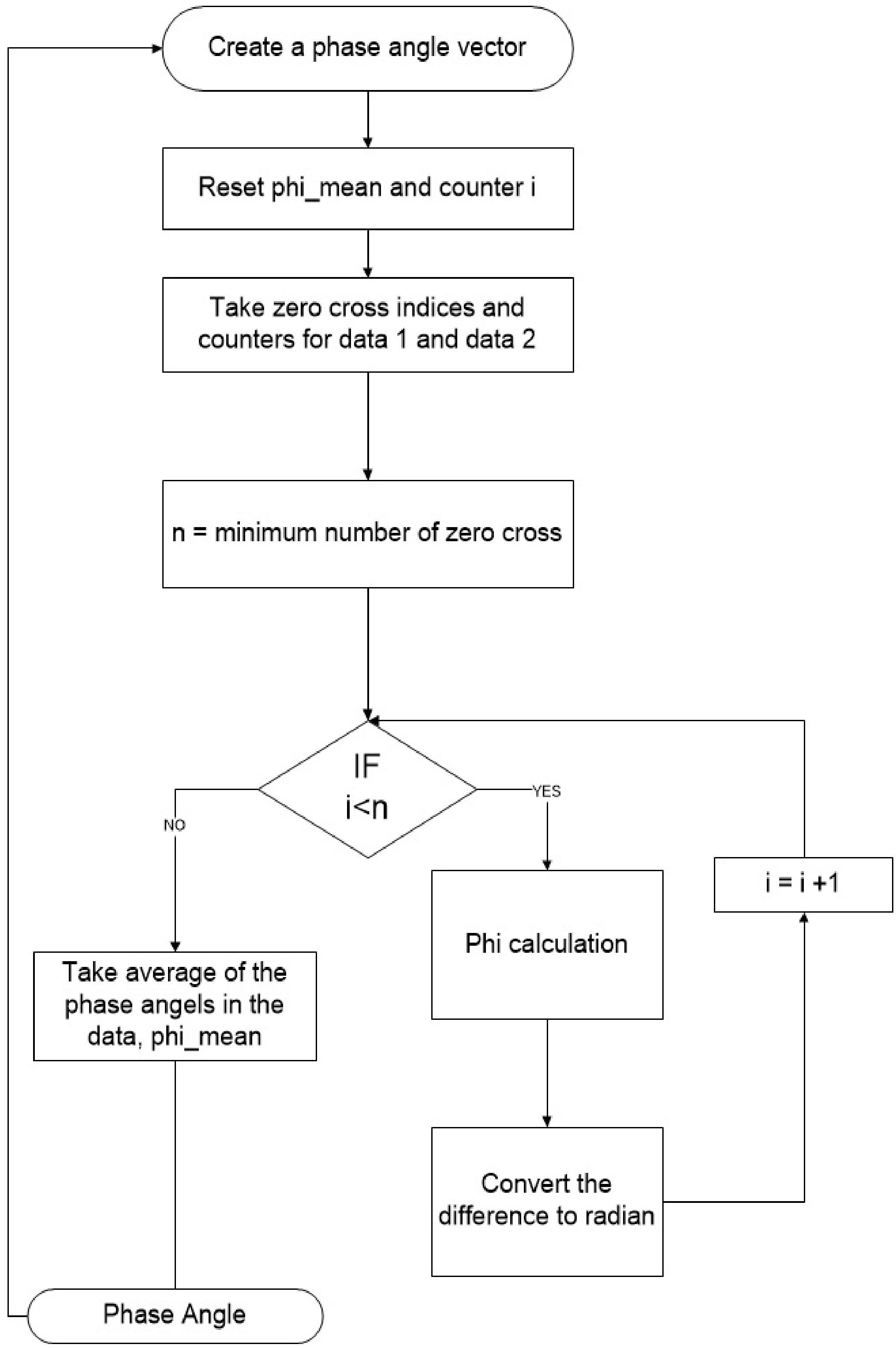


Figure 3.10: Flow chart for power calculation algorithm

nent. Therefore, in the Mini-PQ system, sampling frequency is chosen as 1.5 KHz, which is able to detect frequencies up to 750 Hz.

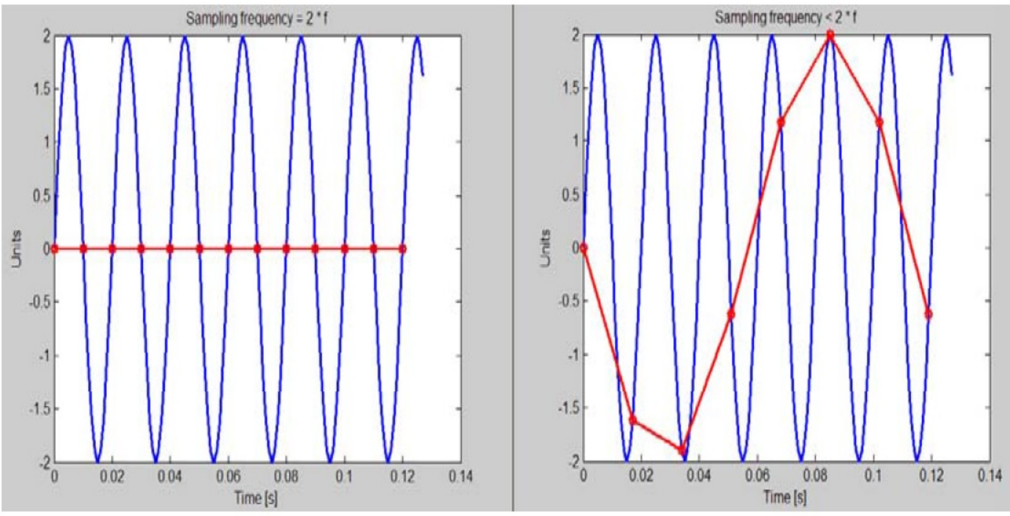


Figure 3.11: Illustration of the phenomenon of frequency aliasing [6]

The continuous Fourier Transform of a continuous time domain signal g(t), which comes out as G(jw) in the frequency w, is given as [6]:

$$G(jw) = \int_{t=-\infty}^{\infty} g(t)e^{-jwt}dt \tag{3.7}$$

The equation is not practical to be used with a DSP and therefore for a signal sampled at discrete times tn and in the finite duration, the so called Discrete Fourier Transform (DFT) in equation 3.8 is used instead of 3.7.

$$G(w) = \sum_{n=1}^{k} g(t_n)e^{-jwt_n} \tag{3.8}$$

In the Mini-PQ, the frequency f in Hz is used instead of w in rad/s. Therefore, equation 3.8 becomes:

$$G(w) = \sum_{n=1}^{k} g(t_n)e^{-j2\pi ft_n} \tag{3.9}$$

The DFT formula in equation 3.9 contains both real and complex components. A DSP processor cannot perform complex processes. Therefore, it is required to disregard the complex exponential e^{jw}. By using the Euler formula, we can disregard this complex exponential. According to this formula, exponential e^{jw} is related to the cosine and sine via the definition:

$$e^{j\theta} = \cos\theta + j\sin\theta \tag{3.10}$$

$$e^{-j\theta} = \cos\theta - j\sin\theta \tag{3.11}$$

Now equation 3.9 is divided into two parts, real part with cosine and complex part with sine. DFT formula in equation 3.9 is applied by using Euler's expansion. Finally, real and complex components are summed up and harmonics of the current are calculated up to 13^{th} order.

It is already stated that, the power spectrum represents the average distribution of power of a time signal related to (integer multiples of) the fundamental frequency. However, a problem experienced when there is power components of the time domain signal at the frequency components which are not harmonics of the fundamental frequency (interharmonics). Since 200 msec data windows are recommended for FFT analysis is IEC 61000-4-7, the FFT frequency resolution is 5 Hz. As the interharmonic occurs, the power of these components is misrepresented. This problem is referred in the literature as Spectral Leakage [39].

In order to minimize spectral leakage, the frequencies at ±5 Hz of each harmonic component are included in geometric mean calculation of amplitudes of harmonics. Spectral leakage effect is shown in Figure 3.12. As seen in this figure, to calculate the power of 3^{th} harmonic component of a 50 Hz signal, the frequency components at 145 Hz and 155 Hz are also included in the calculation as geometric means of the amplitudes of 145 Hz, 150 Hz and 155 Hz components as recommended in IEC 61000-4-7, which is called subgroup method of harmonic computation. The spectral leakage problem also occurs during any fundamental frequency deviations. The subgroup method also aims to solve the spectral leakage for this case as given in [34]. Finally, all harmonic components are normalized by the main component to represent them as percentage of the fundamental component.

Flowchart for harmonics calculation is given in Figure 3.13

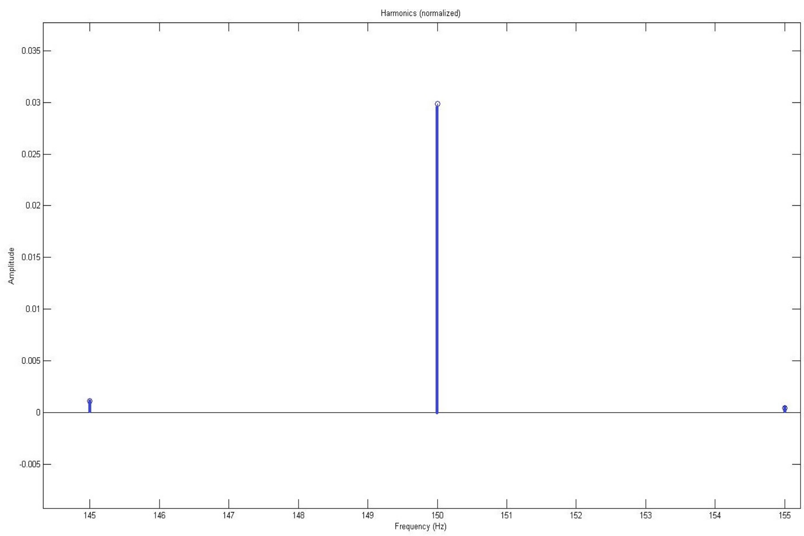


Figure 3.12: Spectral Leakage

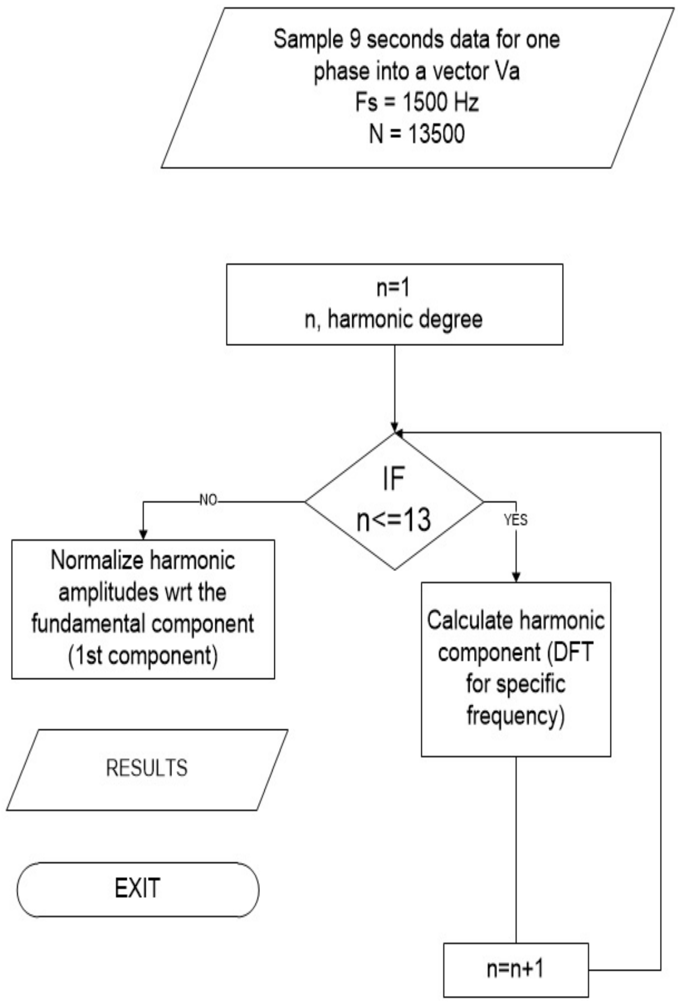


Figure 3.13: Flow chart for harmonics calculation algorithm

To test the algorithm for harmonics calculation, synthetic data are created in MATLAB environment. The data is composed of 8 sinusoidal components, whose relative amplitudes and frequencies are 100% 50 Hz, 9% 100 Hz, 7% 150 Hz, 11% 250Hz, 13% 350 Hz, 9% 450 Hz, 17% 550 Hz and 19% 650 Hz. At the end of the simulation, it is expected to observe the following harmonic results:

1^{st} harmonic component is 1,
2^{nd} is 0.09,
3^{th} is 0.07,
4^{th} i 0,
5^{th} is 0.11,
6^{th} is 0,
7^{th} is 0.1,
8^{th} is 0,
9^{th} is 0.09,
10^{th} is 0,
11^{th} is 0.17,
12^{th} is 0,
13^{th} is 0.19.

The simulation results are shown in Figure 3.14 and in Table 3.1.

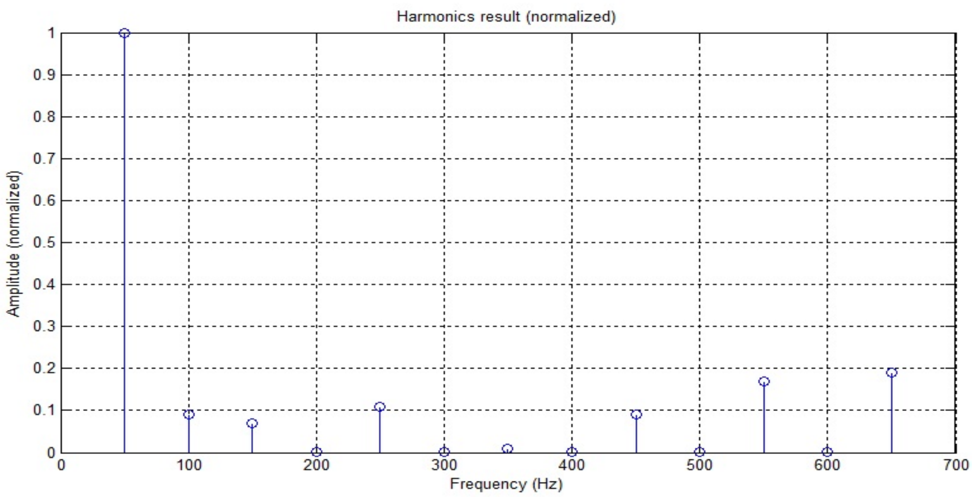


Figure 3.14: Harmonic algorithm simulation result

Table 3.1: Harmonics simulation results

Harmonic Number	**Expected Result %**	**Obtained Result %**	**% Error wrt to expected**
1	100	100	0.00
2	9	8.98	0.22
3	7	7.01	0.14
5	11	11.02	0.18
7	13	12.98	0.15
9	9	9.02	0.22
11	17	17.02	0.11
13	19	19.01	0.05

Results are quite close to the expected harmonics values as shown in Table 3.1.

CHAPTER 4

HARDWARE DESIGN AND POWER LINE COMMUNICATION

The Mini-PQ analyzer developed within the scope of this thesis, acquires instantaneous-voltage and current data on three phases and performs real-time analysis from the gathered raw data. Three voltage and three current inputs are sampled at a sampling rate of 1.5 kHz per channel corresponding to 30 samples per cycle of a 50 Hz signal. Total sampling rate of the Mini-PQ is "6 x 1.5 kHz = 9 kSamples/sec (kS/s)". The device consist of the following units: signal conditioning unit for gathering current and voltage data, Analog to Digital (A/D) conversion unit, digital signal processing unit, battery and Power Line Communication (PLC) modem. First, signal conditioning unit is used to collect and filter the data and sends the signal to the ADC unit for sampling and conversion. Sampled data is sent to the digital signal processing unit by the A/D conversion unit. The processor makes all necessary calculations in accordance with the designed algorithms to analyze power quality (PQ) parameters. This unit uses serial port (RS232) to send the PQ parameters. Finally, PLC modem accepts the data from the DSP (Digital Signal Processor) through RS232 and sends it through the power line. The Mini-PQ is designed to operate stand alone. Simplified hardware block diagram of the Mini-PQ is shown in Figure 4.1.

The device has two operational modes: minimum and maximum. In the minimum mode, as the PLC modem is available, the Mini-PQ sends reduced size of data due fact that PLC modem has certain data rate limitations. The reason of the data transfer limitation will be described in detail in Section 4.4. In the maximum mode, the device sends all the PQ parameters via serial port communication. Detailed hardware design

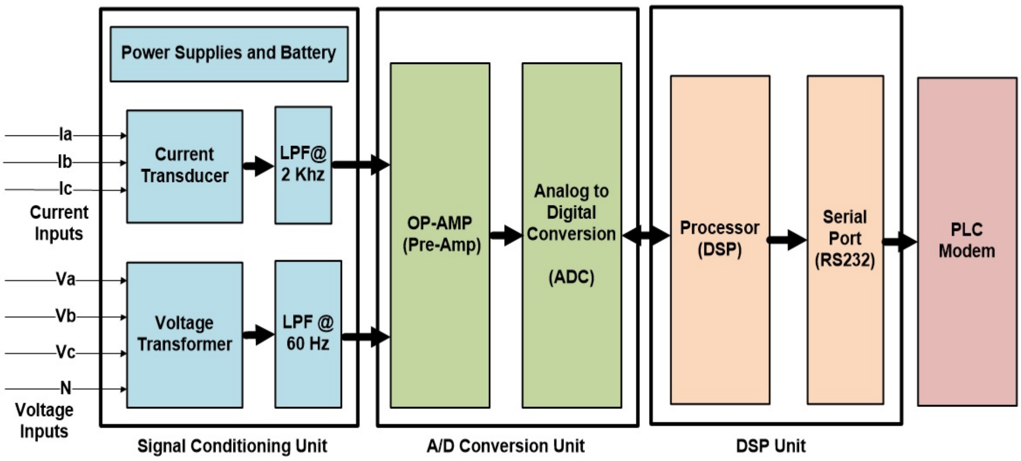


Figure 4.1: Simplified hardware block diagram of the Mini-PQ

including PLC is given in the following sections, as well.

4.1 Signal Conditioning Unit

Main functions of the signal conditioning unit are given as:

- Attenuation of the voltage signals to be compatible with the ADC (Analog to Digital Converter) inputs,
- Converting AC currents to AC voltages for ADC input compatibility,
- Filtering and adapting signals (anti-aliasing filtering) to the ADC sampling rate,
- Generating necessary DC voltages for transducers, the A/D conversion unit and the DSP unit,
- Switching between battery and regulator voltages and battery charging.

The voltage transformers used in this unit are purchased form EL-KOM [40] company as professional products. The nomenclature of the transformer is EI30/10,5 RN130242, which has been designed in accordance with VDE0570 and EN61558 standards [41]. These products are short-circuit-proof devices. Furthermore, the voltage transformer provides the electrical insulation between input (high voltage) and output (low voltage) sides. The transformer accepts input voltages up to 260 Vrms and the attenuation rate is 20:1 for the phase voltage. The upper limit in the line voltage is 260 Vrms, as a result the output voltage of this transformer is 13 Vrms, which is out of range for ADC inputs. Therefore, together with the transformer, a voltage divider is used for more attenuation. Division ratio of the divider is 2/5, and total attenuation becomes 50:1 ((20/1)x(5/2)=50/1). 260 Vrms (364 V peak value) input voltage is attenuated by using the transformer and the divider circuit in order to have an output of 7.28 V peak value. Since, Mini-PQ is designed for three-phase systems, three of these voltage transformers are employed for three phase lines.

The current transducer used in the device is a product of LEM [42]. The model of the transducer is CKSR-15NP, which is capable of measuring currents between ± 51A range. This sensor can measure both AC and DC currents with galvanic isolation between the primary and secondary sides. CKSR-15NP uses closed loop hall effect current sensing method, which is based on employing magnetic sensors. Magnetic sensors inside the transducer, operates by the principle of measuring the magnetic field generated due to current flowing in the line. In this method, inputs of the sensors are completely isolated from the output signals. An external buffer in the current sensing circuit is not required due to the fact that Magnetic sensors' output ports have low impedance. Functional block diagram of the current transducer is shown in Figure 4.2.

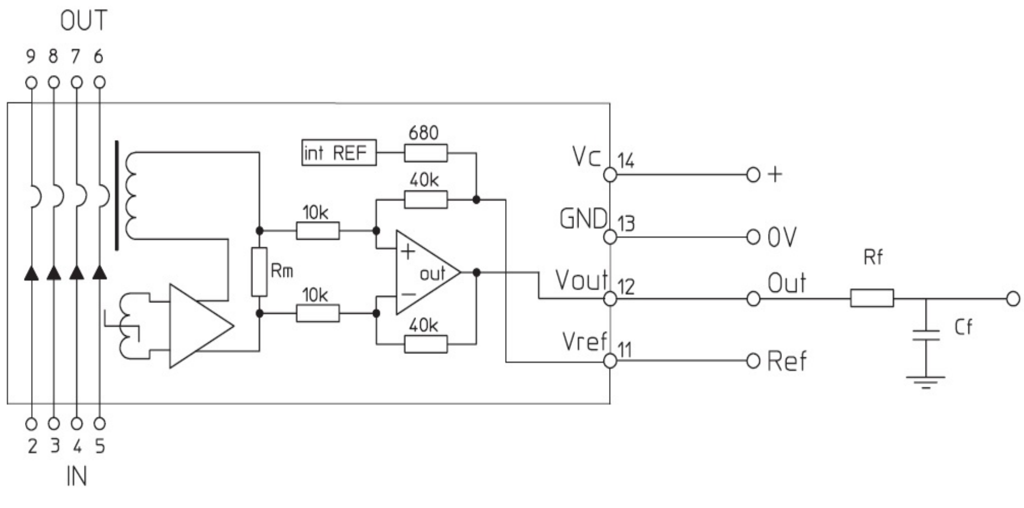


Figure 4.2: Current transducer functional block diagram [7]

Output voltages of the current transducer is in between 0.375 (V_{lower}) and 4.625 V (V_{upper}). As stated above , measurement range of the transducer is in between -51A(I_{lower}) and +51A (I_{upper}). In equations 4.1, 4.2 and 4.3 relationship between input current and output voltage is given. By using these equations, sensitivity is calculated as 41.67mV/A, which means the transducer output increases 41.67mV for 1A increase in the input.

$$V_{range} = V_{upper} - V_{lower} \tag{4.1}$$

$$I_{range} = I_{upper} - I_{lower} \tag{4.2}$$

$$I_{sensitivity} = \frac{V_{range}}{I_{range}} \tag{4.3}$$

where

V_{range} : Output voltage range of the current transducer,
V_{upper} : Maximum output voltage of the current transducer,
V_{lower} : Minimum output voltage of the current transducer,
I_{range} : Current transducer current measurement range,
I_{upper} : Maximum measured current magnitude,
I_{lower} : Minimum measured current magnitude,
$I_{sensitivity}$: Current transducer measurement sensitivity.

In addition to the digital filter described in Chapter 3, an analog RC low pass filter is implemented in the signal conditioning unit. The RC filter has a cut off frequency of 60 Hz for voltage and 2 kHz for current inputs. Frequency response of the analog filter for voltage signals is shown in Figure 4.3. As seen in this figure, the RC filter has -3dB magnitude at the frequency of 60 Hz, which is the cut-off frequency.

All supply voltages, which are necessary to power up the whole system, are generated by the DC/DC converters in the signal conditioning unit. Mini-PQ is powered by applying a +18 V_{DC} in the supply input and all voltage conversions are carried out by this supply. ADC unit requires $\pm 12V_{DC}$ for conversion, a 5 V_{DC} for analog processing and a 5 V_{DC} for digital processing. The DSP unit requires +5 V_{DC} and finally current transducers work by applying a 5 V_{DC}. Therefore, 5 different voltage converters are employed to generate all the required supply voltage for all units of the Mini-PQ.

