LOW COST POWER QUALITY ANALYZER FOR ACADEMIC APPLICATIONS

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Abstract - ***This work presents a low cost power quality analyzer (LCPQA) using Texas Instruments microcontroller TMS320F28027 with a product cost less than 200 USD that will be capable of measuring and displaying all the power quality parameters displayed by a high end power quality analyzer available in the market. The LCPQA is developed exclusively for academic laboratory applications, which doesn't need to survive the stringent industrial conditions, which enables the low cost. The LCPQA will serve as tool for an enhanced study of power quality issues created by various Non-linear loads. The algorithm for measurement of various Power quality parameters which includes, true rms, fundamental, harmonics, symmetrical comp, real, reactive and apparent power etc. is implemented using classical instantaneous p-q theory and instantaneous symmetrical components. The LCPQA is built using current and voltage sensors and the control circuit includes a C2000 launch-pad, signal conditioning board and Sharp Memory LCD Booster Pack for display of parameters. The LCPQA is validated and benchmarked using a FLUKE 434-II power quality analyzer and the results are presented in this paper.***

Keywords— power quality, harmonics, true rms

1. INTRODUCTION

The main motivation behind the development of LCPQA is our interest towards power quality. The FLUKE Power quality meter available within the institution is capable of measuring all power quality parameters such as three phase currents, voltages, real, reactive and apparent power, powerfactor, symmetrical comp etc. which can be stored and retrived later. The cost of this high end power quality analyser is very high. For acadamics such costly metres are not necessary so we framed our goal in such a way that the power quality metre which we develop,

1. Willserve as a experimental facility that will serve multiple branch of students
2. will act as a huge supplement to the theoretical course
3. will be cost effective and maintains good efficiency

The Instantaneous Reactive Power (IRP) p-q Theory [1] is based on the Clarke Transform of voltages and currents in three-phase systems into α and β orthogonal coordinates. Its development was a response to "...the demand to instantaneously compensate the reactive power..." Originally, this theory was formulated by Akagi, Kanazawa and Nabae for the active power filter control. Power properties of three-phase systems are described by the IRP p-q Theory in two orthogonal α and β coordinates in terms of two, p and q instantaneous powers. They are referred to as the instantaneous real and the imaginary powers or more commonly, as the instantaneous active and reactive powers. According to "The instantaneous reactive power, q was introduced on the same basis as the conventional real power, p in three- phase circuits and then the instantaneous reactive power in each phase was defined with the focus on the physical meaning and the reason for naming" Because of it, the IRP p-q Theory has become a very attractive theoretical tool not only for the active power filter control, but also for analysis and identification of power properties of three-phase systems with non-sinusoidal voltages and currents.

Power properties of three-phase systems are expressed by the IRP p-q Theory in terms of only two, active and reactive, p and q, powers, while power properties of such systems, even without any harmonic distortion, depend on three independent phenomena. The IRP p-q Theory has been developed for three-phase systems with nonsinusoidal voltages and currents.

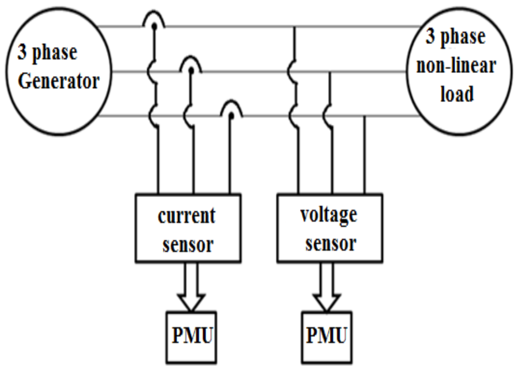


Fig.1. Power circuit diagram

2. *PROPOSED SOLUTION*

1. The three phase voltages and currents of the non-linear loads are sensed using voltage and current sensors as shown in Fig. 1
2. The sensed outputs are interfaced with ADC of TMS320F28027 using a signal conditioning board
3. The digital algorithms are developed for the processor to implement the equations shown below based on p-q theory and instantaneous symmetrical components.
4. The calculated parameters will be displayed in an LCD display.
5. The functional block diagram of the control unit of the proposed LCPQA is shown in Fig. 2
6. Functional features of LCPQA– Measure and display True rms, fundamental, harmonics, % THD, unbalancing, power(real, reactive and apparent), power factor, symmetrical components, frequency

Formulas based on generalized instantaneous pq theory [2]

a). Real power ,

$$\boldsymbol{p = v.i \quad or \quad p = v_a i_a + v_b i_b + v_c i_c} \ldots\ldots\ldots 1$$

b). Reactive Power , $\boldsymbol{q = v \times i = \begin{bmatrix} q_a \\ q_b \\ q_c \end{bmatrix} =}$

$$\begin{bmatrix} \begin{vmatrix} v_a & v_c \\ i_a & i_c \end{vmatrix} \\ \begin{vmatrix} v_c & v_a \\ i_c & i_a \end{vmatrix} \\ \begin{vmatrix} v_a & v_b \\ i_a & i_b \end{vmatrix} \end{bmatrix} \quad or \quad q = \|q\| \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2$$

$$q = \sqrt{q_a^2 + q_b^2 + q_c^2}$$

c). ***Apparent Power ,*** $\boldsymbol{s \overset{\text{def}}{=} vi} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3$

where $\boldsymbol{v = \|v\| = \sqrt{v_a^2 + v_b^2 + v_c^2}}$ **and**

$$\boldsymbol{i = \|i\| = \sqrt{i_a^2 + i_b^2 + i_c^2}}$$

d). Power Factor , $\boldsymbol{\lambda \overset{\text{def}}{=} \frac{p}{s}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4$

e).***THD*** $\boldsymbol{= \sqrt{\frac{I_{rms} - I_{Hrms}}{I_{Hrms}}}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5$

Using the above equations 1, 2, 3, 4 and 5 the various power and power factor are calculated. These are the formulas used in the code composer studio to do the calculations and displays the results.

3. IMPLEMENTATION

3.1 Hardware Implementation