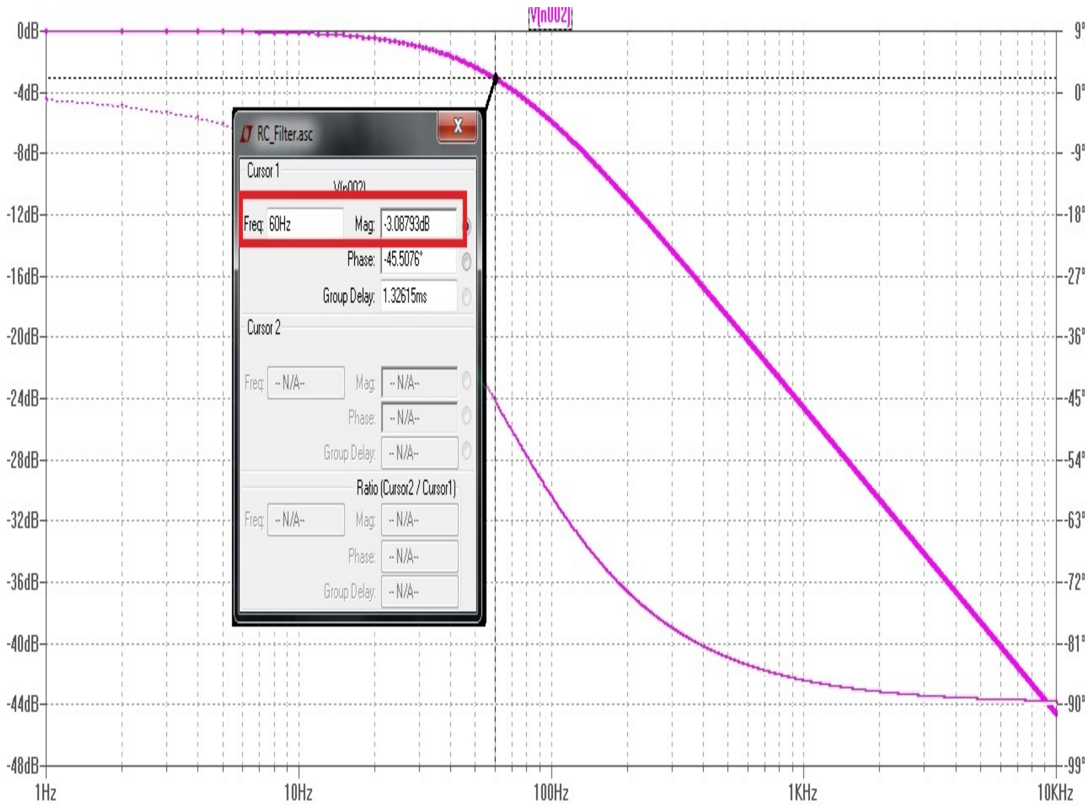


Figure 4.3: Frequency response of RC low pass filter

Mini-PQ includes a battery inside in order to backup supply voltage to provide adequate voltage during a possible voltage interruption and any short-duration voltage reductions. The +18 V_{DC} input supply charges the battery during normal voltage conditions. When an interruption or voltage reduction occurs, Mini-PQ is supplied by the battery power. Switching operation is performed by means of ORing method between supply and battery power. ORing method is based on using two Schottky diodes. Functional diagram of the battery charging and switching is given in Figure 4.4. As seen in the figure, the common power bus feeding DC/DC converter is supplied by the higher of 2 supplies, which are +18 V_{DC} input supply and battery power. Only the higher one is passed through the diodes to the output. The red line in Figure 4.4 indicates battery charging line during normal voltage conditions and battery feeds the DC/DC converters when input supply drops below the battery terminal voltage, which is shown as the green line in the figure.

Picture of the signal conditioning unit is shown in Figure 4.5

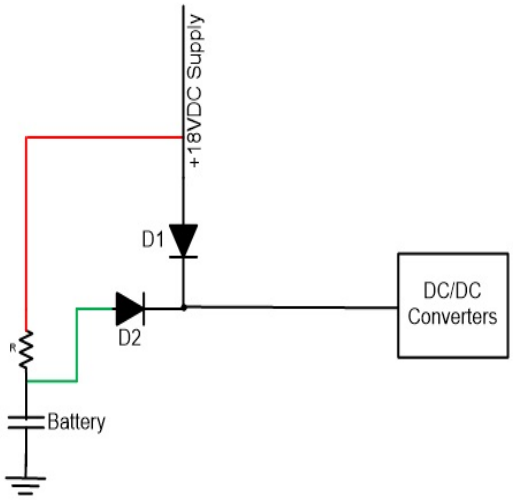


Figure 4.4: ORing and battery charging circuit

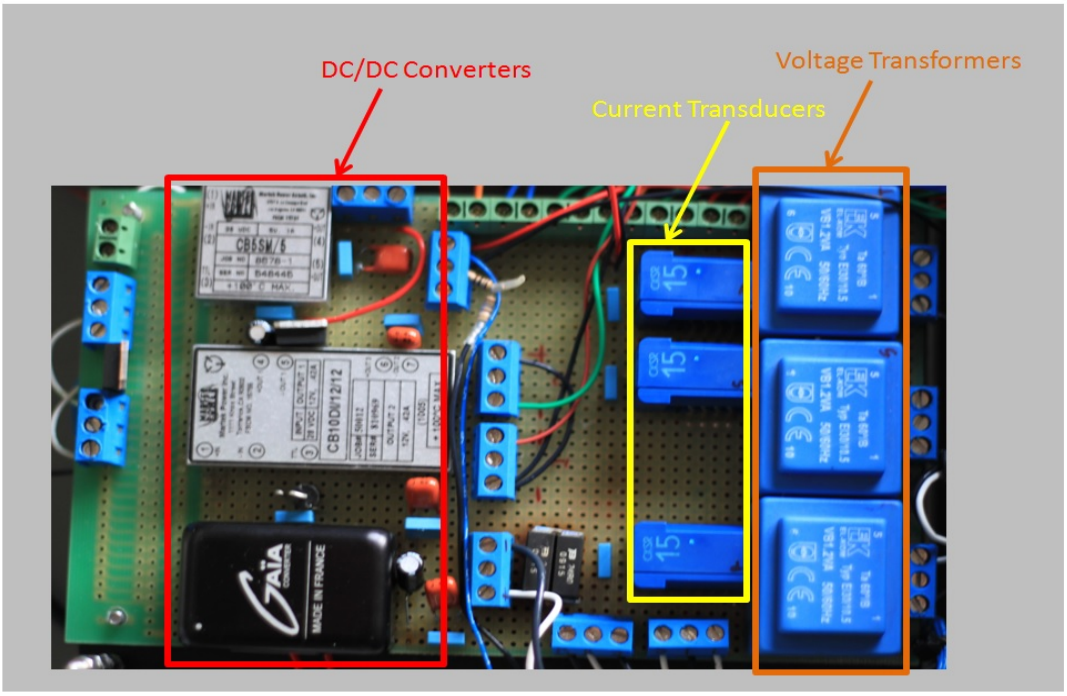


Figure 4.5: Signal Conditioning Card

4.2 Analog to Digital (A/D) Conversion Unit

Implementation of power-line systems requires monitoring current and voltage on three phases with A/D converters (ADCs). In order to meet the standard [5] requirements, these converters should be synchronized. It is ensured that the three phases are sampled at the same time by synchronizing the ADCs. Various ADC vendors offer simultaneous-sampling ADCs in a single package because it is often hard to synchronize individual converters manually.

If an ADC has a high input impedance (Z_{in}), voltage and current measurements can be directly fed via the interface of the ADC. High Z_{in} eliminates the need for additional precision buffers and amplifiers, thus providing small board area and consequently less cost. The relation for the input impedance of an ADC is given in equation 4.4

$$Zin = \frac{1}{Cin \times fsample} \tag{4.4}$$

where *fsample* is the sampling frequency and *Cin* capacitance is typically 15 pF.

A phase shift occurs in the output of the voltage transformer which is described in the previous section. Therefore, ADC should be capable of adjusting signal-phase digitally, which makes it preferable. Measurement of harmonic distortions in the current input requires at least a 16-bit ADC [43].

Because of the problems described above, AD7656 of Analog Devices [44] is selected as the analog to digital converter for Mini-PQ. One advised operation area of this ADC is power line monitoring systems [9]. The AD7656 is a 250 kS/S, 6-Channel, simultaneous sampling, bipolar ADC. It provides six analog input channels with 16-bit resolution and maximum data throughput rate up to 250 kS/S. It is also capable of handling the phase shift phenomenon. Six-channel analog input is divided into three groups since the device is used for three-phase systems. Channel-1 and 4 are used for V1 and I1, Channel-2 and 5 for V2 and I2 and Channel-3 and 6 for V3 and I3. Functional block diagram of AD7656 is provided in Figure 4.6

Main features of the AD7656 :

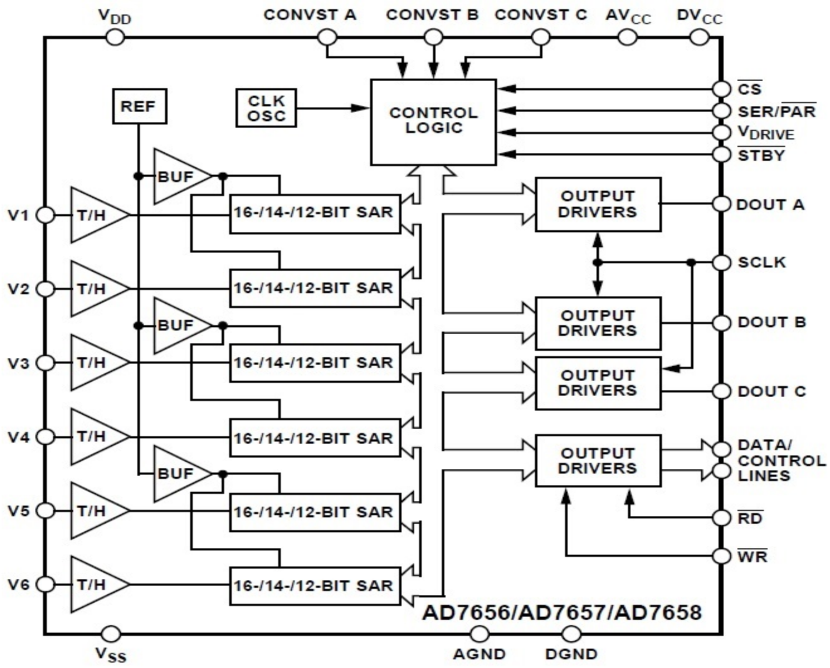


Figure 4.6: Functional block diagram of AD7656 REF

- Contains six 16-bit independent SAR (Successive Approximation Register) ADCs,
- Simultaneous sampling,
- Maximum data throughput rate up to 250 kS/s,
- High input impedance Z_{in},
- Wide input range $\pm$10V,
- High speed serial interface,
- Parallel, serial, and daisy-chain interface modes.

Rather than designing a Printed Circuit Board (PCB) for the A/D conversion unit, the evaluation board of AD7656 is purchased. The Analog Devices EVAL-AD7656 evaluation board (EVB) serves as the A/D conversion unit. The evaluation board consists of a 16-bit ADC, six pre-amplifiers and four EMC filters. Functional block diagram of EVAL-AD7656 is given in Figure 4.7

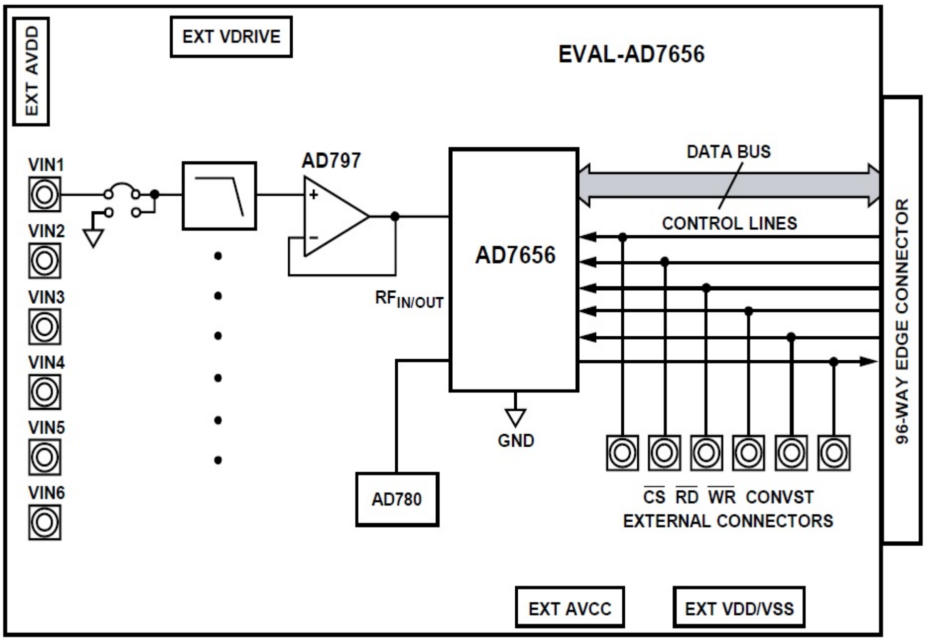


Figure 4.7: Functional block diagram of EVAL-AD7656 [8]

The output coding of the AD7656 is defined as 2's complement. The least significant bit size (LSBS) is given as in equation 4.5:

$$LSBS = \frac{FSR}{2^n} \tag{4.5}$$

where *LSBS* is the size of the LSB, *FSR* is the full scale range and *n* is number of bits which is 16 for the AD7656. LSB sizes and FSRs are given in Table 4.1 for different input ranges. The code transitions occur between integer LSB values, those are 1/2 LSB and 3/2 LSB. Finally the AD7656 ADC ideal transfer characteristic is given in Figure 4.8

Table 4.1: LSB size and FSRs for different input ranges

Input Range	Least Significant Bit Size	Full Scale Range
±10 V	0.305 mV	20V / 65536
±5 V	0.152 mV	10 V / 65536

Two interface options are offered by the AD7656: a serial interface and a parallel interface. Serial interface is preferred in Mini-PQ because of its high transfer rates

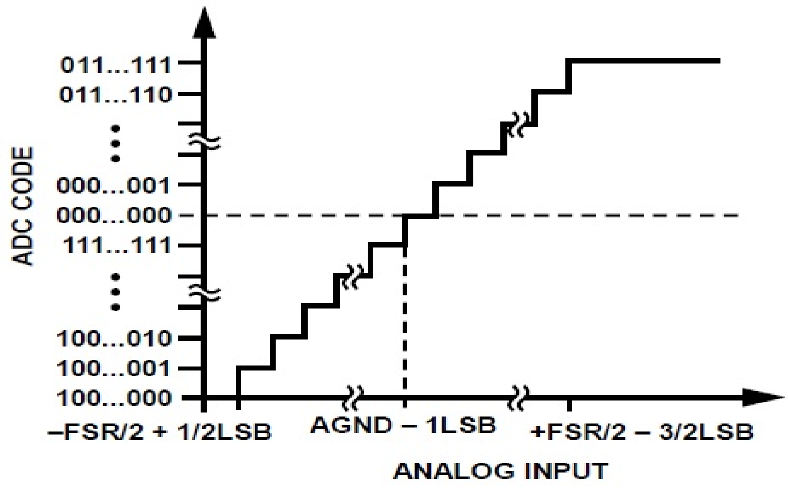


Figure 4.8: AD7656 Ideal transfer characteristic [9]

and compactness. The AD7656 sends output data via serial peripheral interface (SPI). This interface allows devices to communicate in master and slave modes, where the master device initiates the data frame. In this study, AD7656 serves as the slave whereas the digital signal processor (DSP) is used as the master device. The output data is read from the ADC by the DSP. Timing diagram for reading data from the AD7656 is shown in Figure 4.9. BUSY signal goes high after the rising edge of CONVST (Conversion signal) for conversion start indication. The BUSY signal returns low when the conversion is complete 3 μs later. Output registers of the ADC is loaded with the new results, and the data can be read from the AD7656. The input serial clock signal (SCLK) is the clock signal source for the serial interface. The chip select (CS) signal goes low to read data from the AD7656. Data is valid on the SCLK falling edge and 16 clock must be provided to the AD7656 to access each conversion result. The output data can be read from DOUT line.

A picture of the analog to digital conversion unit used in the Mini-PQ is shown in Figure 4.10

4.3 Digital Signal Processing Unit

Digital signal processors (DSP) are embedded systems for real time applications. The DSP must be supported by memory and interface hardware. Embedded systems,

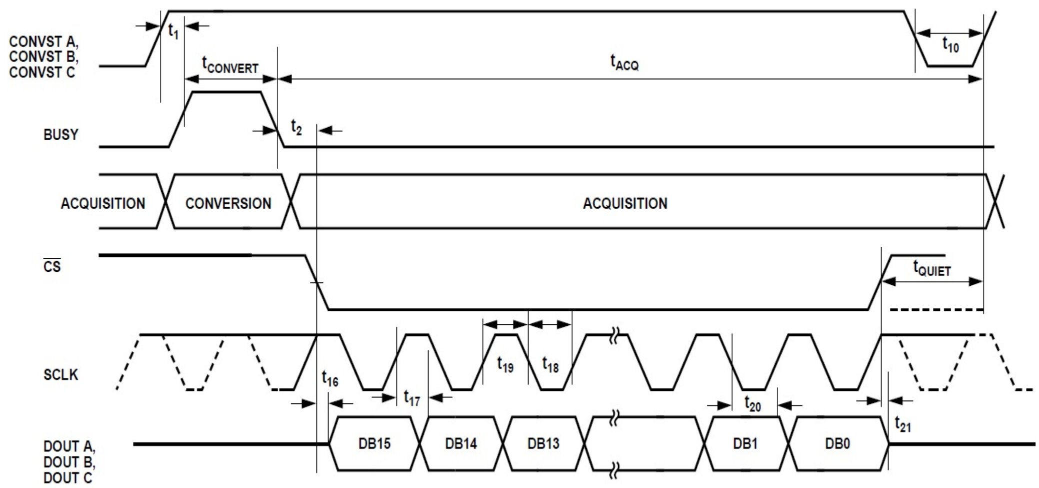


Figure 4.9: AD7656 Serial read operation [9]

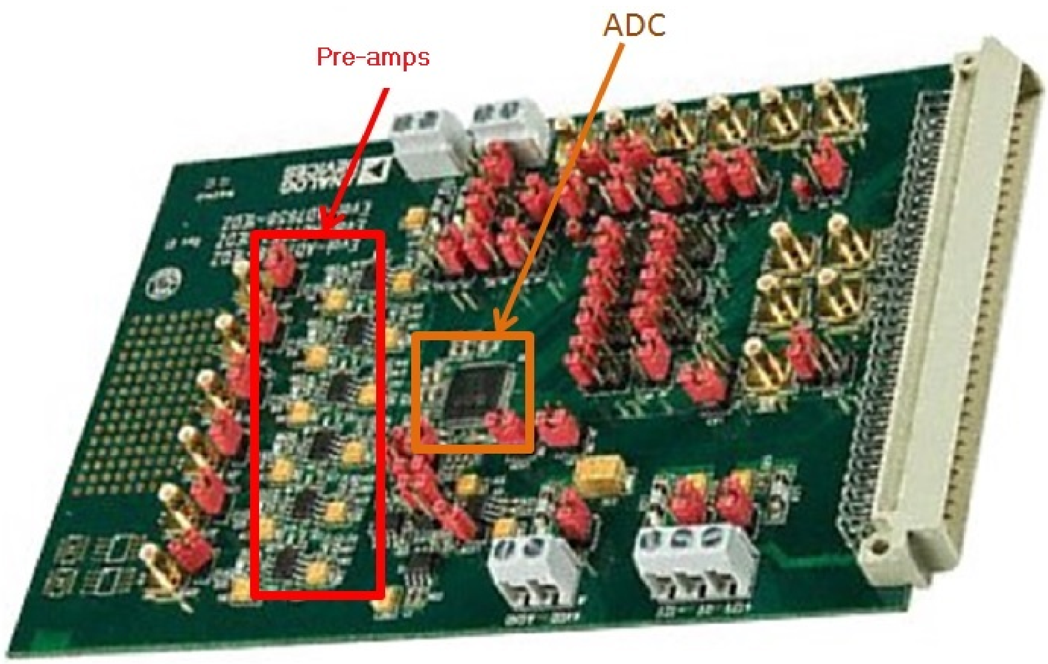


Figure 4.10: Analog to digital conversion unit

such as DSPs, provide high-performance for the real-time tasks. However, DPSs are system components hard to develop. They are used in various applications, such as image , speech and data processing etc REF [37]. The DSPs are advantageous for their properties of being software upgradable, low power consumption and low cost. Prior to selection of a DSP, the application must be thoroughly understood and system requirements must be assessed. The issues in selecting a DSP are [24]:

i) Computation speed: Speed performance of the DSPs can be compared by the time it takes to execute benchmark algorithms such as performance of Finite Impulse Response (FIR) filters and Fast Fourier Transform (FFT).

ii) Fixed Point versus Floating Point: For wide dynamic range applications floating-points DSPs are suitable. High cost is a major drawback. Although a fixed-point DSP cost less, provide lower dynamic range.

iii) Memory: If data are available on the fast memory or on static random access memory (SRAM), a DPS operates at the maximum throughput rate. Therefore, a DSP should have enough on-chip memory in order to store the input data buffer.

iv) Interface: Interface capability of the DSP is an important aspect for performance. The input/output (I/O) interface between an external device and the DSP should maximize the data transfer rate.

v) Ease of programming: Programming the floating-point DSPs are easier compared to fixed-point ones. If a DSP-based system is developed, choosing a floating-point DSP is a more reasonable choosing than fixed-point DSP.

vi) Real-time concerns: A timer is necessary for synchronization in real time systems. Therefore, a programmable on-chip timer is desirable when choosing a DSP. In order to handle non-synchronous tasks, interrupts are exploited.

vii) Cost: DSPs are generally expensive chips. However, in a complex system, they eliminate the need for a lot of external hardware. Functions of expensive external hardware are performed on on-chip software, thus reducing the cost of the whole system.

In the Mini-PQ, the DSP chip is used for:

- Driving the ADC chip, AD7656,
- Front-end data collection, pre-calculation and processing,
- Serial communication management,
- Data storage management.

The Mini-PQ needs to make fast accumulation and multiplication operations. In order to ensure the Mini-PQ to satisfy the desired functions and performance, Texas Instrument [45] TMS320C6747 DSP chip is used as the core processor chip, which is a floating-point processor and based on the very-long-instruction word (VLIW) architecture. The TMS320C6747 processor is an ideal choice for mathematical processing. It supports features that facilitate efficient high-level language compilers development [37].

Highlights of the TMS320C6747 [10] are:

- 300 or 200-MHz C6747 VLIW DSP,
- TMS320C674x Fixed/Floating-Point VLIW ,
- Enhanced Direct-Memory-Access Controller 3 (EDMA3),
- 128K-Byte RAM Shared Memory,
- Two External Memory Interfaces,
- Three Configurable 16550 type UART modules,
- LCD Controller,
- Two Serial Peripheral Interfaces (SPI),
- Multimedia Card (MMC)/Secure Digital (SD),
- Two Master/Slave Inter-Integrated Circuit,
- One Host-Port Interface (HPI) (C6747 only),
- USB 1.1 OHCI (Host) With Integrated PHY(USB1)

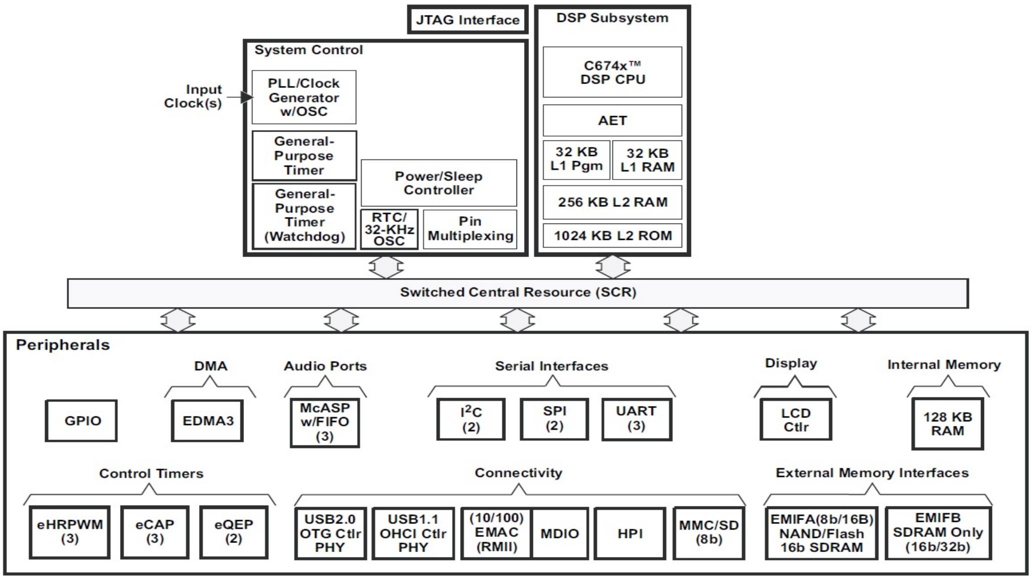


Figure 4.11: Functional block diagram of TMS320C6747 [10]

Functional block diagram of TMS320C6747 is shown in Figure 4.11

The Mini-PQ architecture makes use of the Spectrum Digital OMAPL137 evaluation module (EVM). OMAPL137 is a Texas Instrument device with a C6747 VLIW DSP floating point processor and an ARM926EJ-S processor. The EVM achieves full complement of on-board devices which are suitable for a wide variety of application environments. It comes with all necessary hardware and software tools for real-time processing, including the Code Composer Studio (CCS). The EVM is designed to work with Texas Instrument (TI) CCS with the board through a JTAG (Joint Test Action Group) emulator which is on board.

Key features of the EVM are[11]:

- A Texas Instruments OMAP-L137 device with a C674x VLIW DSP floating point, processor and an ARM926EJ-S processor operating up to 300 Mhz.,
- 64 Megabytes SDRAM,
- SPI Boot EEPROM,
- 2 Port Ethernet Physical/switch,
- Secure Digital (SD)/ Multimedia Card (MMC)/MMC Plus media card inter-

faces,

- TLV320AIC3106 Stereo Codec,
- USB 1.1 High speed interface,
- USB2 2.0 Full speed interface,
- RS-232 Interface,
- On chip real time clock,
- Configurable boot load options,
- 4 user LEDs/4 position user DIP switch,
- Single voltage power supply (+5V),
- Expansion connectors for daughter card use,
- Embedded JTAG Emulation,
- 14 Pin TI JTAG/20 Pin ARM JTAG Interfaces

Using OMAP-L137 EVM, containing all these listed features is much more practical than designing a new PCB.

Block diagram of OMAP-L137 EVM is given in Figure 4.12

The Mini-PQ collects the 9-s data via the six input channels. As stated before in Chapter 3, sampling frequency is 1.5 kHz and ADC sends the data in 16-bit format. The data size (DS) of the output data in a 9-s data block can be evaluated as:

DS = 9-s x 1500 (samples / s) x 6 channel x 16 bit = 1,296,000 bit.

After conversion of the DS to bytes, taking 1 byte as 8 bits, DS becomes 162000 bytes. This data size is too long to save in the DSP internal memories. Therefore, one of the two SDRAMs on the EVM should be used for this purpose. The EVM uses two 16-bit, 256-Megabit memories on the SDRAM bus which is a dedicated 32 bit wide memory bus. In order to control the SDRAM memory timing, the internal SDRAM

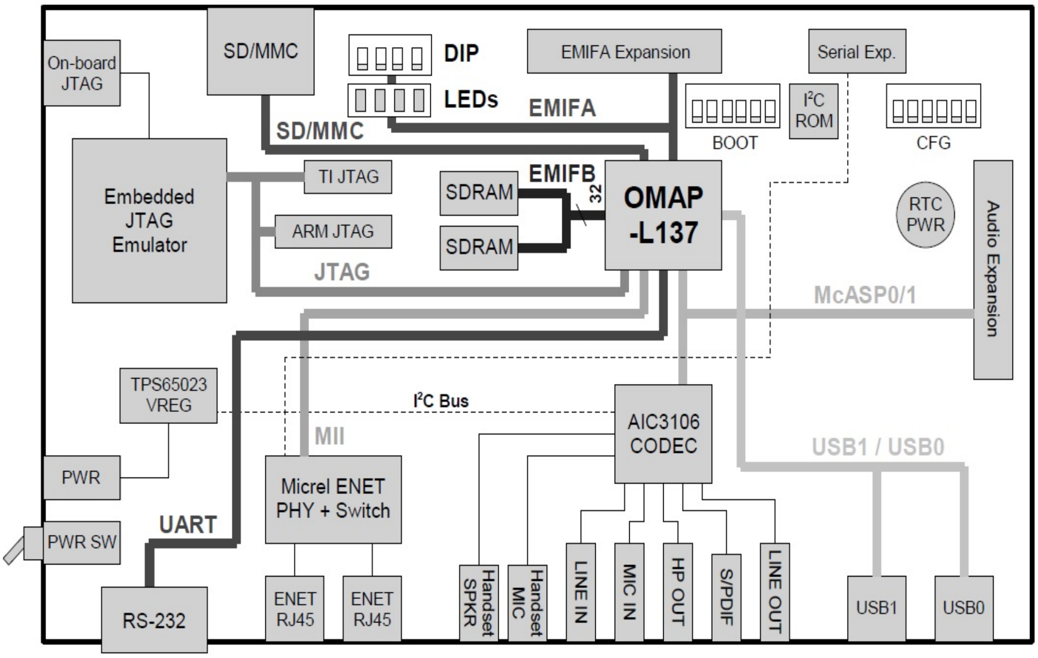


Figure 4.12: Block diagram of OMAP-L137 EVM [11]

controller uses a PLL (phase locked loop). The OMAP-L137 internal SDRAM controller handles automatically memory refresh for the SDRAM. EMIF-B is used for the SDRAM memory interface, see Figure 4.12.

The AD7656, which is described in the previous section of this Chapter is interfaced directly to the SPI1 port of the TMS320C6747. General purpose input/output (GPIO) pins are also used to drive the ADC, which are sent through EMIF(External Memory Interface)A-4 and EMIF A-6 pins of the DSP. Communication between the PLC modem or PC is facilitated through a serial interface between UART1 port on the DSP.

Picture of the digital signal processor unit is shown in Figure 4.13

4.4 Power Line Communication Modem

Local area network (LAN) is normally used as a method for investigating the status of PQ monitoring devices [15, 23, 27, 28, 19]. To establish a new LAN is a difficult process in buildings which are already equipped. It is a high cost process, as well.

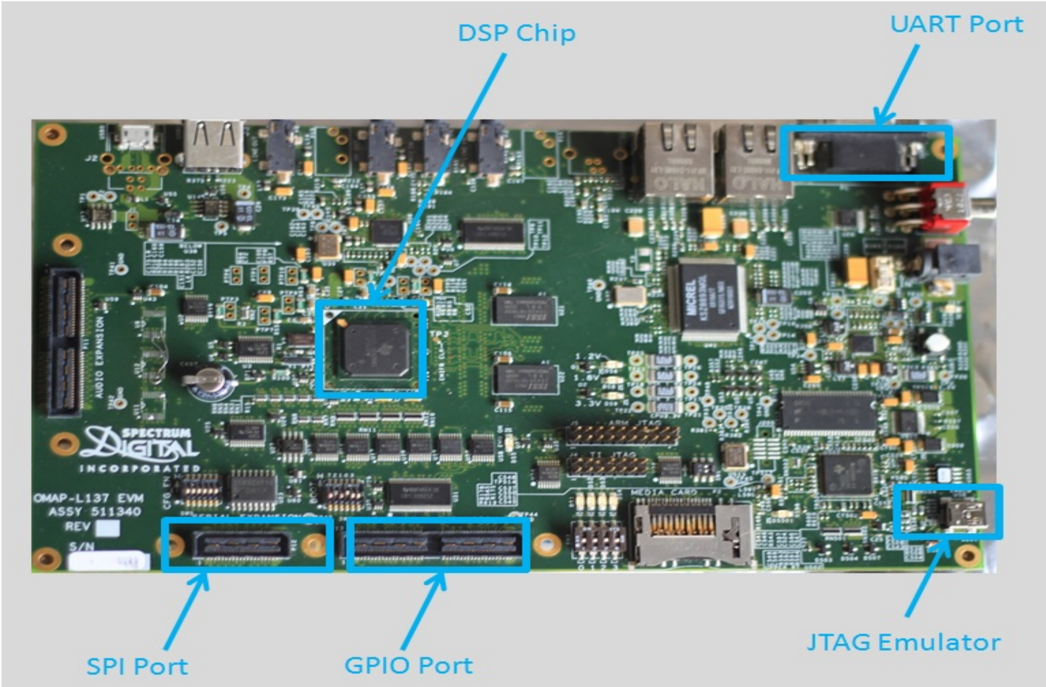


Figure 4.13: Picture of the digital signal processor unit

Power Line communication (PLC, also called BPL in the USA, where the acronym stands for Broadband over Power Line, or NPL, Narrow band over Power Line) is a communication technology which uses power lines as the communication medium. Since the same wires are used for communication and power distribution, the need of new establishing costs for data network are eliminated by using the existing power lines. In order to operate PLC systems, a modulated carrier signal is added to the existing wiring system. The PLC can transmit data easily everywhere electricity is used without any additional installing of communications, and also it has an advantage of convenience to change the measurement sites to measure the status of power [46].

A typical communication system contains four major components:

- 1. Receiver,
- 2. Transmitter,
- 3. Communication medium,
- 4. The signal.

In PLC, the communication medium is the power line, as mentioned before. A block diagram for a typical power line communication system is given in Figure 4.14. The signal is modulated and injected into the power line. At the end of the power line link, the signal is demodulated and retrieved by the receiver. Due to the nature of power-line channel, it is not suitable for applications which requires high data transfer rates, such as controlling applications. However, it is an applicable and cost-effective way of data transfer for monitoring purposes [47].

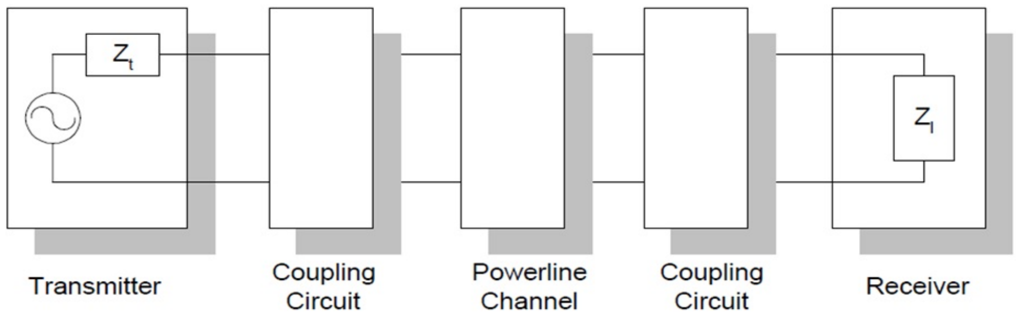


Figure 4.14: Block diagram of a powerline communication system

While the signal travels to the receiver through the power line, the impedance of the power line attenuates the signal. Also, any noise in the medium corrupts the transmitted signal. The noise in the power line is generated due to all loads connected to the grid. In addition to this noise, broadcast radio signals interfere with the power line. The integrity of the signal is dependent upon the amount of the noise on the power line, hence as noise level increases, data corruption rate on the line increases, as well. Noise on the line can be investigated in two types [12]: continuous and impulse noise. Impulse noise is unpredictable and occurs in burst sequence. Thus it is difficult to design a system that can tolerate impulse noise without compromising its data rate. On the other hand, continuous noise has more predictable characteristics. It is usually a function of the power line installation quality. An example for a continuous and an impulse noise is shared in Figure 4.15.

The power-line is often considered as a harsh environment due to time-varying noise and attenuation characteristics. As a result, only limited performance can be achieved on the PLC. The reason causing poor characteristics of the PLC in terms of noise robustness and attenuation is that, the power line channel has not been designed to carry data on the electrical energy [48].

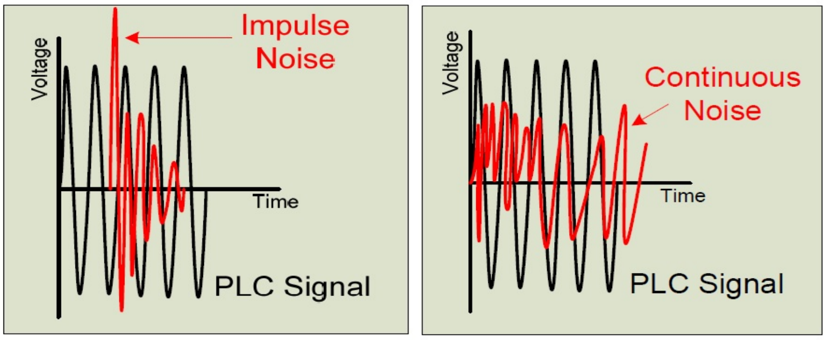


Figure 4.15: Impulse and continuous noise types on the power line [12]

Signal attenuation is the most limiting parameter when low-voltage power cables are investigated in terms of data transfer of the power line. The maximum data transfer distance is determined by the signal attenuation. Another considerable parameter is the electromagnetic wave propagation speed that is determined at high frequencies by insulation material's electromagnetic characteristics. The interface of the power line is designed as a band pass filter which has a pass band at the carrier signal frequency. Node conditions of the power line are required to be examined in order to solve the voltages and the currents in each node on the transmission line. Impedance and sources of all loads must be modeled to get satisfactory PLC performance. Since the phases are dependent to each other, impedance and source modeling problem becomes challenging.

In addition to noise on the power line, other disturbance sources exist. For instance, the intersymbol interference (ISI) occurs due to the low-pass behavior of the power line channel, which smooths the very rapid fronts of the digital information. Increasing the bit rate is not suitable because of the ISI, as shown in Figure 4.16

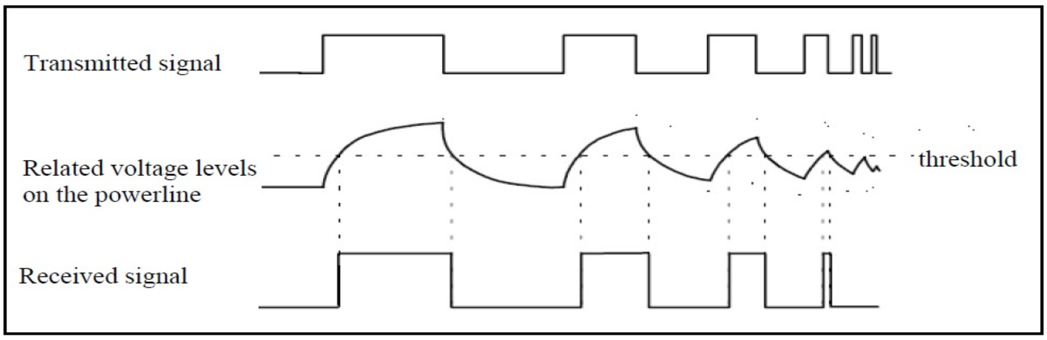


Figure 4.16: The intersymbol interference (ISI)

In European countries, PLC modems use CENELEC (French: Comite Europeen de Normalisation Electrotechnique; English: European Committee for Electrotechnical Standardization)-standardized frequency band. The European PLC regulation norm is called CENELEC EN 50065-1: "Signalling on low-voltage electrical installations in the frequency range 3 kHz to 148.5 kHz."[2]. It defines the allowed frequency ranges of power-line communication, maximum signal amplitudes, as well as the limits of the interference to the surrounding frequency bands. The frequency range division is shown in Table 4.2

Table 4.2: Frequency range limits [2]

Band	Frequency range	Purpose
	3 kHz - 9 kHz	for electric distribution companies use only
A	9 kHz - 95 kHz	for electric distribution companies use and their licenses
B	95 kHz - 125 kHz	available for consumers with no restriction
C	125 kHz - 140 kHz	available for consumes only with media access protocol
D	140 kHz - 148.5 kHz	available for consumers with no restriction

As seen in Table 4.2, the standard allows frequencies between 3 kHz and 148.5 kHz. This causes a restriction on power line communications and is not enough to support high-bit-rate applications. Maximum output levels in the range from 9 kHz to 150 kHz for a single-phase-device is shown in Table 4.3. As stated before, the US FCC (The United States Federal Communications Commission) Part 15 defines the available range of frequency much wider because in the US the LW (Long Wave) radio transmission range is not used. North America vs. European regulation in the area of PLC is given in Figure 4.17.

Table 4.3: Frequency range limits [2]

Frequency range	Maximal transmission level	Type of devices
3 kHz - 95 kHz	134 dB (μV)	
95 kHz - 148.5 kHz	116 dB (μV)	general purpose devices
95 kHz - 148.5 kHz	134 dB (μV)	special devices (such as industry applications)

A PLC modem executes the following operations:

- Send the packet structure,

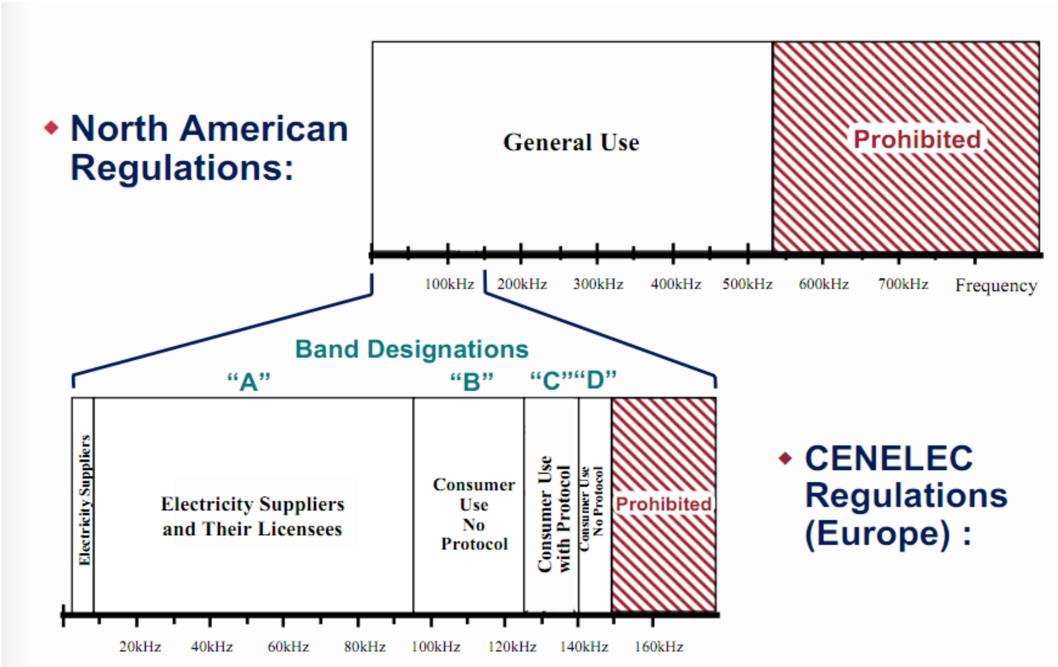


Figure 4.17: North America vs. Europe regulation in the area of PLC REF

- Level converting to allow communication with PC in RS232,
- Transmission of the data through power line.

In the Mini-PQ, UPLM-M16 PLC modem is used which is purchased from UDEA [49] company including RS232 interface. The UPLM-M16 does support the European CENELEC A or B band standard. Only external component have to be modified to adapt to the selected standard REF. UPLM-M16-A for the CENELEC A band is used in the Mini-PQ.

Technical features of UPLM-M16 [3]:

- Modulation : DCSK (Differential Code Shift Keying)
- Frequency A : 3 kHz – 95 kHz
- Frequency B : 95 kHz – 125 kHz
- Data Rate PLC : Max. 2.5 kbps – Min. 0.62 kbps
- Network ID : Max. 1023

- Node ID : Max. 2047
- Communication Port : RS232
- Data Rate Communication Port : 9.6 kbps
- Protocol : Proprietary udea
- Supply : 220 VAC

In the modem, to connect the communication system to the power line a coupling circuit is used. The aim of the circuits is two-fold. Firstly, it prevents damaging 50 Hz signal used for power distribution, to enter the equipment. Secondly, it certifies that the major part of the received/transmitted signal is within the frequency band used for communication. This guarantees that the transmitter introduces no interfering signals on the channel. The modem enables extremely robust communication over the existing electrical wiring.

The modem uses YITRAN IT800 as PLC modem chip, which is a highly integrated SoC (System on a Chip) modem. It provides an ideal solution for a variety of applications and supports the implementation of various protocols. The PLC modem general scheme based on YITRAN IT800 is shown in Figure 4.18.

Application circuity in Figure 4.18 is part of the Application Subsystem. It implements specific applications, providing the user interface for the device. Host is also part of the application subsystem. It is implemented using a general-purpose microcontroller. It also provides an interface allowing the device application to communicate with the IT800D over the UART host interface. IT800D handles the entire communication over the line in addition to handling the channel access on behalf of the device. Analog front end and line coupler is between the IT800D and the physical network. It connects the device to the power line with amplification and filtering. Finally, the line coupler couples data to the power line. A picture of the modem is given in Figure 4.19

The modem uses ASCII (American Standard Code for Information Interchange) coding to send the data on the power line. MAC (Media Access Control) command frame of the modem is given in Table 4.4. As seen in the table, the command "Send Data"

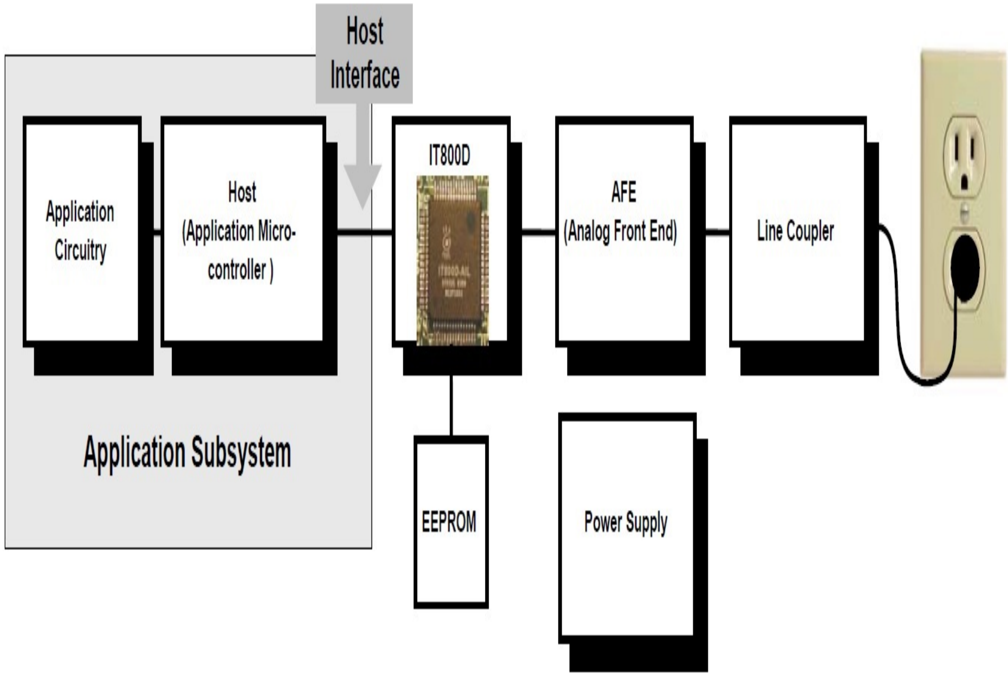


Figure 4.18: The PLC modem general scheme based on YITRAN IT800 [13]

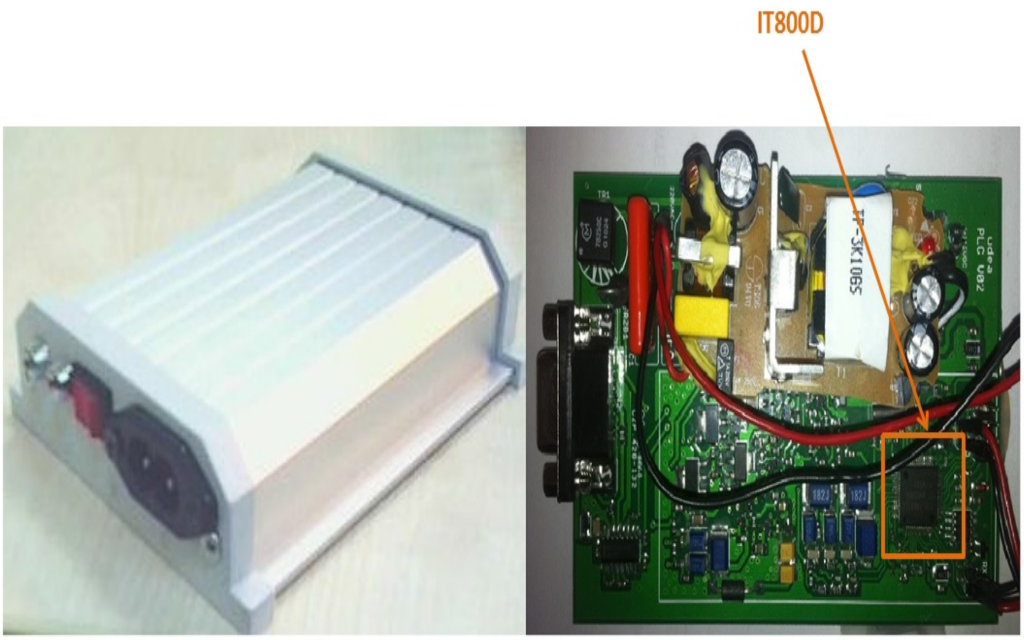


Figure 4.19: The PLC modem outside (left) and inside (right) view

should start with the character B following by the destination identity of the receiver modem. After placing data stream in the command frame, data package is finished by placing the characters 0D to the end of the data.

Table 4.4: MAC Command Frame of the PLC Modem [3]

COMMAND	COMMAND FRAME	FUNCTION
ID command	<C> <NIDXXXX> <$0D>	C: command header NIDXXXX: network ID (XXXX = 1 – 1023) $0D : enter code
	<C> <SIDXXXX> <$0D>	C: command header SIDXXXX: source node ID (XXXX = 1 – 2047) $0D : enter code
Transmission commands	<C> <TXR1><$0D>	C: command header TXR1 : auto transmission rate $0D : enter code
	<C> <TXR2><$0D>	C: command header TXR2 : rate is robust 2.5kbps $0D : enter code
	<C> <TXR3><$0D>	C: command header TXR2 : rate is exterme robust 0.625kbps $0D : enter code
Transmission mode command	<C> <EACK><$0D>	C: command header EACK : Enable ACK Mode $0D : enter code
	<C> <DACK><$0D>	C: command header DACK : Enable NACK Mode $0D : enter code
Send data commands	<D> <DID> <SEND DATA STREAM><$0D>	D: Unicast transmit for command header DID : destination node ID (0001 – 2047) SEND DATA STREAM : send data max 120 char $0D : enter code
	<B> <DID> <SEND DATA STREAM> <$0D>	B: Broadcast transmit for command header DID : destination node ID (0001 – 2047) SEND DATA STREAM : send data max 120 char $0D : enter code
	<C><EACK><$0D>	EACK: Enable ACK mode
	<C><DACK><$0D>	DACK: Enable NACK mode
User command	<C><k><$0D>	NID, SID and DID show
	<C><h><$0D>	All parameters is show

Due to the fact that the data rate of the power line communication is limited in the Turkish Distribution System, small-size data can be transferred. The sources of the data rate limitations are described in this section. In field applications, the maximum data rate is measured as 700 bps (bits per second) by the manufacturer of the modem, UDEA company. Performance and reliability of a PLC system is affected by several factors as stated previously. These factors are:

- Noise on the powerline,

- Powerline network's impedance,
- Protocol of the network,
- Sensitivity of the receiver,
- Signal strength of the transmitted signal.

Due to the slow data rate and ASCII coding of the modem, the Mini-PQ cannot send all obtained PQ parameters. When in minimum mode, the Mini-PQ sends the data only when an event or disturbance occurs. When there is no event or disturbance on the power line, the Mini-PQ sends a message which is defined as NORMAL to the PQ++. During a voltage interruption, there is no voltage signal on the power line, which means there is no signal to measure. Therefore, power required for Mini-PQ is supplied by the battery during the interruption and the Mini-PQ holds the track of the interruption duration. It does not send data via power line during the interruption. The Mini-PQ stores the interruption duration into the SDRAMs which are placed on the signal processing unit. When the line voltage appears again, before making calculations, the Mini-PQ sends the duration of the voltage interruption to the PQ++.

PQ parameters which are obtained by the Mini-PQ are mapped to ASCII code. That means, each result is mapped to a symbol represented in ASCII table. This mode of the Mini-PQ is already named as minimum mode at the beginning of this chapter.

An operator in the DSO, which is shown in Figure 2.10, is assuming to be following the PQ parameters. When a long duration PQ event is realized, which is determined by the Mini-PQ, the operator saves the ID number of the Mini-PQ. In order to detect the problem in detail, the operator goes nearby the Mini-PQ and follows the detailed PQ parameters via serial communication port of it. This serial communication mode is also named as maximum mode as stated at the beginning of this chapter, as well.

In summary, in this chapter, hardware design of the Mini-PQ and implementation of power line communication modem has been described in detail. Firstly, hardware components are summarized and visuals of each component are shared. In terms of hardware, The Mini-PQ consists of a signal-conditioning unit, an A/D conversion unit, a digital signal processing unit and a PLC modem. These units are shown in Figure 4.20 all together in the Mini-PQ as a rear view.

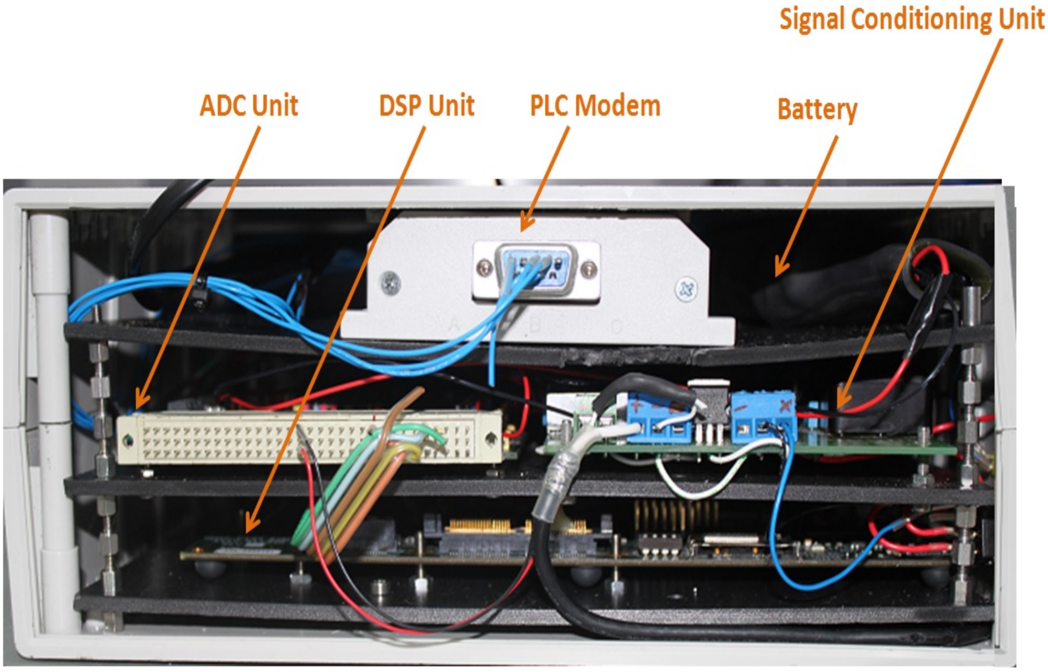


Figure 4.20: Units of the Mini-PQ

A case has been designed specifically for the Mini-PQ. Analog input ports of the Mini-PQ is shown in Figure 4.21, as seen in this figure it has three current inputs, three voltage inputs and one input for neutral. The Mini-PQ has switches and LEDs on it to be controlled by an operator. As shown in Figure 4.22, there are two switches and three LEDs on the case. The Red LED indicates that the Mini-PQ is supplied by a +18V_{DC} supply. A/D conversion unit is controlled by the switch-1, when the switch is turned to ON position, the yellow LED is light and this means A/D conversion unit is in operation. The DSP unit is controlled by the switch-2, when this switch is turned to ON position the green LED is light and the DSP unit starts to operate. The Mini-PQ is programmed through the program port of it on the case.

Final front and rear views are shown in Figures 4.23 and Figure 4.24.

Figure 4.21: Analog input ports of the Mini-PQ

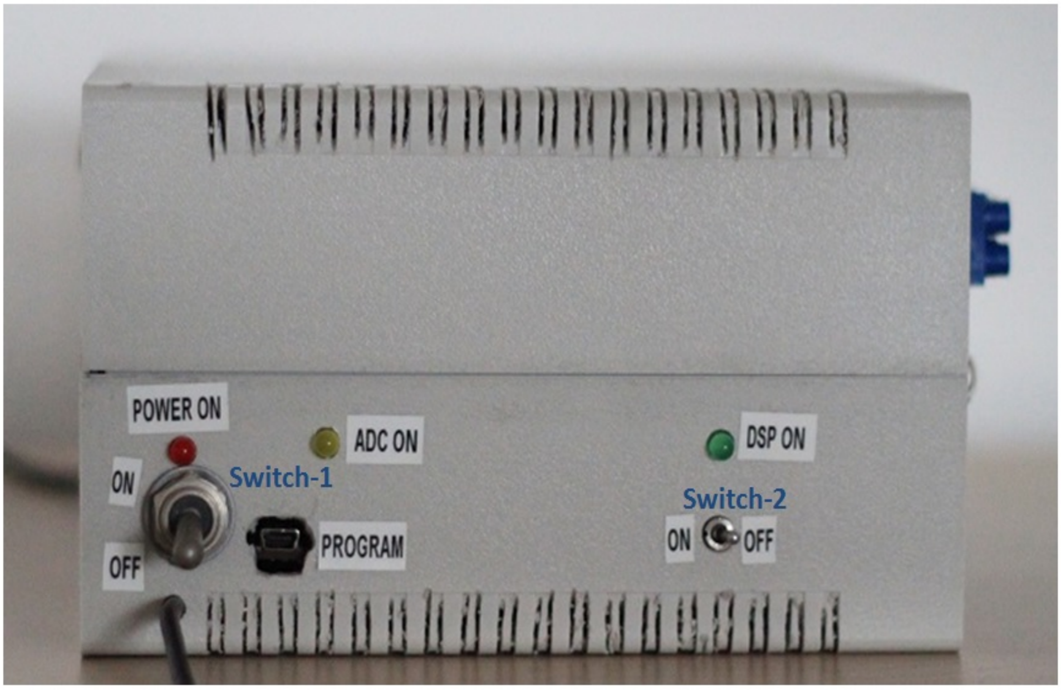


Figure 4.22: The Mini-PQ's switches and LEDs

Figure 4.23: Front View of the Mini-PQ

Figure 4.24: Rear View of the Mini-PQ

CHAPTER 5

SOFTWARE AND INTERFACE DEVELOPMENT

Design of software in this thesis is composed of two parts: Digital signal processor (DSP) program and user application software (interface program between the Mini-PQ and PQ++), which is planned to run on the PQ++ computers in the PQ management center illustrated in Figure 2.10 in section 2.3. The DSP program implements data acquisition and raw data processing, transferring data between the Mini-PQ and the PQ center tasks. The user application program displays and stores the PQ parameters in the PC. As stated in Chapter 4, the Mini-PQ has two operational modes: minimum and maximum modes. Software are designed separately for each of these modes, in other words, a DSP program and an interface program are designed for each individual mode. In maximum mode, Universal Asynchronous Receiver/Transmitter (UART)-DSP program and UART-Interface programs run, whereas in the minimum mode, Power Line Communication (PLC)-DSP and PLC-Interface programs run. If the PLC modem is connected, the Mini-PQ sends the reduced-size data and the PQ++ at the PQ center accepts this data to display on the screen and stores it into a hard drive. In the case of serial port usage (maximum mode) instead of a PLC modem, the Mini-PQ sends detailed PQ parameters and the upper PQ center accepts the data to display and store them.

5.1 DSP Software Design

In the Mini-PQ, a real-time environment is developed by using a mixture of C and assembly languages. The current and voltage waveforms are sampled in the Analog to Digital (A/D) conversion unit and processed in the TMS320C6747 DSP processor. The measurements, which are described in Chapters 3 and 4, are realized by the DSP. Besides that, driving ADC (Analog to Digital Converter) and data transferring to the upper PQ center are implemented by the DSP. The DSP software is designed in C language in The Code Composer Studio (CCS) environment, which is developed by Texas Instruments. The CCS provides a complete environment to obtain PQ parameters in the DSP. The operator may observe input signal and perform signal analysis in the main dialog of the CCS. Real-time analysis of the input signal is easy to perform by using CCS [25]. A snapshot for the CCS is show in Figure 5.1.

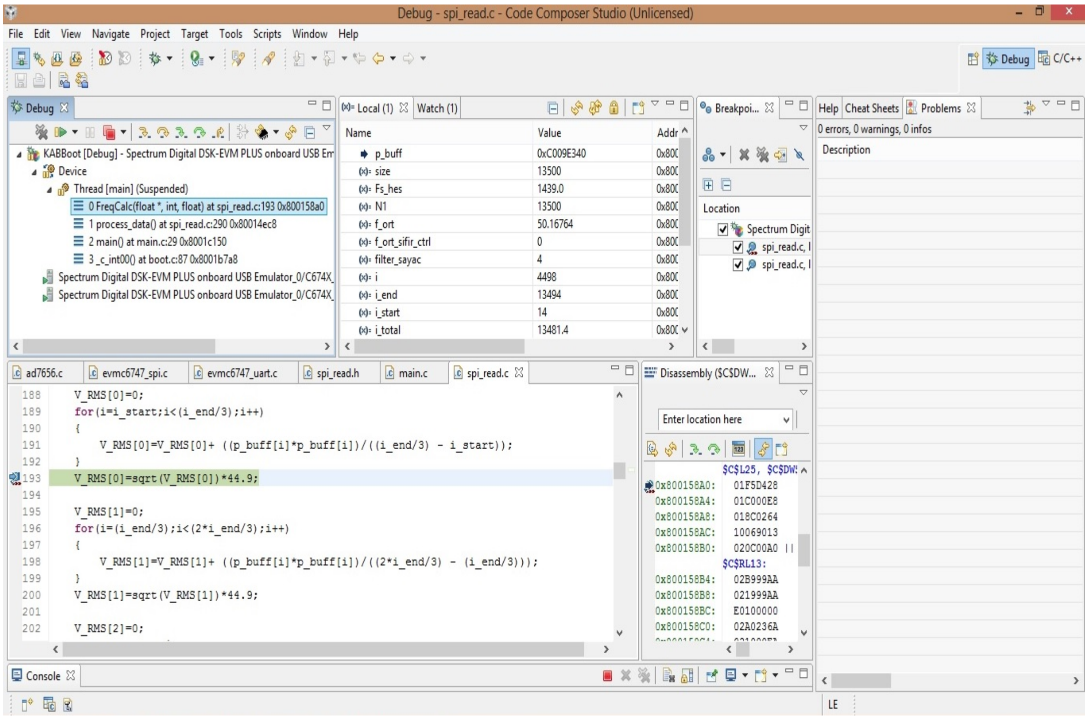


Figure 5.1: A snapshot for Code Composer Studio (CCS) with the DSP codes running.

Main features provided by the CCS are:

- Integrated code development environment,
- Software tools for code generation such as C language compiler and assembler,
- Graphical capabilities,
- Real-time debugging support.

The DSP software is designed to fulfill the tasks which are to perform all the codes, to capture the data coming from the ADC, to measure the PQ parameters and to send the data via PLC or serial communication port. The DSP program consists of the initialization of the whole system, interrupts for data acquisition, data processing, parameter calculation and communication. Firstly, in a timer interrupt the DSP program reads the sampled data from the ADC unit. After the required size of data acquitted, the DSP program computes power frequency, amplitudes of the voltages and currents, phase angles, active-reactive and apparent powers, voltage interruption based on the developed algorithms, which are described in Chapter 3. Meanwhile, another buffer is filled by using the timer interrupt with sampling frequency. While one buffer is processed the other buffer is filled with data by the help of interrupts and the system goes on. Block diagram of the DSP program is given in Figure 5.2.

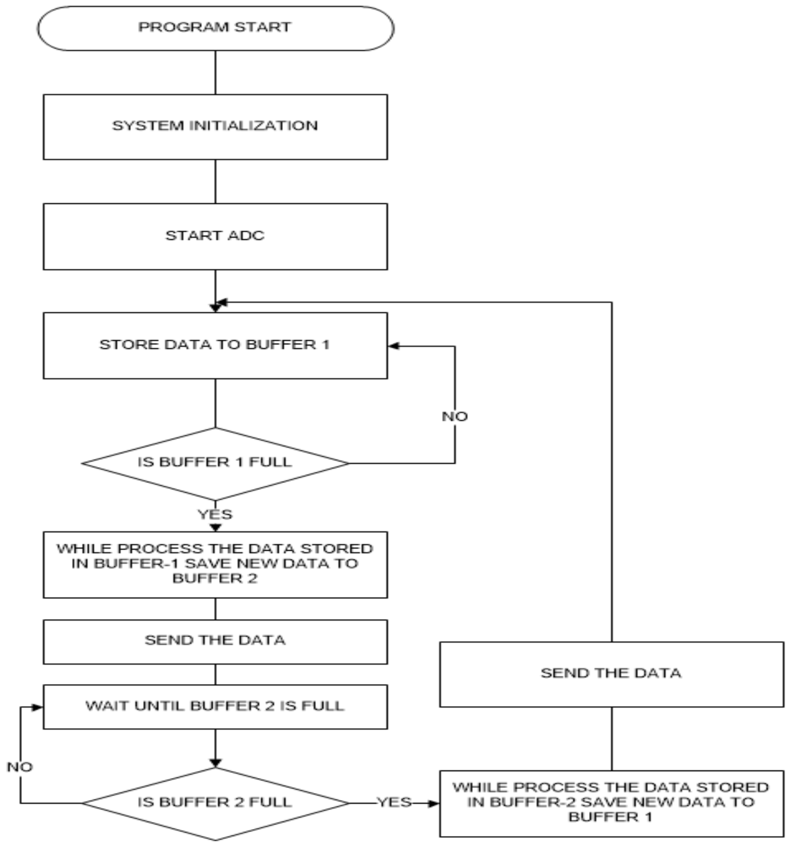


Figure 5.2: Block diagram of the DSP program.

Firstly, the DSP initializes the sub-systems such as central processing unit (CPU), serial peripheral interface (SPI), serial communication interface, interrupts, external devices and data acquisition. Secondly, the DSP starts the AD7656 (ADC) to save the sampled data. Timing diagram for the AD7656 is described in Chapter 4. All timing requirements to drive the ADC unit are set by the DSP via SPI and GPIO (General Purpose Input Output) ports. In order to communicate with a PLC modem or through serial port, the DSP performs corresponding communication protocols. The DSP uses UART protocol for serial communication.

As stated before, DSPs are used in real-time system designs. Real-time systems need to perform calculations in a certain amount of time, in other words, the DSP must finish processing before the fresh data becomes available. A DSP is not capable of performing parallel computations, therefore an interrupt based architecture should be used in the DSP in order to guarantee that no data is lost during computations. The DSP cannot read new data during computations from the ADC unless an interrupt is set . As a result, in the DSP program a multiple-buffering system which is known as ping-pong buffer is designed. Implementation of the ping-pong buffer is shown in Figure 5.3. Firstly, the read data stored into the ping buffer till this buffer is full, then, the DSP starts to implement ping buffer data. Meanwhile, the fresh data is pumped into the pong buffer in the background. The DSP finishes the processing of the ping buffer data before the pong buffer is full. When the processing is finished, the roles of the buffers are switched.

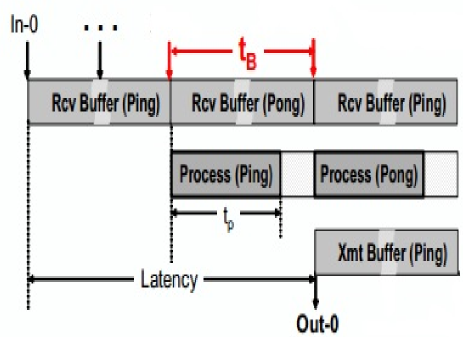


Figure 5.3: Implementation of ping-pong buffer [14]

In the Mini-PQ, two 9-s length buffers are employed to implement multiple-buffering system. At system start, the DSP controls whether Buffer-1 is full or not while interrupts in the DSP fills the buffer. When the Buffer-1 is full, a flag is created and it starts to save the new data into Buffer-2. While new data are stored into Buffer-2, the DSP processes the data in Buffer-1. Processing time for a data of one buffer length is shorter than the length of the individual buffer; therefore, no data loss is experienced. After finishing processing the data in the Buffer-1, the DSP again controls whether Buffer-2 is full or not. When Buffer-2 is full, a flag is created and it starts to save the new data into Buffer-1, and the process goes on.

5.1.1 DSP Design for Maximum Mode

In the maximum mode, the DSP and upper PQ center communicates via serial port, that is RS-232 port. The DSP opens UART1 port in 9600 bps (bits per second) data rate which is enough to send detailed PQ parameters. After 9-s calculations, the DSP sends one frequency value, which is measured in the reference channel. For each channel three Vrms, three Irms values are also sent by the DSP. In addition to these, phase angles are sent for Channel-1 (voltage) and 4 (current), Channel-2 and 5, Channel-3 and 6, separately, as well. Block diagram for the maximum mode of the Mini-PQ is shown in Figure 5.4.

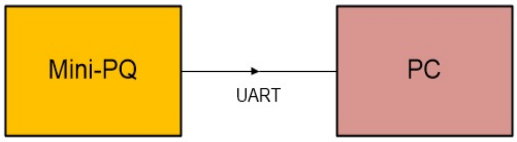


Figure 5.4: Block diagram for the maximum mode of the Mini-PQ

The main function of the Mini-PQ is monitoring the PQ on the power line. Therefore, it has to detect events and disturbances on the power line. In order to achieve this aim, limits which are described in EN50160 standard [1] and shown in Table 2.1 in section 2.2 are defined as thresholds in the DSP software. Calculated PQ parameters are compared with these thresholds. After the comparison, the DSP decides whether an event or disturbance occurred or not. If there are no events or disturbances occurring on the line, the DSP sends a NORMAL message to the PC. If the DSP detects an event or a disturbance, it sends the type of characteristics of event or disturbance to the upper PQ center. For instance, in Table 2.1 supply voltage variation limit is defined as $\pm$ %10 for a week. In Turkey, low voltage electric grid supply voltage has a magnitude of 220 Vrms. If the supply voltage decreases below its % 10 nominal value, that is 198 Vrms, the DSP sends an under voltage error message to the upper

PQ center.

5.1.2 DSP Design for Minimum Mode

In the minimum mode, the DSP performs all calculations similar to the maximum mode. However, it does not send detailed PQ parameters due to PLC limitations, which are described in Chapter 4. After 9-s of calculations, six channel parameters are send to the upper PQ center. The Mini-PQ executes its main function, that is PQ monitoring, when operates in the minimum mode. The DSP makes comparison with respect to the EN50160 standard and maps the results to the ASCII table. For example, if everything is normal on Channel-1, the Mini-PQ sends a message which is actually the character "N". It does not send the actual value of the channel voltage. If the Mini-PQ detects a frequency deviation, it classifies the deviation. If frequency is below its 1% value, the Mini-PQ sends a character "A" message, which means under frequency error. Block diagram for the minimum mode of the Mini-PQ is shown in Figure 5.5.

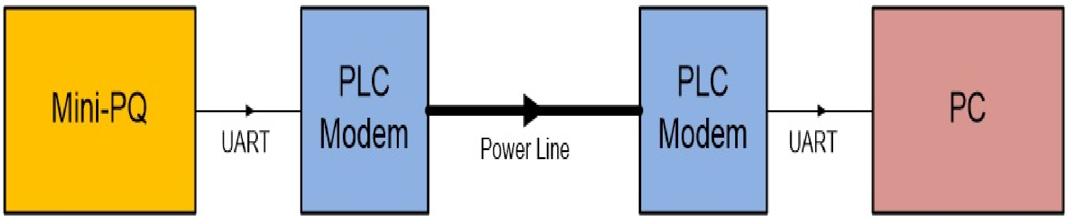


Figure 5.5: Block diagram for the minimum mode of the Mini-PQ.

5.2 Interface Design

To monitor the PQ parameters in the upper PQ center in real time; a graphical user interface (GUI) program is designed and implemented within the scope of this thesis. In addition, the GUI is used to save calculated PQ parameters. The GUI provides a friendly environment to monitor the PQ parameters in the upper PQ center. GUI software is designed in the Borland Developer Studio. The Borland Developer Studio has several key benefits on developing a GUI program. It is based on C++ language, which makes an interface easier to develop. The GUI is updated at every 9-s period, because the DSP sends data with a 9-s period . In order to capture the update on the GUI screen, the DSP also sends message number for the incoming data. GUI updates PQ parameters in accordance with the information in the incoming message .

The GUI program is compatible with two operation modes of the Mini-PQ. First mode is the minimum mode GUI and second is the maximum mode GUI. In the maximum mode, the DSP sends PQ parameters in hexadecimal (base 16) positional numeral system format. Therefore, when the Mini-PQ operates in this mode, the GUI reads the data in hexadecimal format. The GUI is capable of reading data in hex format and displaying it on the screen. On the other hand; in the minimum mode, the Mini-PQ sends the data in ASCII format. Hence another GUI program has to be designed for the minimum mode, which can read the data in ASCII format and display it on the screen.

Detailed explanations of various windows of the GUI for both modes are given below:

Communication Setting Window: Serial port number selection of the PC for the UART communication is made by the available combo-box in the "Serial Port" part of the GUI. After selecting and opening the serial port, the GUI starts to read data which are sent by the Mini-PQ. The GUI also creates a file to save the data. After closing the serial port, the file is closed and saved by the GUI program in a selected folder, which is created by the operator. Communication settings of the GUI is shown in the Figure 5.6.

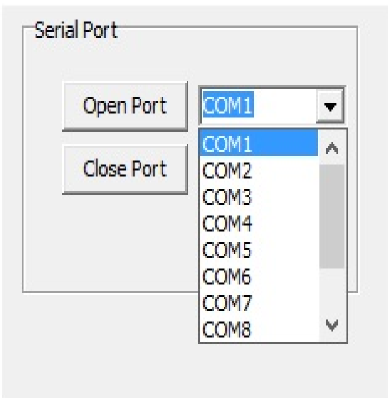


Figure 5.6: Communication setting window of the GUI.

Logs Window: Event or disturbance logs are displayed in the logs window of the

GUI. If the Mini-PQ sends an event or disturbance information, the GUI reads and displays it on the log window with the corresponding date information. All data on this window are saved to a log file after closing the serial port of the PC. In addition, this window displays status of the serial port. For example, if the serial port is open, "Port is open" message is shown in logs window. Logs window of the GUI is shown in the Figure 5.7.

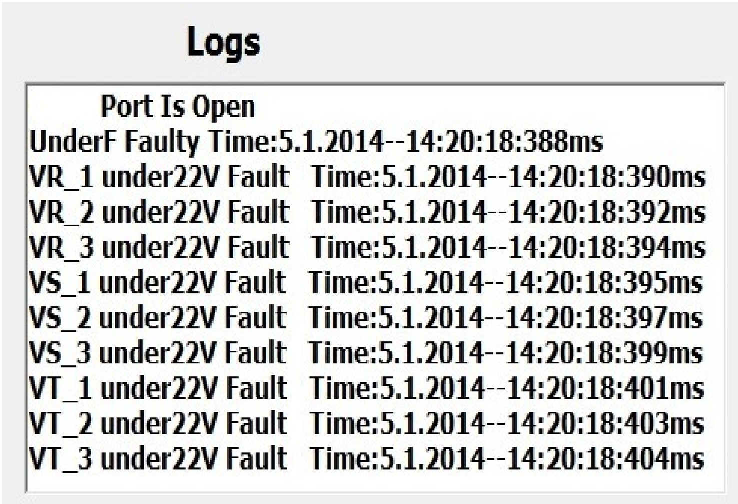


Figure 5.7: Logs window of the GUI.

Line Interruption Log Window: As stated in Chapter 4, the Mini-PQ logs the track of the voltage interruption durations and sends it to the upper PQ center, which is a PC in this study. The Mini-PQ makes calculations for 9-s data blocks, therefore resolution of the voltage interruption durations is 9-s in the Mini-PQ. When voltage interruption duration is read by the GUI, this information is displayed on the line interruption log window for each phase. The GUI never erases this information from the screen in order to save the interruption information. Line interruption log window of the GUI is given in the Figure 5.8.

Power Monitor Window: This window is active only when the Mini-PQ operates in the maximum mode. This window is refreshed every 9-s period and gives detailed information about PQ parameters. Three RMS values for each channel (since 3-s data are measured for each channel in 9-s period), one apparent power for each channel and one frequency value are displayed on the power monitor window. The GUI creates a file to save power monitor values for post-processing purposes. Power monitor

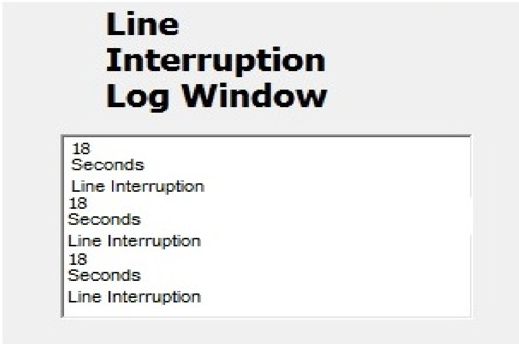
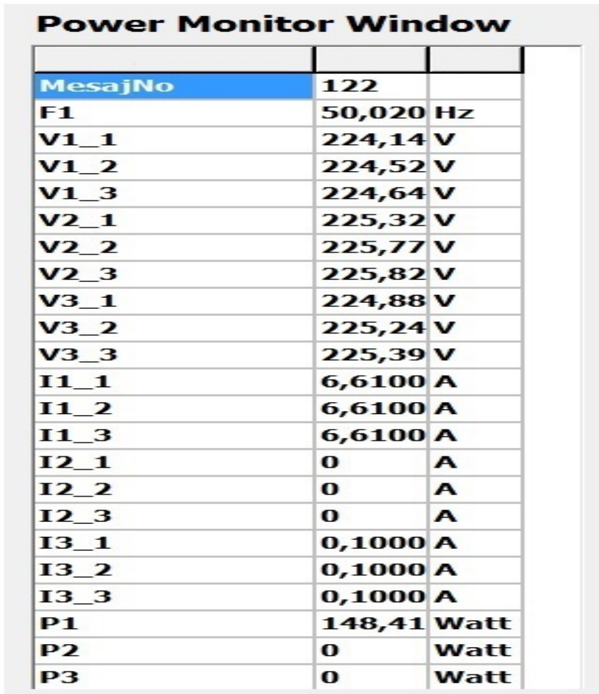


Figure 5.8: Line interruption log window of the GUI.

window of the GUI is shared in the Figure 5.9.



Power Monitor Window

MesajNo	122	
F1	50,020	Hz
V1_1	224,14	V
V1_2	224,52	V
V1_3	224,64	V
V2_1	225,32	V
V2_2	225,77	V
V2_3	225,82	V
V3_1	224,88	V
V3_2	225,24	V
V3_3	225,39	V
I1_1	6,6100	A
I1_2	6,6100	A
I1_3	6,6100	A
I2_1	0	A
I2_2	0	A
I2_3	0	A
I3_1	0,1000	A
I3_2	0,1000	A
I3_3	0,1000	A
P1	148,41	Watt
P2	0	Watt
P3	0	Watt

Figure 5.9: Power monitor window of the GUI.

Harmonics Information Window: Similar to the Power Monitor Window, harmonics information window is active only when the Mini-PQ operates in the maximum mode. The Mini-PQ calculates current harmonics of a current channel up to 13^{th} order. In the maximum mode, the Mini-PQ sends the detailed harmonics information to the upper PQ center with a period of an hour. The GUI reads data through serial port and displays the harmonics information on the screen. In addition, it creates a file to save harmonics information for post-processing purposes. Harmonics information window of the GUI is given in the Figure 5.10.

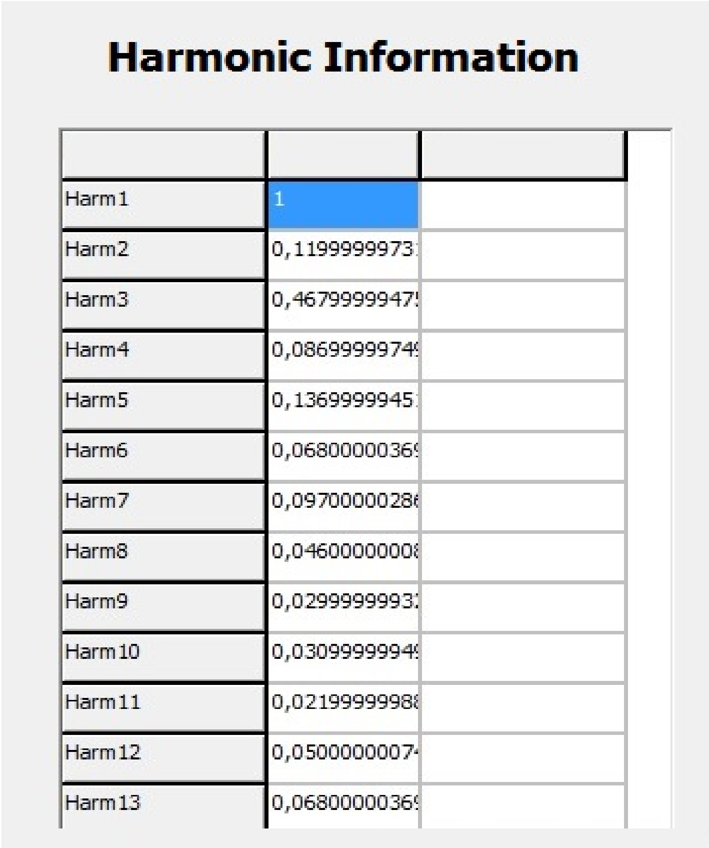


Figure 5.10: Harmonics information window of the GUI.

All of the explained GUI windows above are arranged together in the whole GUI program window as shown in Figure 5.11.

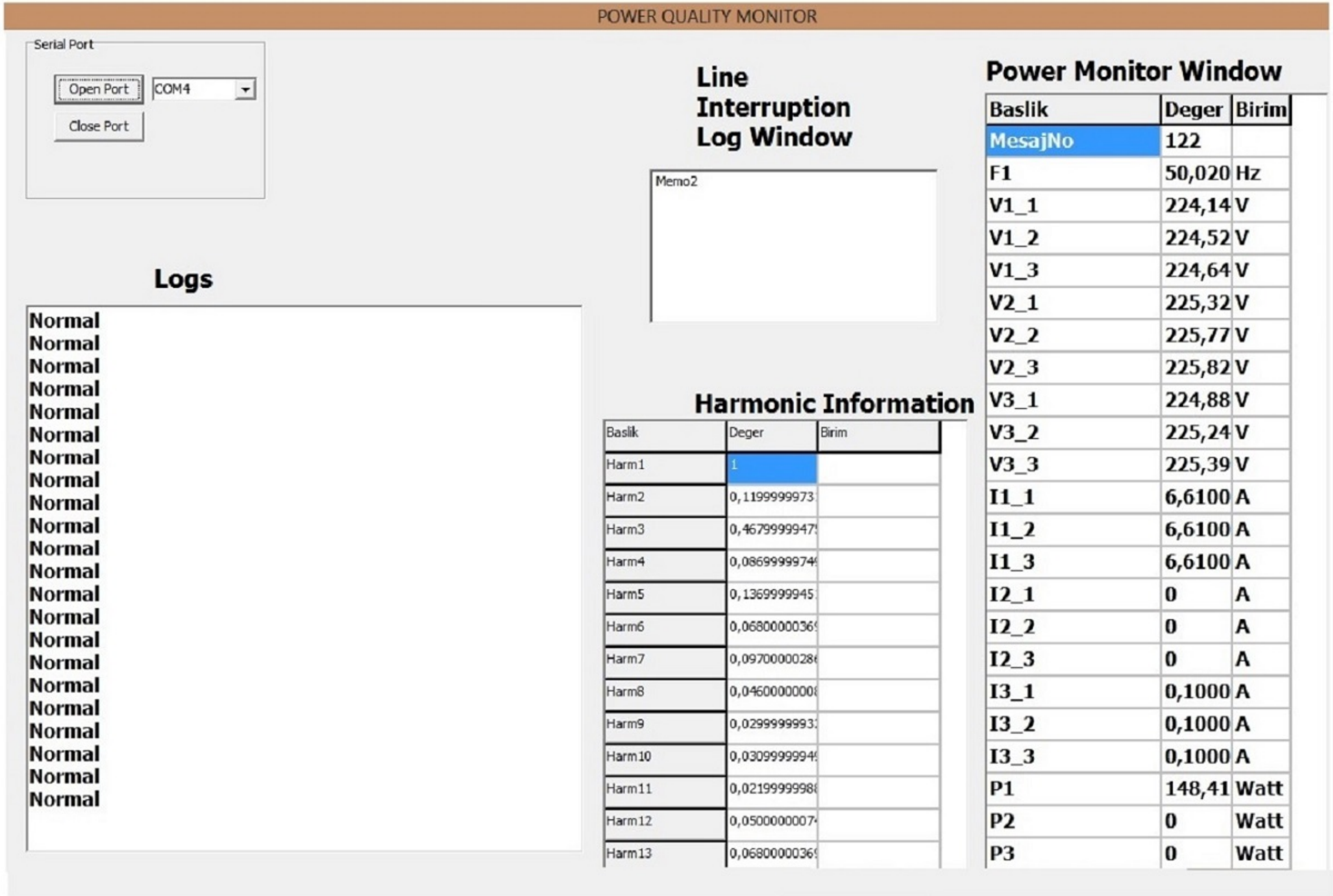


Figure 5.11: The GUI program.

CHAPTER 6

SYSTEM VERIFICATION AND FIELD MEASUREMENTS

6.1 System Verification

In order to implement and test the performance of the Mini-PQ, a test setup has been installed for both maximum and minimum modes. Setup structures for the two modes will be explained in this chapter. All measurements have been performed in TÜBİTAK SAGE [50] electronic design department laboratory, with their equipment. The digital information of PQ parameters such as RMS value, frequency value, apparent power, active power, voltage interruption and current harmonics are displayed in the GUI window. All data are calculated real-time every 9-s period.

General block diagram of the test setup is provided in the Figure 6.1. The test station, adopted for performance verification of the Mini-PQ consists of:

- Mini-PQ
- Oscilloscope
- Voltage Probe
- Current Probe
- AC Supply
- RS232 to USB serial converter
- Laptop PC for using GUI
- Hair dryer as a load (as any AC load)

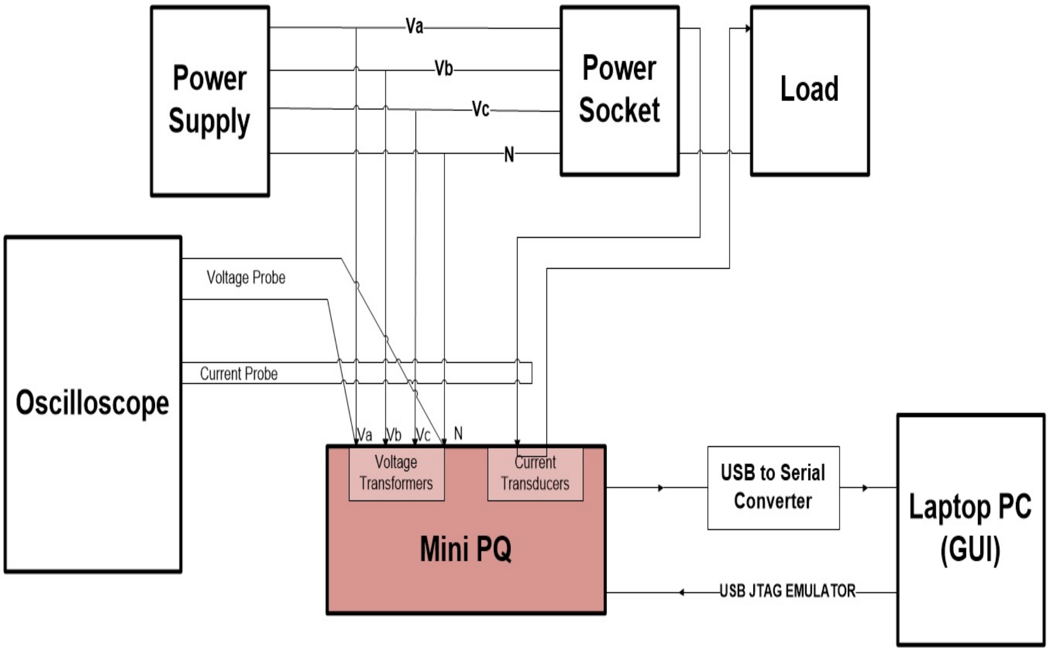


Figure 6.1: General block diagram of the test setup.

The oscilloscope that has been used is a Tektronix DPO7104 oscilloscope [51] with the following specifications:

- 4 channels,
- 3.5 GHz bandwith,
- 140 GS/s sample rate,
- Advanced math functions,
- 500 Mega-point optional record lengths.

All equipment used for verification of the Mini-PQ are calibrated every year at TÜBİTAK UME (National Metrology Institute), which acts as the reference for measurements conducted in Turkey and is the highest national authority in this field [52]. A hair dryer is used here as an AC load, because its output power can be controlled easily by changing its output level. The AC supply has the capability of giving output voltage between 2-312 Vrms ranges and frequency between 10-400 Hz ranges. Functional tests of the Mini-PQ have been done by changing supply voltage and frequency level and load current level. During the functional tests, the oscilloscope with a current and a voltage probe is used for verifying the measurements of the Mini-PQ. Voltage and current waveforms have been measured and monitored on the oscilloscope screen. Measurement results of the oscilloscope and the Mini-PQ have been compared during the verification tests. The Mini-PQ has been connected to the laptop PC in order to load the DSP program. The PC does not have a serial port on it, therefore a USB-to-serial converter manufactured by the MOXA company has been used to make conversion between RS232 and USB signals. The Mini-PQ sends the PQ parameters via its serial port to the MOXA converter, which converts serial port signals to the USB signals. Picture of the measurement setup is shown in Figure 6.2.

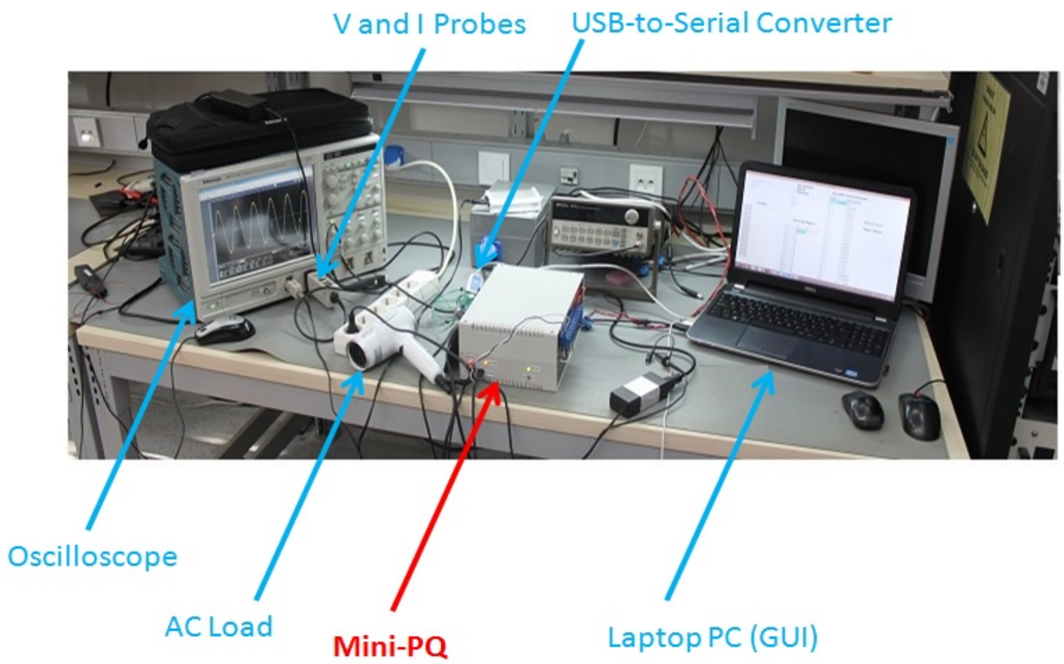


Figure 6.2: Picture of the measurement setup

The AC supply has been set to give an output voltage which has an amplitude of 220 Vrms and frequency of 50 Hz. The oscilloscope measurement is given in Figure 6.3 and the Mini-PQ measurement is given in Figure 6.4. As seen in Figure 6.3 the osciloscope measurement for voltage is 220.4 Vrms and frequency is 50.0 Hz. In Chapter 3, it is stated that the Mini-PQ gives three 3-s voltage outputs for each channel for a 9-s period. Hence, in Figure 6.4, three voltage results for each voltage channel and one frequency value are shown. IEC 61000-4-30 [5] describes the measurement uncertainty of the frequency as ±50 mHz over the measuring ranges 42.5 Hz and

57.5 Hz. The Mini-PQ frequency measurement is 50.02 Hz as in Figure 6.4, which is inside the uncertainty range ±20 mHZ.

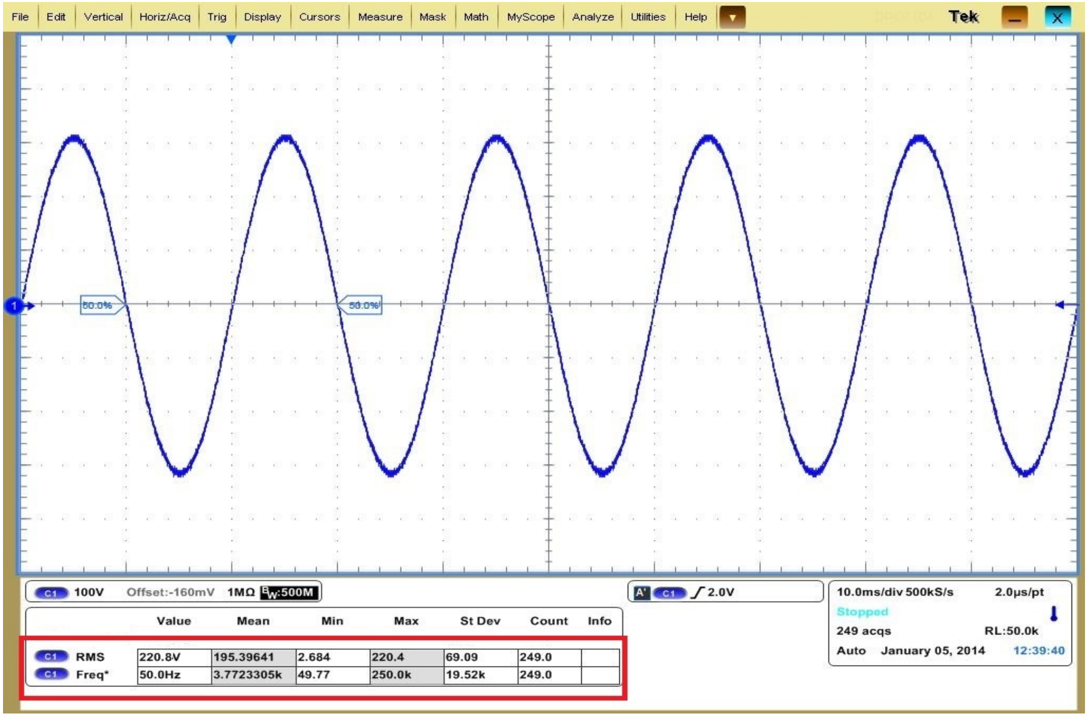


Figure 6.3: The oscilloscope measurement for 220 Vrms output

IEC 61000-4-30 describes the measurement uncertainty of the voltage measurement as ±0.5 % of supply voltage over the range of 20 % and 120 % of the supply voltage. For 220 Vrms input, +0.5 % is 221.50 Vrms and -0,5 % is 219.30 Vrms. Therefore, obtained voltage values should be in between 221.50 Vrms and 219.30 Vrms. There are 9 results for voltage measurements in Figure 6.4. The minimum obtained voltage value is 220.47 Vrms and the maximum obtained voltage value is 221.24 Vrms, which are inside the uncertainty range defined by the IEC standard. Results for different frequency values are given in Table 6.1 and results for different voltage values are given in Table 6.2.

Table 6.1: Frequency measurement results

Test Number	Expected Result	Obtained Result	% Error of the Mini-PQ
1	50 Hz	50.02 Hz	0.04
2	50 Hz	49.98 Hz	0.04
3	49 Hz	49.03 Hz	0.06
4	51 Hz	50.97 Hz	0.05

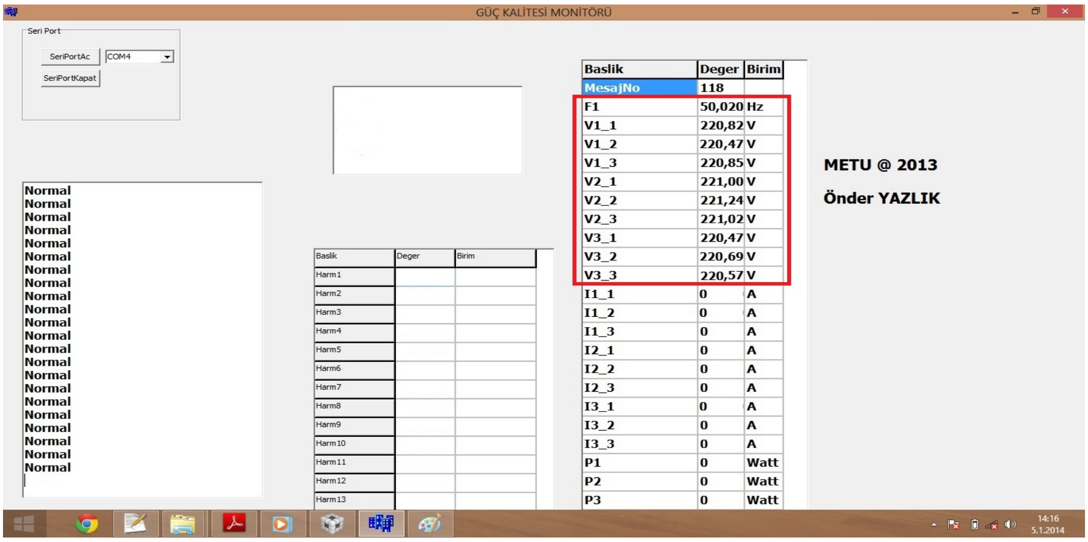


Figure 6.4: The Mini-PQ measurement for 220 Vrms output

As seen in Table 6.1, all frequency measurements are in the range +20 mHz and -30 mHz. This uncertainty range satisfies the standard requirement [5]. In addition, maximum frequency measurement error is 0.06 % for the Mini-PQ.

Table 6.2: Voltage measurement results

Test Number	Expected Result	Obtained Result	% Error of the Mini-PQ
1	220.80 Vrms	221.24 Vrms	0.19
2	220.80 Vrms	220.47 Vrms	0.14
3	220.80 Vrms	221.02 Vrms	0.09
4	245.20 Vrms	245.01 Vrms	0.19
5	245.20 Vrms	244.86 Vrms	0.13
6	245.20 Vrms	246.12 Vrms	0.37
7	198.10 Vrms	197.75 Vrms	0.17
8	198.10 Vrms	198.86 Vrms	0.38
9	198.10 Vrms	198.46 Vrms	0.18

The Mini-PQ calculates voltage amplitude with a maximum error of 0.38 %, which is inside the uncertainty range defined by the IEC standard [5].

The hair dryer has been connected to the I1 input channel as a load. The hair dryer has been operated at its maximum performance (1800 W) and load current is measured with the oscilloscope by using the current probe. The oscilloscope measurement result is shown in Figure 6.5. As shown in this figure, drawn current by the hair dryer is 6.64 Arms. The current values measured by the Mini-PQ are shown see Figure 6.6.

Hence, measurement uncertainity of the Mini-PQ for current measurement is 0.4 % for 6.64 A measurement. This test has been repeated for three current channels and the results for different Irms values are given in Table 6.3. The Mini-PQ calculates current amplitude with a maximum error of 0.88 %.

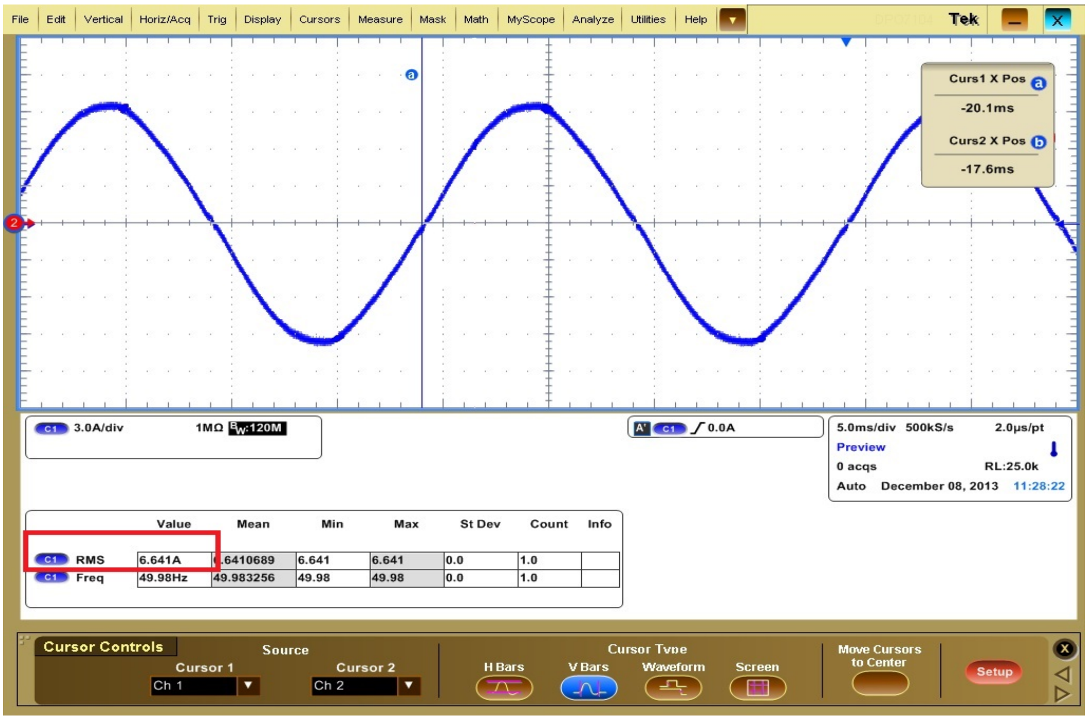


Figure 6.5: The oscilloscope measurement for current.

Table 6.3: Current measurement results

Test Number	Expected Result	Obtained Result	% Error of the Mini-PQ
1	6.64 Arms	6.63 Arms	0.15
2	6.64 Arms	6.61 Arms	0.45
3	6.64 Arms	6.62 Arms	0.30
4	3.42 Arms	3.39 Arms	0.88
5	3.42 Arms	3.40 Arms	0.58
6	3.42 Arms	3.40 Arms	0.58

In order to verify power calculations, the hair dryer was connected to I1 channel and supplied by V1 channel. In Chapter 3, it is stated that for power calculation, phase angle between voltage and current waveforms should be obtained. The voltage probe has been connected to the Mini-PQ's V1 channel and the current probe has been connected to the hair dryer's power cable at the same time. The two waveforms have been monitored on the oscilloscope screen simultaneously. Time difference between

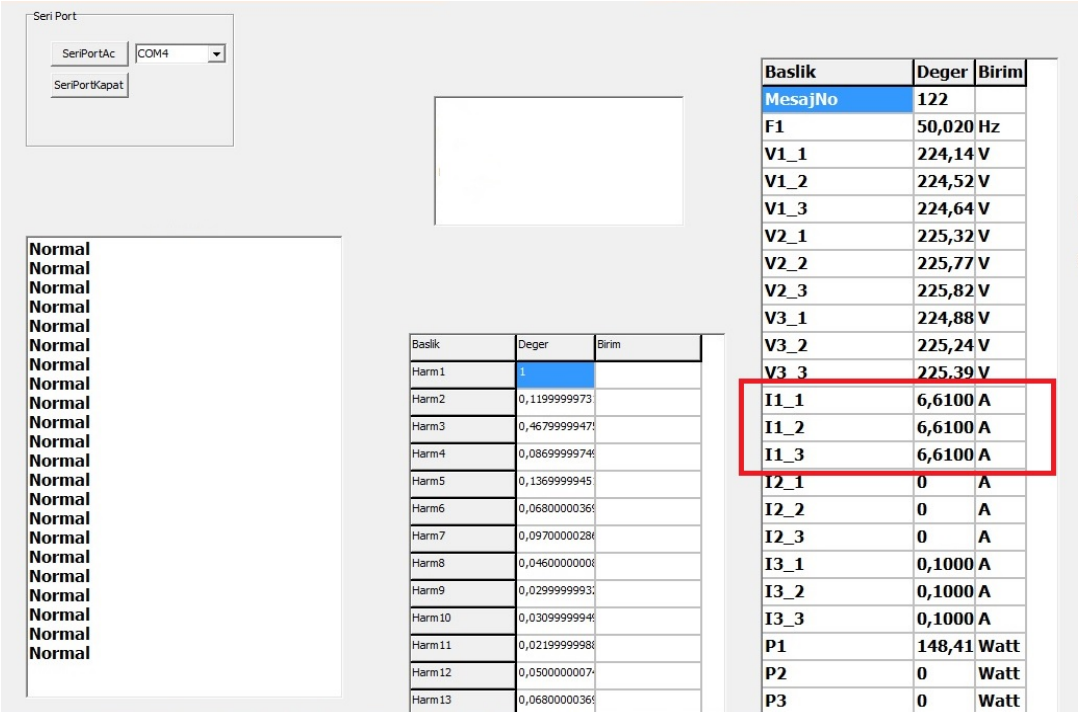


Figure 6.6: The Mini-PQ measurement for current.

the voltage and the current waveforms which has been measured by the oscilloscope is shown in Figure 6.7. In this figure, the red line indicates voltage waveform and the blue line indicates current waveform. Time difference between them is 2.4 ms as shown in the figure. Converting this time value to radians, we obtain 0.75 radians. By inserting these values into the equations 2.2,2.3 and 2.4 we obtain cos teta = 0.73. So active power in Channel-1 should be 1066 W and apparent power should be 1460 W. The GUI displays apparent power on the GUI window. Due to the data size limitations, the DSP sends power values by dividing them by 10. This means, the Mini-PQ shows 10 % value of the calculated power. As shown in Figure 6.8 the Mini-PQ has obtained apparent power as 1487 W with a % 1 measurement uncertainty error.

To verify active power calculation performance of the Mini-PQ, a DSP code was generated in CCS environment. As stated before, time difference between voltage and current waveform has been measured as 2.4 ms (Figure 6.7). Radian equivalent of this time difference is 0.75 rad. as stated before. The DSP in the Mini-PQ obtains this value as 0.749 rad., which is shown in Figure 6.9. The measurement uncertainty is % 0.1 for this measurement.

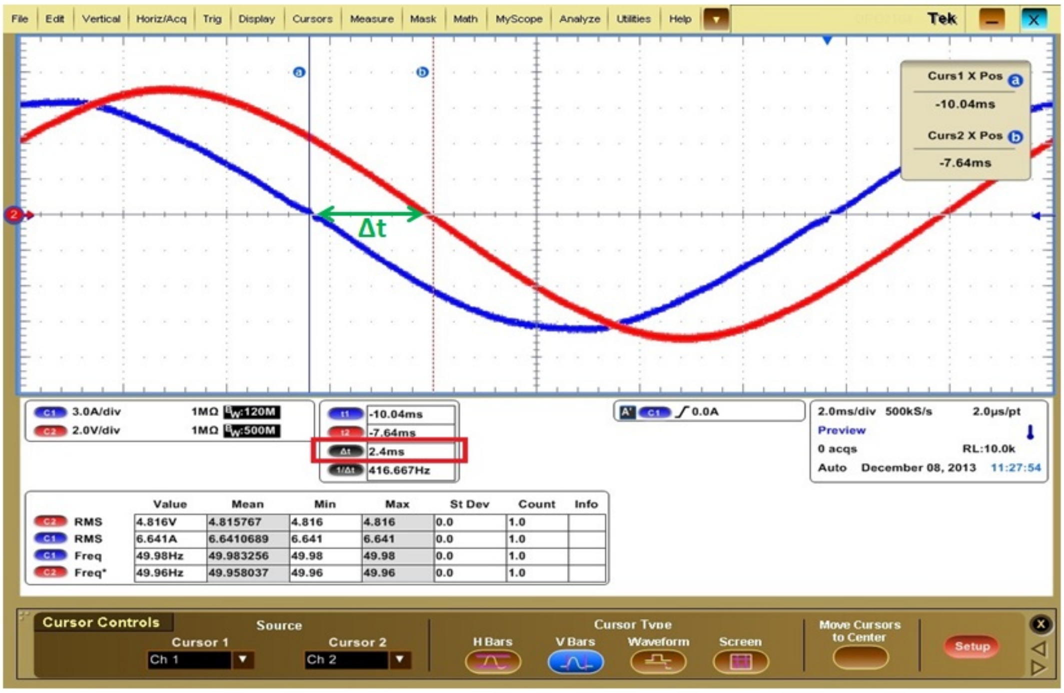


Figure 6.7: Time difference between the voltage and the current obtained by the oscilloscope.

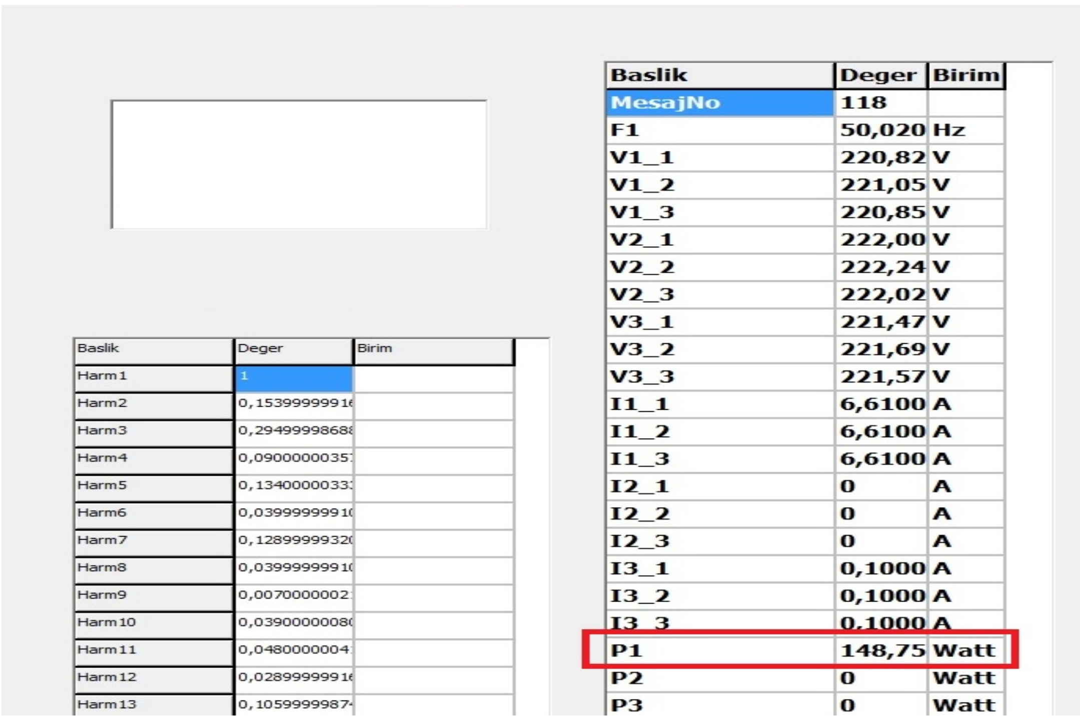


Figure 6.8: The Mini-PQ apparent power result.

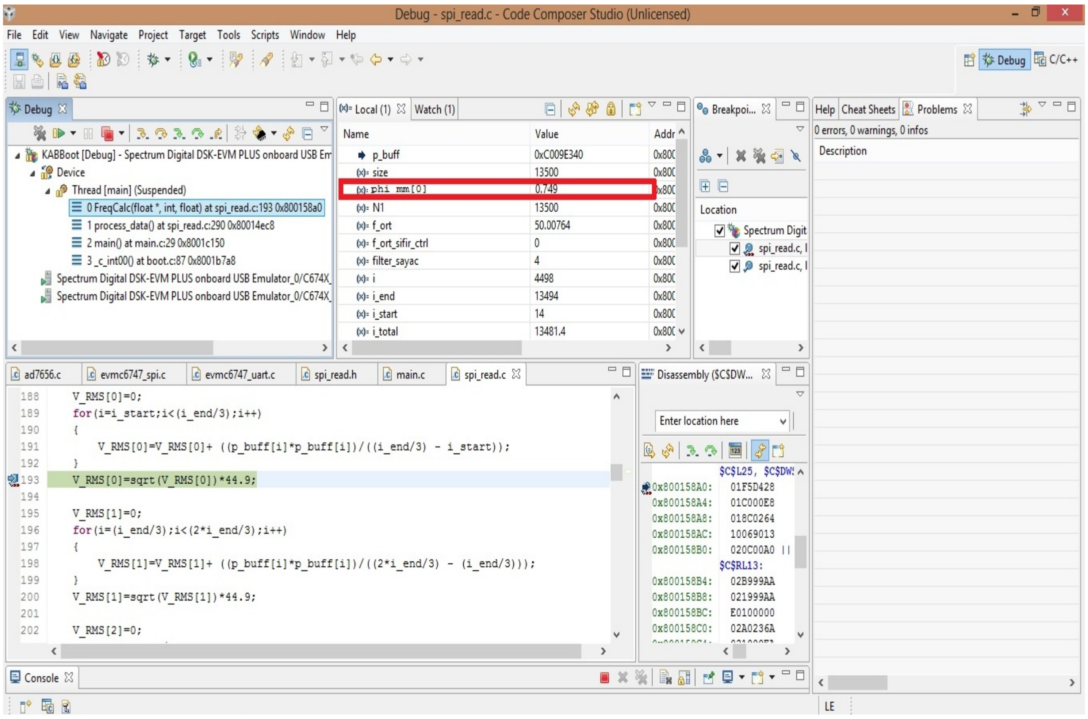


Figure 6.9: Phase angle measurement of the Mini-PQ.

Harmonics measurement of the hair dryer by the oscilloscope when operates at the maximum load is shown in Figure 6.11. In Chapter 3, it is stated that the Mini-PQ obtains the current harmonics up to 13^{th} order. Calculated harmonic results by the Mini-PQ are shown in Figure 6.10.

We see that, fundamental and 3^{rd} harmonics are big enough to be displayed on the oscilloscope screen. The Mini-PQ obtained 3^{rd} harmonic as 46 % of the fundamental component. Comparing oscilloscope results and the Mini-PQ results, it has been observed that 3^{rd} harmonic is approximately 46 % of the fundamental frequency in both measurements. The rest of the harmonics are so small to be monitored by the oscilloscope. However, the Mini-PQ still obtains those very small harmonic values as given in Figure 6.10. As seen in Figure 6.11, harmonics analysis tool of the oscilloscope is not good enough to analyze small-valued harmonics.

In order to be more satisfactory harmonics performance verification of the Mini-PQ, the collected current raw data have been analyzed in the MATLAB environment with the implemented harmonics algorithm described in Chapter 3. Hence, the results of the Mini-PQ and those obtained in the MATLAB environment have been compared for the verification of the harmonic algorithms running on the Mini-PQ. Harmonics

Baslik	Deger	Birim
Harm1	1	
Harm2	0,1199999973	
Harm3	0,467999994	
Harm4	0,0869999974	
Harm5	0,1369999945	
Harm6	0,0680000036	
Harm7	0,0970000028	
Harm8	0,0460000000	
Harm9	0,0299999993	
Harm10	0,0309999994	
Harm11	0,0219999998	
Harm12	0,0500000007	
Harm13	0,0680000036	

Figure 6.10: Harmonics measurement of the Mini-PQ.

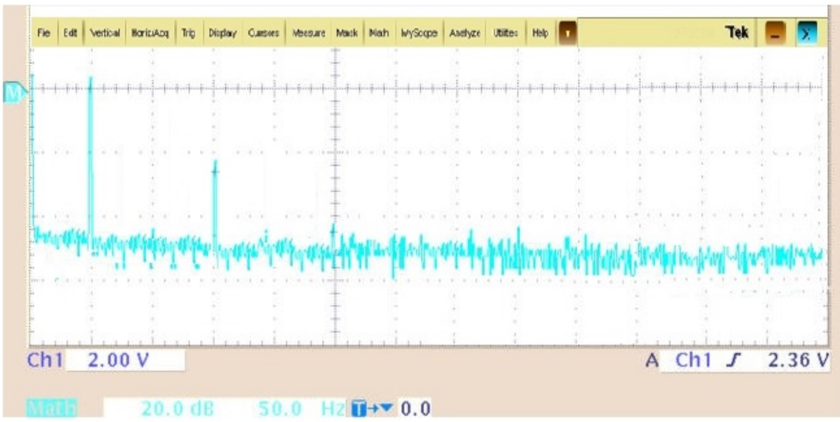


Figure 6.11: Harmonics measurement by the oscilloscope.

results obtained using MATLAB are shown in Figure 6.12.

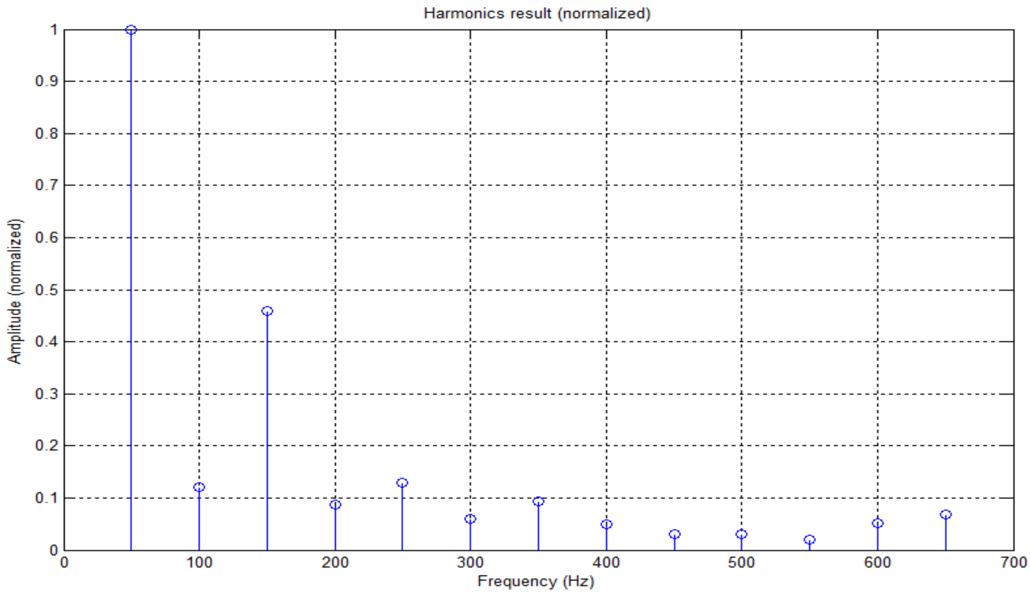


Figure 6.12: Harmonics measurement by using raw data.

Comparison of the Mini-PQ measurement and results in MATLAB environment is shown in Table 6.4. The Mini-PQ calculates the harmonics with a maximum error of 13.1 % which is a satisfactory result.

Table 6.4: Harmonics simulation results

Harm.No.	**MATLAB Results%**	**Mini-PQ Results%**	**% Error Mini-PQ**
1	100	100	0.00
2	12.09	11.99	0.83
3	46.01	46.79	1.69
4	8.80	8.69	1.25
5	12.99	13.69	5.11
6	6.01	6.80	13.1
7	9.38	9.70	3.41
8	4.90	4.60	6.12
9	3.09	2.99	3.23
10	2.94	3.09	5.10
11	2.00	2.19	9.50
12	5.10	5.00	1.96
13	6.89	6.80	1.30

In Chapter 5, it is stated that duration of a voltage interruption has a 9-s resolution in the Mini-PQ. Therefore, the Mini-PQ obtains the duration of a voltage interruption as the multiples of 9-s periods. To verify the Mini-PQ in terms of voltage interruption, supply voltage was shut-down and started again to measure the time the supply voltage was off. For this example, time duration between turning-off and on of the supply voltage was 54 s. After turning on the supply again, the Mini-PQ sent 54-s voltage interruption messages for all phases as shown in Figure 6.13, which verifies that the Mini-PQ is able to measure the supply voltage-off time accurately.

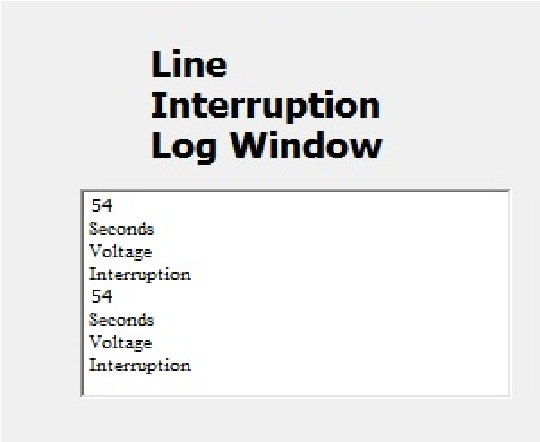


Figure 6.13: Voltage interruption measurement by the Mini-PQ.

6.2 Field Measurements

Field measurements have been carried out in TÜBİTAK SAGE laboratories. Due to two different operational modes of the Mini-PQ, two setups are configured for the field measurements.

6.2.1 Field Measurements for Maximum Mode

Block diagram for field measurement setup for the maximum mode is shown in Figure 6.14. Picture of the setup for the maximum mode field measurement is shown in Figure 6.15.

The Mini-PQ collects data on the power line and sends them to the PC via serial port communication. As stated in Chapter 5, the Mini-PQ can store all the data in a file. The AC supply is used in field measurements in order to create PQ faults. After

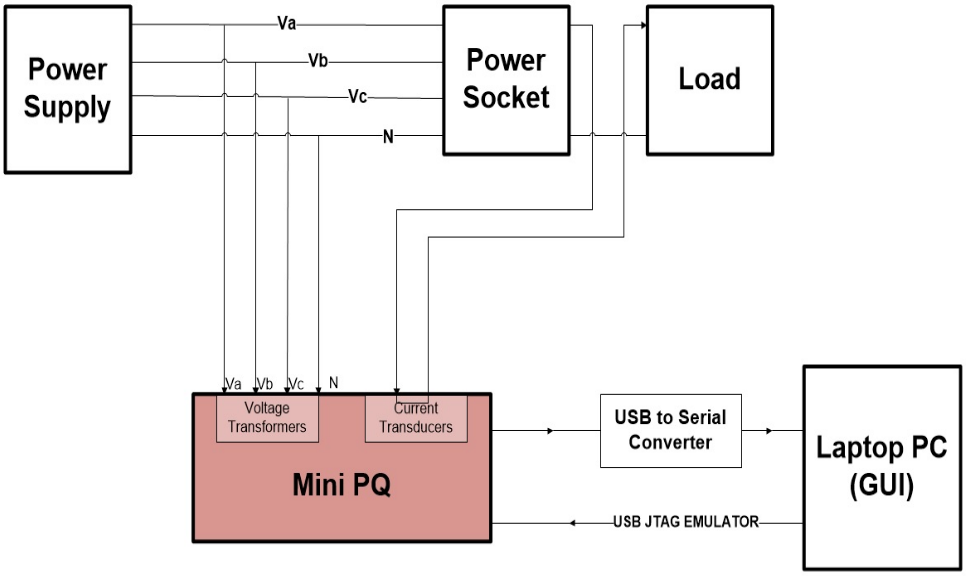


Figure 6.14: Block diagram for maximum mode field measurement.

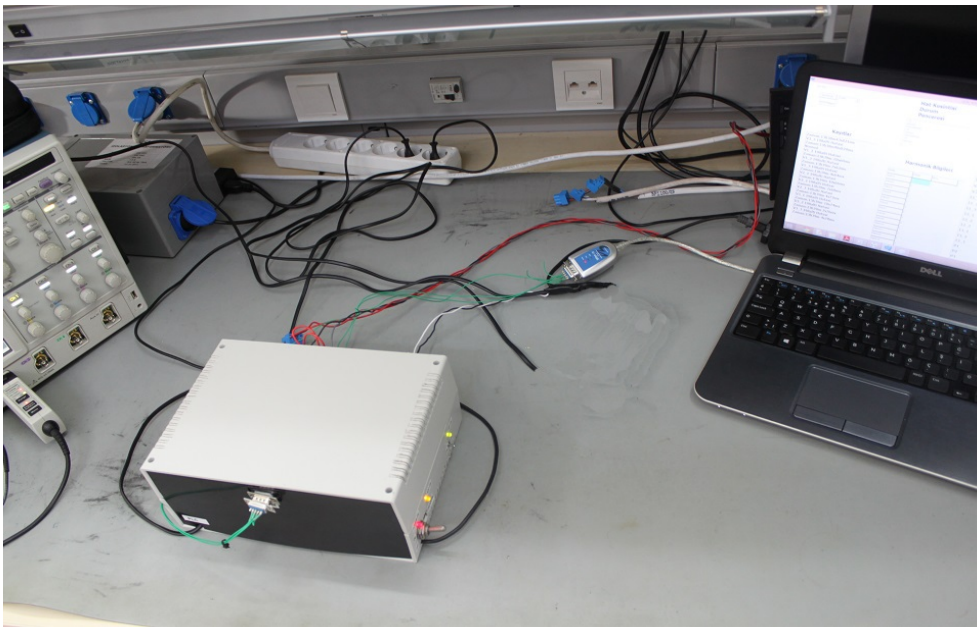


Figure 6.15: Picture of the maximum mode field measurement setup.

connecting the Mini-PQ to the power line, serial port is opened and the GUI starts to collect the PQ parameters, which are sent by the Mini-PQ. During measurements, output voltage and frequency of the AC supply are changed and PQ logs are monitored on the PC. Finally, the serial port is closed in the GUI. The saved file is parsed to the MATLAB environment and by making post-processing the graphs are plotted.

Field measurement starts by applying 50 Hz signal to the power line. Then the frequency is decreased below 49.95 Hz for 10 times and increased above 50.05 Hz for 15 times. The Mini-PQ detected all frequency faults and monitored on the GUI, in addition to saving the frequency faults to the file with date information. The graph of frequency measurement is shown in Figure 6.16.

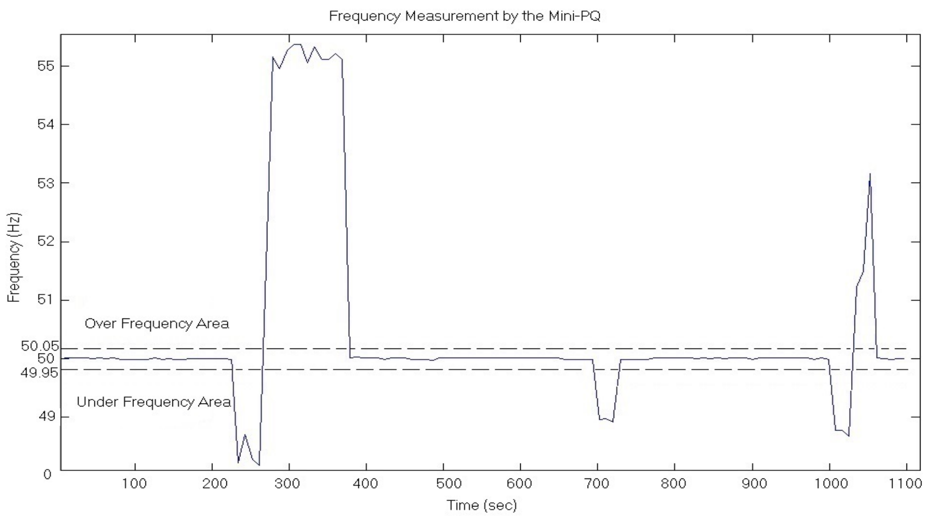


Figure 6.16: Frequency measurement by the Mini-PQ.

As the frequency decreased 10 times below 49.95 Hz, the Mini-PQ detected 10 under frequency faults and as the frequency increased 15 times above 50.05 Hz, the Mini-PQ detected 15 over frequency faults. The field measurements started on January 05, 2014 1:58:20 PM and ended at January 05, 2014 2:16:29 PM. The Mini-PQ sends a message at every 9-s, therefore there are 122 messages in the measurement time interval. Total duration of the measurement is 1098 s. Under and over frequency faults are shown in Figure 6.17. As shown in this figure, at 234-s, 243-s, 252-s, 261-s, 702-s, 711-s, 720-s, 1008-s, 1017-s and 1026-s frequency values are under 49.95 Hz. Total number of under frequency error messages are 10 as expected. Besides, at 279-s, 288-s, 297-s, 306-s, 315-s, 324-s, 333-s, 342-s, 351-s, 360-s, 369-s, 1035-

s, 1044-s and 1053-s frequency values are over 50.05 Hz. Total number of over frequency messages are 15 as expected. Hence it is verified that, all frequency faults are detected by the Mini-PQ.

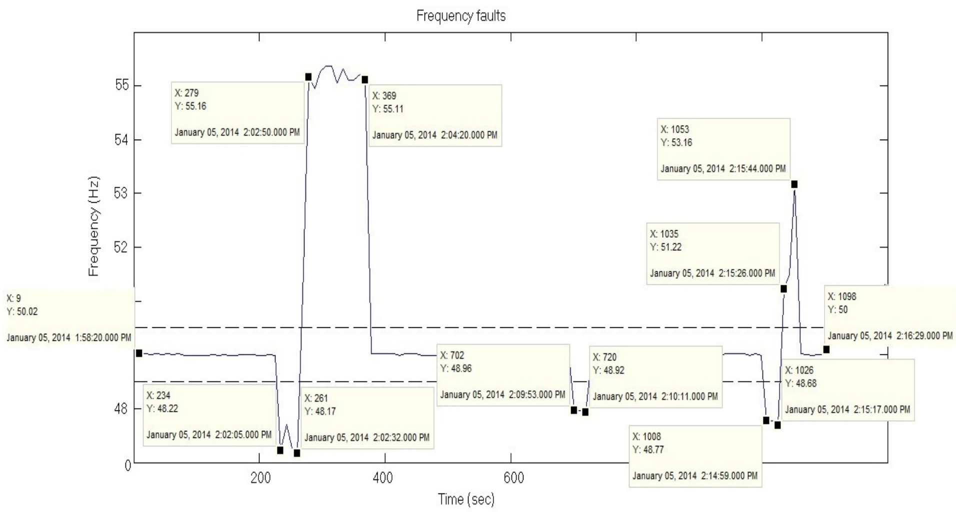


Figure 6.17: Under and over frequency faults.

To test the voltage fault detection capability of the Mini-PQ, the output of the AC supply is set to give 220 Vrms voltage to all phases. During field measurements, output of the AC supply is changed between 0 Vrms and 244 Vrms values. The Mini-PQ obtains three voltage values for a 9-s data block. Therefore, three voltage values are measured during field measurements for each channel. Voltage measurement of the Mini-PQ is shown in Figure 6.18 with respect to time. As shown in the figure, there are three voltage measurements for three channels. Voltage measurements are very close to each other for all channels, as expected.

A closer view of the first 70-s of the voltage measurements are shown in Figure 6.19. The measurement values at 3-s and 63-s are shown in boxes in this figure. Measurement error between the channels, which is also observed in Figure 6.19 is shown in Table 6.5. As seen in the table, maximum error occurs between Channel 1 and Channel 3, that is 0.52 % with respect to the nominal voltage value.

Table 6.5: Current measurement results.

Channel 1	Channel 2	Channel 3	% Error (Ch1-Ch2)	%Error (Ch1-3)	%Error (Ch2-3)
221.1 V	220.6 V	220.0 V	0.22	0.50	0.27
209.9 V	209.3 V	208.8 V	0.28	0.52	0.23

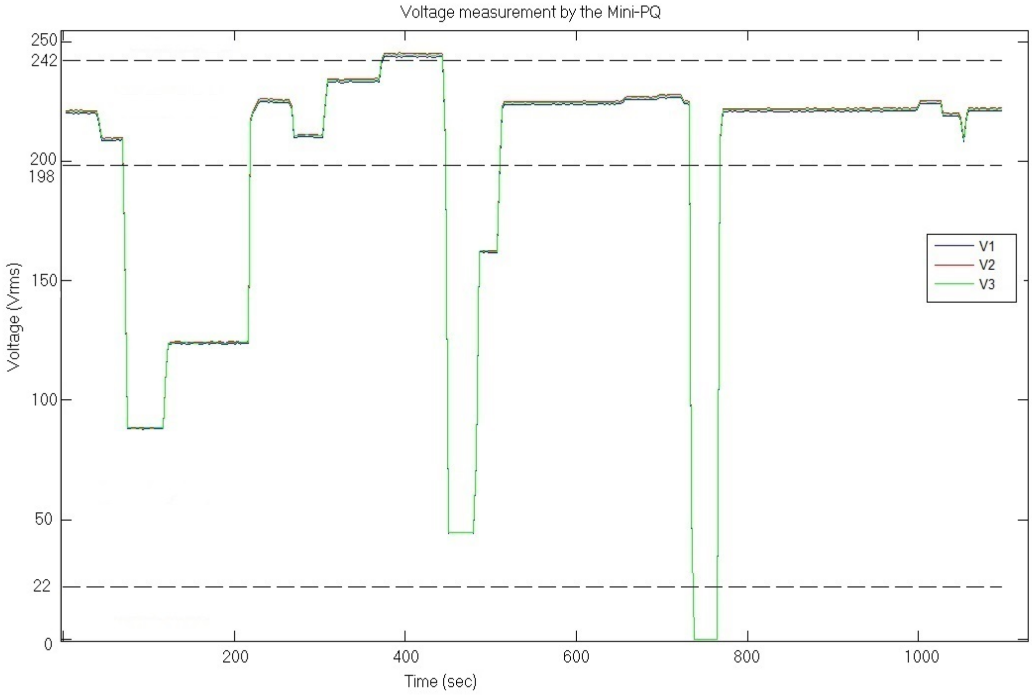


Figure 6.18: Voltage magnitude measurement of the Mini-PQ.

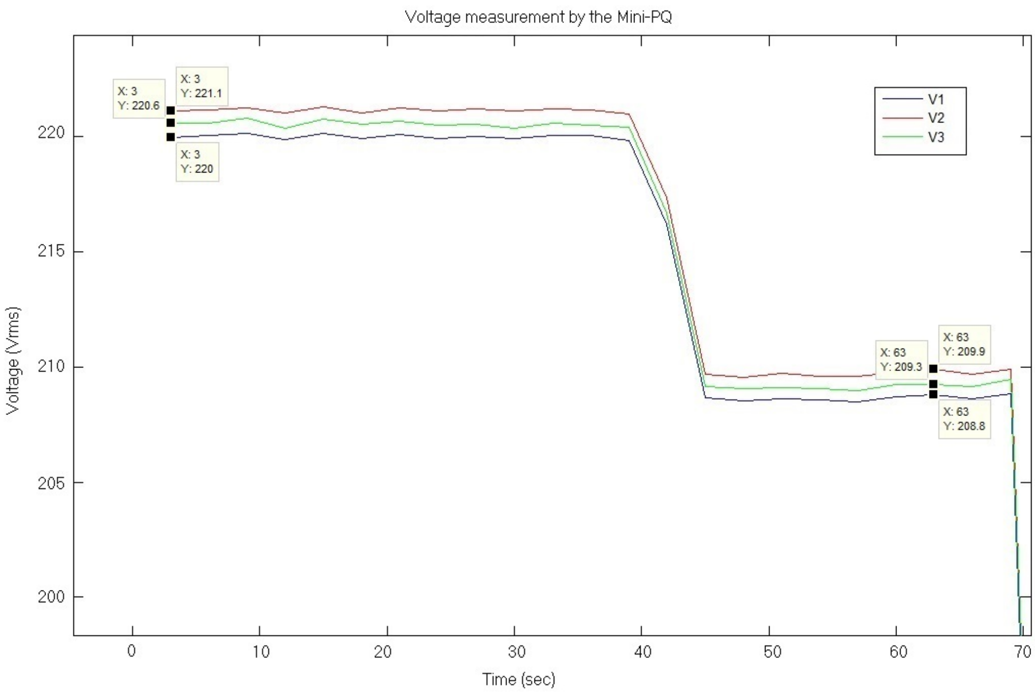


Figure 6.19: First 9 measurement of the Mini-PQ.

The field measurement started on January 05, 2014 1:58:20 PM and ended at January 05, 2014 2:16:29 PM. The Mini-PQ sends a message at every 9-s, therefore there are 122 messages in the measurement time interval. Total duration of the measurement is 1098-s. Voltage faults for Channel-1 is shown in Figure 6.20. As shown in the figure, at 75-s voltage decreases to 87.99 Vrms and the Mini-PQ sends an under 198 Vrms error to the GUI for this measurement. All voltage magnitude faults are shown in this figure. In total, the Mini-PQ sends 8 over 242 Vrms fault error messages, 24 under 198 Vrms fault error messages and 4 under 22 Vrms fault messages. In addition to under 22 Vrms fault messages, the Mini-PQ sends 36-s voltage interruption error messages to the GUI.

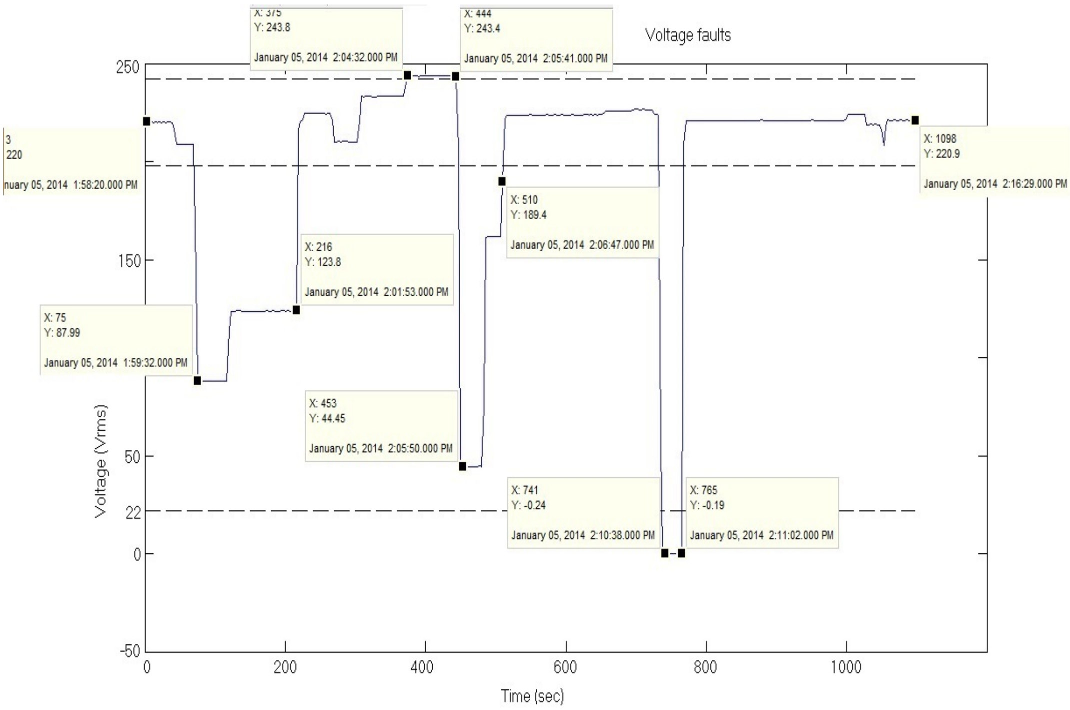


Figure 6.20: Voltage faults captured by the Mini-PQ.

In order to verify current measurements, the hair dryer as a load is operated between 549-s and 576-s and 1071-s and 1098-s as shown in Figure 6.21. RMS current at I1 channel is measured at these time intervals. In addition, power is measured only during current measurements. Power calculation with voltage and current measurements are shown in Figure 6.22.

Although the Mini-PQ obtains current harmonics every hour, for this measurement, current harmonics are measured at every 9 min. The field measurement started on

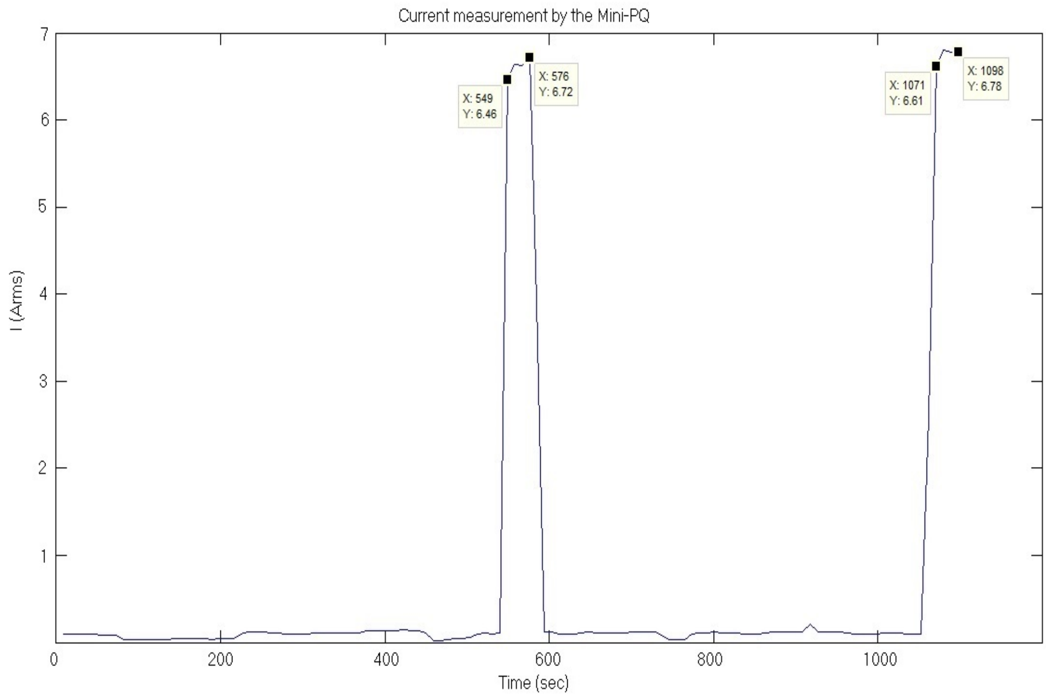


Figure 6.21: Current measurement of the Mini-PQ.

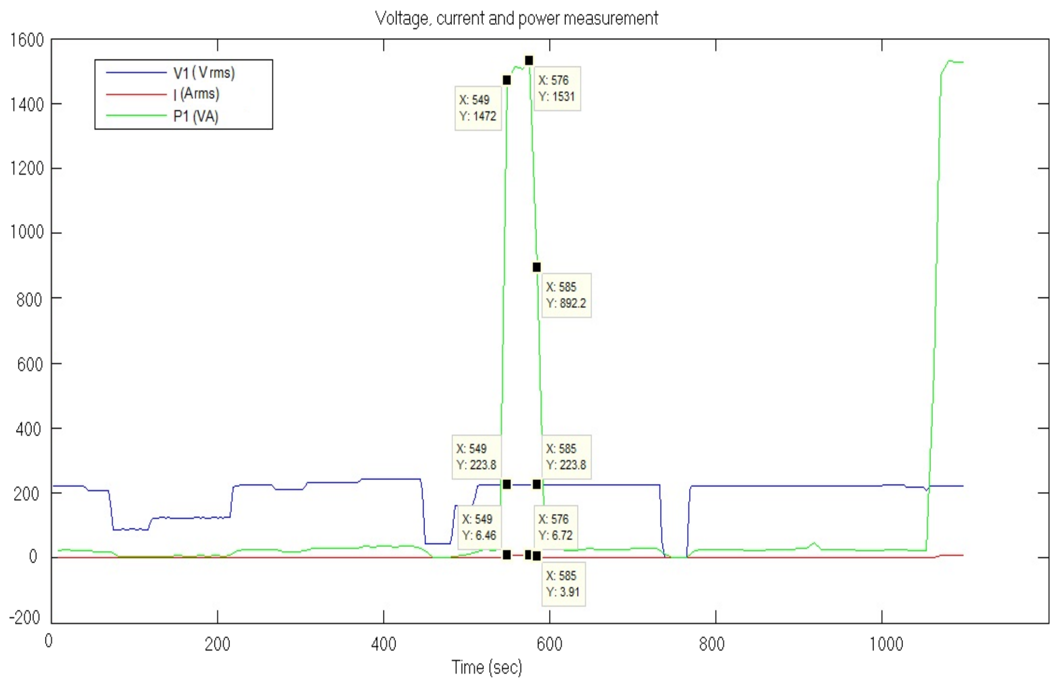


Figure 6.22: Power measurement of the Mini-PQ.

January 05, 2014 1:58:20 PM and ended at January 05, 2014 2:16:29 PM. Total duration of the measurement is 1098 s. Since 9 min. makes 540 s, the Mini-PQ obtains current harmonics in the Channel-4 twice in 1098 s. As seen in Figure 6.21, the hair dryer starts at the 549th s and 1071st of the measurement period. The obtained harmonics at 1071st s by the Mini-PQ is shown in Figure 6.23.

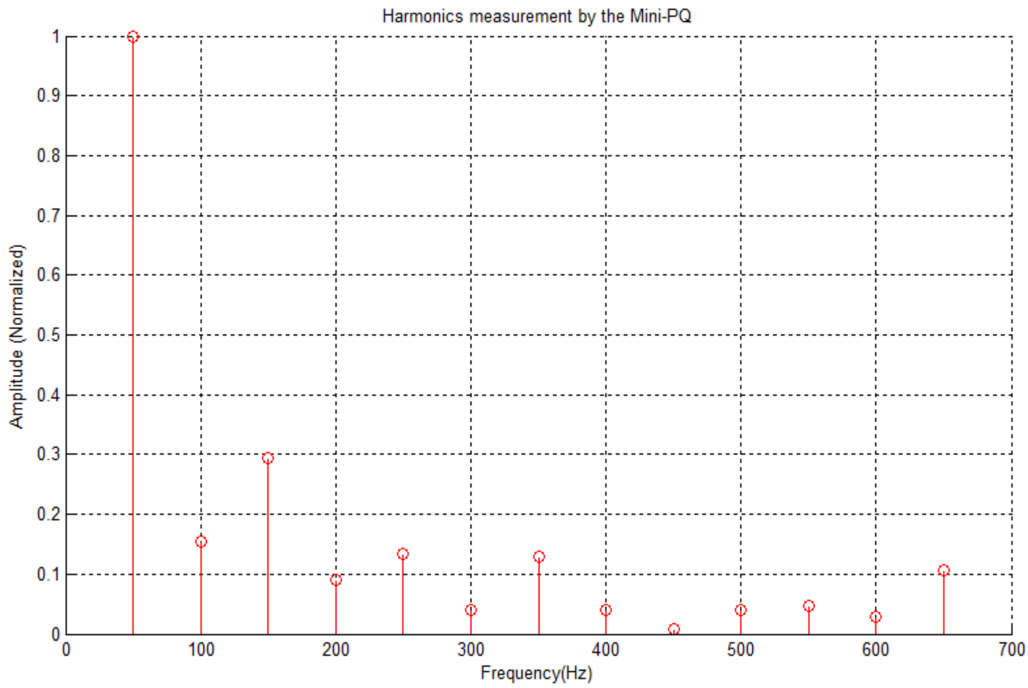


Figure 6.23: Harmonics measurement of the Mini-PQ.

6.2.2 Field Measurements for Minimum Mode

Block diagram for field measurement setup for the minimum mode is shown in Figure 6.24. Picture of the setup for the minimum mode field measurement is shown in Figure 6.25. The Mini-PQ collects data on the power line and sends the data to the PC via PLC.

As stated in Chapter 5, in the minimum mode the Mini-PQ doesn't send detailed PQ parameters. Instead of this, the Mini-PQ sends only type of PQ events or disturbances to the PC. Field measurements were made at TÜBİTAK SAGE. Similar to the minimum mode measurements, in this mode a variable AC supply is used. By changing the output of the AC supply, the GUI in the PC is monitored and tracked. After finishing the measurement saved data files can be used to view the PQ logs.

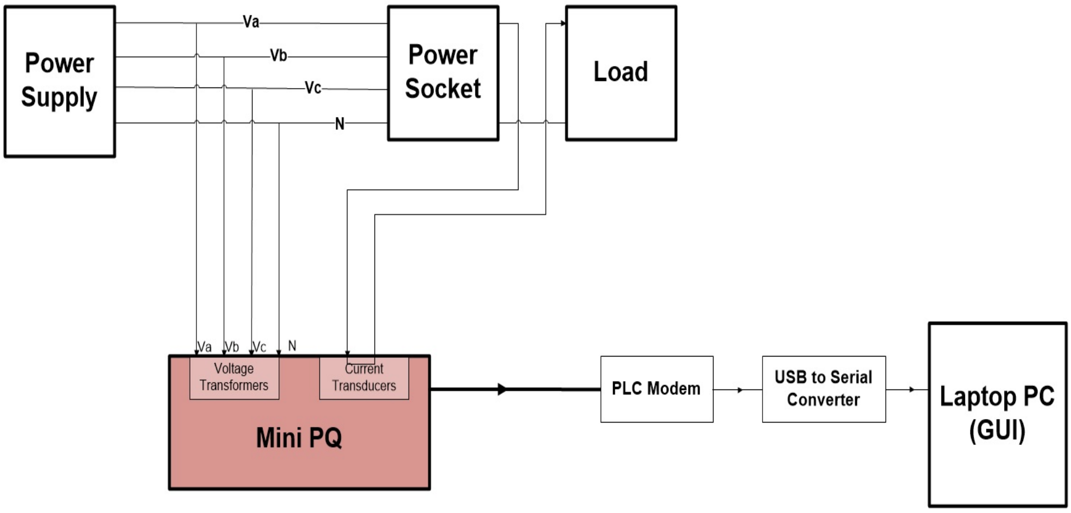


Figure 6.24: Block diagram for minimum mode field measurement..

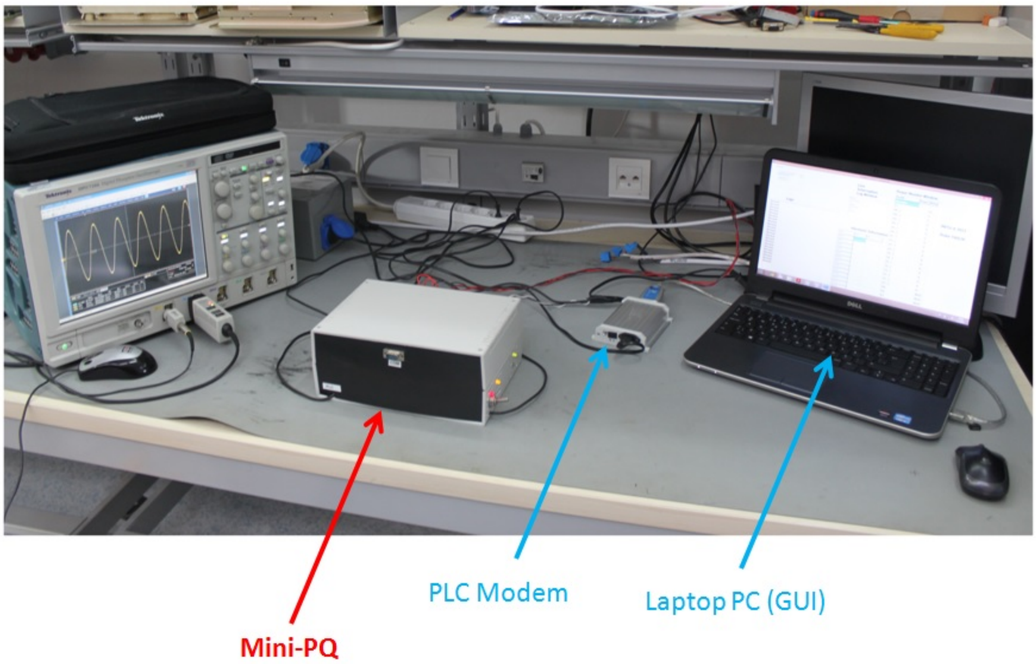


Figure 6.25: Picture of the setup for the minimum mode.

Firstly, the AC supply of the setup is turned-off to create voltage interruption and under 22V faults. The GUI displayed under frequency and under 22 V faults on the screen as shown in Figure 6.26.

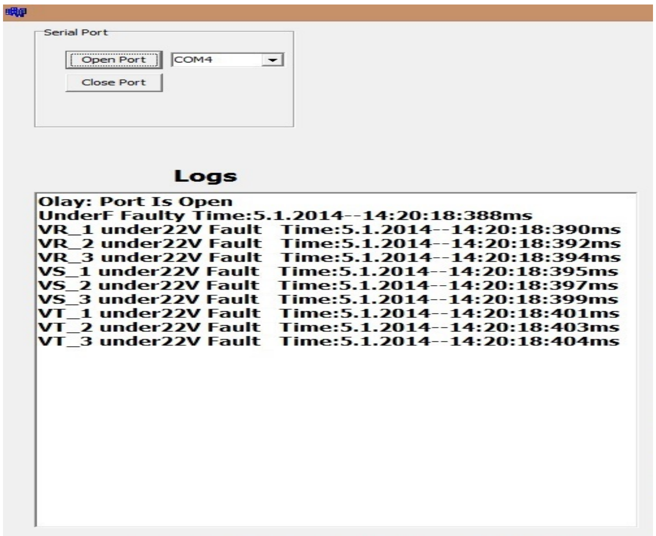


Figure 6.26: Voltage magnitude and interruption messages on the GUI.

After setting the output of the supply to 220 Vrms and 50 Hz, the Mini-PQ sends the duration of the voltage interruption, which is 54-s for this measurement. The Mini-PQ sends a NORMAL message for the frequency measurement and under 198 V fault error messages V1-1, V2-1 and V3-1 as expected. This situation is shown in Figure 6.27. The reason for under 198 V error is that, the voltage output of the AC supply gradually increases in 9-s period.

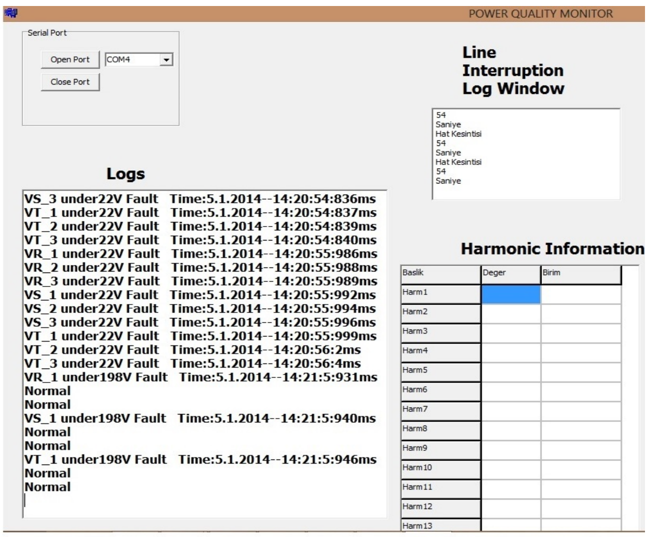


Figure 6.27: Normal frequency and under voltage fault messages on the GUI.

Another scenario is decreasing the voltage frequency value. The frequency is decreased to 49 Hz and under frequency fault error is displayed on the GUI. Other PQ parameters are in the normal limits, therefore other parameters are displayed as normal in this scenario. Snapshot of the GUI for this scenario is shown in Figure 6.28.

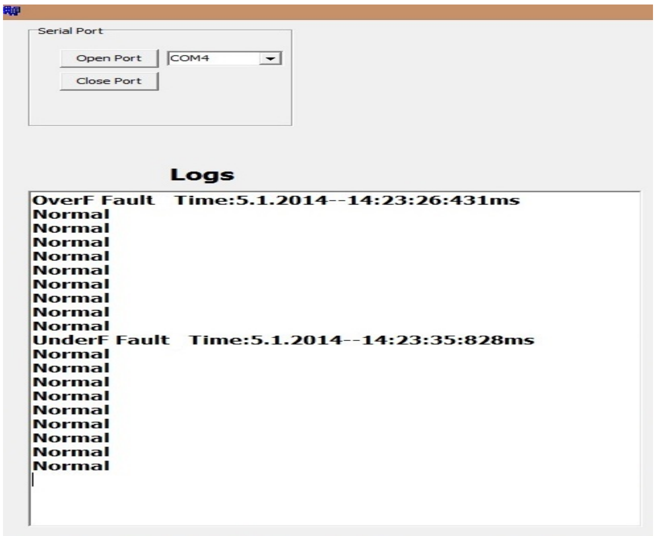


Figure 6.28: Under frequency error on the GUI.

CHAPTER 7

CONCLUSION AND FUTURE WORK

Monitoring of the power quality (PQ) is essential for all generation, transmission and distribution of the electricity grid all over the world for supplying the continuity of the service. There are various PQ monitoring devices developed for all system levels. However, existing PQ monitoring devices have some disadvantages in terms of application in the distribution system level. Typically, these PQ analyzers are equipped with a data acquisition card, which requires a PC (Personal Computer) for processing raw data later. However, they are insufficient for online PQ assessments in the distribution system level. Usually, the analyzer have such designs that their hardware structure enables calculation of all PQ parameters recommended in the IEC standard 61000-4-30. However, all these parameters need not to be measured at this level. Therefore, they are not compact enough, usually not stand-alone devices and they have high price to be equipped into the distribution system level, which requires large number of PQ analyzers compared to generation and transmission levels.

The purpose of this thesis is to design and implement a flexible, low-cost, high-performance PQ monitoring device dedicated to the distribution system level, and make it able to communicate with a PQ center via PLC by using power line as the communication medium. In this thesis, a PQ monitoring device dedicated to the distribution system level using PLC is implemented. The PQ monitoring device uses the existing power lines instead of building a new local area network. The designed PQ monitoring device is named Mini-PQ. The Mini-PQ is a compact, low-cost, high-performance device which is able to satisfy IEC 61000-4-30 standard requirements for just the required PQ parameters. The Mini-PQ is able to send the obtained PQ parameters to an upper PQ center. Both hardware and software running on the Mini-PQ have been developed in this thesis work. In addition, a graphical user interface (GUI) software has also been developed to be used by the PQ++ devices at the upper PQ center. Moreover, communication protocol software has been implemented for the communication of Mini-PQ and PQ++ devices via PLC.

The Mini-PQ is able to measuring three-phase electric grid with three inputs for voltages and three inputs for currents. It can analyze the PQ parameters for all three phases. Due to the fact that some PQ parameters are not crucial for the distribution system levels, the Mini-PQ obtains the listed PQ parameters below:

- Continuity of service,
- Power frequency,
- Voltage and current RMS values,
- Voltage dips, swells and interruptions,
- Current harmonics up to 13^{th} order,
- Active, reactive, apparent power.

Designing a stand-alone and a real-time PQ monitoring device is one of the goals of this thesis. Because there are excessive numbers of customer in the distribution system level in the electrical grid. Achieving this goal, the device is based on the system-on-chip concept. All signal processing routines are implemented in a single digital signal processor (DSP) chip in the scope of this concept. Besides the signal processing, analog to digital converter (ADC) driver and communication modules are implemented in the same DSP chip.

The Mini-PQ consists of a signal conditioning unit, an ADC unit, a DSP unit and a PLC modem. The signal conditioning unit filters and adapts the input signals to the ADC and provides required supply voltages of the Mini-PQ. The ADC unit samples the input signals and sends them to the DSP unit. The DSP unit makes all computations to obtain PQ parameters, in addition to this, the DSP controls the ADC and the communication protocol.

The measurement methods are analyzed according to the recommendations of the IEC 61000-4-30 Standard. To calculate PQ parameters, algorithms are designed and simulated in MATLAB environment. The designed algorithms are embedded into the DSP chip by using a C language environment, which is Code Composer Studio (CCS) in this thesis.

Two PLC modems are used to implement communication over the power line. One is connected to the Mini-PQ and other one is designed to be connected to the PQ++ in the upper PQ center. In other words, one serves as the transmitter and the other one serves as the receiver modem.

Due to the data rate limitations, the Mini-PQ is designed for two modes; minimum and maximum modes. In the minimum mode, the Mini-PQ sends reduced size of data via PLC. On the other hand, in the maximum mode, the Mini-PQ sends all PQ parameters in detail via serial communication. Therefore, two DSP codes and two GUI codes are developed for each mode of operation. In order to display the PQ parameters, a GUI program is designed within scope of this thesis. User interface program reads the data from the Mini-PQ via Universal Asynchronous Receiver/Transmitter (UART) communication protocol by connecting to the PLC modem or directly to the DSP depending on the operation mode.

Verification of the Mini-PQ has been made by applying different waveforms to its inputs. Measurement sensitivity of the Mini-PQ satisfied the IEC 61000-4-30 Standard requirements. In addition to verification, field measurements have been made by the Mini-PQ for both operation modes: The Mini-PQ and a PC have been connected via PLC modems and then they have been connected via serial communication port. During the tests, the Mini-PQ has been able to detect all PQ events and disturbances (those can be measured by it) on the power line.

The Mini-PQ hardware and software are designed to be upgradable, which provides the ability of making much more powerful computations and analyzes in the future. In order to increase the compactness and flexibility of the Mini-PQ, recommendations for future work are listed below:

- In the Mini-PQ, all hardware units are separated from each other. In the future, all units can be lumped to one electronic-board including the PLC modem. To achieve this, a new electronic card can be designed by using selected electronic components used in this thesis.

- The Mini-PQ sends reduced size data when it operates in the minimum mode, because the power lines in the Turkish Transmission System are not designed for communication. In addition to this, available range of frequency in the European standard [2] is not wide enough to send high-speed data. With increasing the technology on the PLC and if the power lines are optimized for communication, the Mini-PQ can send detailed PQ parameters via PLC.
- The DSP unit consists of OMAP L-137 as a core processor chip. OMAP L-137 is a device with a C6747 VLIW DSP floating point processor and an ARM926EJ-S processor. The Mini-PQ uses C6747 as core processor for PQ parameter calculations and all control tasks. To reach more powerful calculations, ARM926 and C6747 can be employed at the same time. In this scenario, ARM926 can be employed as a controller and C6747 as a processor. While ARM926 drives the ADC and implement communication modules, the C6747 can process the raw data simultaneously. This will make the Mini-PQ more powerful and can be used at all levels of the electrical grid with increasing number of measurable PQ parameters.
- The DSP technology improves very rapidly. The speed of the DSP limits the calculation performances of the Mini-PQ. Using new DSPs, may allow to set a higher sampling frequency. All developed algorithms in the scope of this thesis are C language adopted. This provides that, the algorithms can be moved to another DSP easily. In the future, the same algorithm can be moved to a much more faster DSP chip.
- In the future, multiples of the designed Mini-PQ can be connected to electrical grid at the distribution system level and communicated with the National Monitoring Center for Power Quality [27, 19] of the utility in order to monitor the PQ on the Turkish Distribution System through PQ++ monitoring devices.

REFERENCES

[1] *Voltage Characteristics of Electricity Supplied by Public Distribution System.* EN 50160 Standard, 1995.

[2] *Signalling on low-voltage electrical installations in the frequency range 3 kHz to 148.5 kHz.* EN 50065-1:2011 Standard, 2011.

[3] Udea UPLM-M16 PLC Modem Datasheet. Udea datasheet, 2008.

[4] Math H.J.Bollen, Irene Y.H.Gu. *Signal Processing of Power Quality Disturbances.* John Wiley Sons, Inc, 111 River Street, Hoboken, 2006.

[5] *Testing and Measurement Techniques – Power Quality Measurement Methods. Edition 2.0.* IEC 61000-4-30 Standard, 2008-10.

[6] Michael Sek. *Frequency Analysis – Fast Fourier Transform (FFT).* 2006.

[7] LEM Current Transducer CKSR series datasheet. *LEM Datasheet.* 2012.

[8] Analog Devices EVAL-AD7656 ADC datasheet. *Analog Devices Datasheet.* 2010.

[9] Analog Devices AD7656 ADC datasheet. *Analog Devices Datasheet.* 2010.

[10] Texas Instruments TMS320C6747 DSP Datasheet. *Texas Instruments Datasheet.* 2008.

[11] OMAP-L137 EVM Technical Features Document. *Spectrum Digital.* 2008.

[12] A.S. Gill A.Garg. *Designing Reliable Powerline Communications.* Published in EDN network, 2010.

[13] Yitran IT-800 PLC Chip Datasheet. *YITRAN Datasheet.* 2005.

[14] Texas Instruments C6000 Workshop. Implementing a double buffered system, 2006.

[15] L.T. Hua, Z. Xia. The design and implementation of power quality monitor system. *2nd International Conference on Power Electronics and Intelligent Transportation System*, 2:34–37, 2009.

[16] J. Mindykowski, T. Tarasiuk. Dsp-based instrument for power quality monitoring on ships. *JXIX IMEKO World Congress Fundamental and Applied Metrology*, pages 923–927, 2009.

[17] Renato Alves, D.Goncalves, and *et al.* Development of an electrical power quality monitor based on a pc. *IECON 2009 - The 35th Annual Conference of the IEEE Industrial Electronics Society*, pages 3649–3653, 2009.

[18] Ouyang Sen, Huang Shu and *et al.* Design and application of a power quality monitoring equipment based on dsp and cpld. *Power and Energy Engineering Conference (APPEEC)*, pages 1–4, 2011.

[19] I.Cadirci T.Atalik and *et al.* Multipurpose platform for power system monitoring and analysis with sample grid applications. *IEEE Transactions On Instrumentation and Measurement*, PP(99):1–17, 2013.

[20] H. He, Q. Wang and M. He. Design of power quality monitoring system based on dsp. *2009 Second International Symposium on Computational Intelligence and Design*, pages 345–348, 2009.

[21] Lin Tian Hua and Zhao Xia. The design and implementation of power quality monitor system. *2009 2nd International Conference on Power Electronics and Intelligent Transportation System*, pages 34–37, 2009.

[22] Wang Shenghui, Chao Yong, and Jin Xing. Design of power quality monitoring system based on labview. *The 2nd International Conference on Computer Application and System Modeling*, pages 1026–1029, 2012.

[23] Kang Wei, Yan Xiang-wu, and *et al.* Design and realization of power quality monitoring system based on dsp and pci technique. *EPE-PEMC 2006*, pages 420–424, 2006.

[24] J.R. Cloutier, J.H. Evers and J.J. Feeley. A power quality monitoring system: A case study in dsp-based solutions for power electronics. *IEEE Transactions On Instrumentation and Measurement*, 50(3):724–731, 2001.

[25] Mohammad E Salem, Azah Mohamed and *et al.* Development of a dsp-based power quality monitoring instrument for real-time detection of power disturbances. *Power Electronics and Drives Systems, PEDS*, pages 304–307, 2005.

[26] Tomas Radil, Pedro M. Ramos and *et al.* Pq monitoring system for real-time detection and classification of disturbances in a single-phase power system. *IEEE Transactions On Instrumentation and Measurement*, 57(8):1–9, 2008.

[27] Ö.Salor, M.Ermiş and *et al.* Nationwide real-time monitoring system for electrical quantities and power quality of the electricity transmission system. *IET Generation, Transmission and Distribution*, 5(5):540–550, 2011.

[28] Ö.Salor, M.Ermiş and *et al.* Mobile monitoring system to take pq snapshots of turkish electricity transmission system. *Instrumentation and Measurement Technology Conference - IMTC*, pages 1–6, 2007.

[29] Fluke 434/435/437 Three Phase Energy and Power Quality Analyzer. *Fluke Datasheet*. 2012.

[30] Hioki Power Quality Analyzer 3196. *Hioki Datasheet*. 2009.

[31] Veen (Energiened). *Langzaam op weg naar het europa van 230 Volt (Dutch).* 1989.

[32] http://uzay.tubitak.gov.tr/, Accessed January 2014.

[33] *IEEE Recommended Practice For Monitoring Electric Power Quality, Standard*. IEEE Std 1159-1995, 1995.

[34] *Testing and measurement techniques – General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment*. IEC 61000-4-7,2003.

[35] K. Yörür. *Software Development for The Investigation of Power Quality Parameters of Electricity Transmission System*. M.S. Thesis in Hacettepe University, 2008.

[36] P.P. Kumar B.K. Swamy and V. Prasad. A matlab based power quality analyzer (pqa) for enhancing power qulity in the system. *International Journal of Electrical and Electronics Engineering Research (IJEEER)*, 3(1):73–86, 2013.

[37] Rulph Chassaing. *DSP Applications Using C and the TMS320C6x DSK*. John Wiley Sons, Inc, 605 Third Avenue, New York, 2002.

[38] *Star-Hspice Manual Chapter 25*. Avant Corporation, 1998.

[39] Steven L. Bressler. *Spectral Leakaga*. Florida Atlantic University.

[40] www.el-kom.com.tr/, Accessed January 2014.

[41] *Safety of power transformers, power supplies, reactors and similar products*. EN 61558-1:2005 Standard, 2005.

[42] http://www.lem.com/, Accessed January 2014.

[43] Shiun Chen. A. Quantitative analysis of the data acquisition requirements for measuring power quality phenomena. *Power Delivery, IEEE Transactions*, 18(4):1575–1577, 2003.

[44] http://www.analog.com/en/index.html, Accessed January 2014.

[45] http://www.ti.com, Accessed January 2014.

[46] K. Dostert. *Power Line Communications*. Prentice-Hall, 2001.

[47] J. Ahola. *Applicability of Power-Line Communications to Data Transfer of On-Line Condition Monitoring of Electrical Drives*. Phd Thesis Lappeenranta University of Technology, 2003.

[48] J. Bangladesh. *Power Line Communications: Channel Properties and Experiments*. Master Thesis in Lund University, 2008.

[49] http://www.udea.com.tr, Accessed January 2014.

[50] http://www.sage.tubitak.gov.tr/, Accessed January 2014.

[51] Digital Phosphor Oscilloscopes DPO7000 Series Data Sheet. Tektronix datasheet, 2006.

[52] http://www.ume.tubitak.gov.tr/, Accessed January 2014.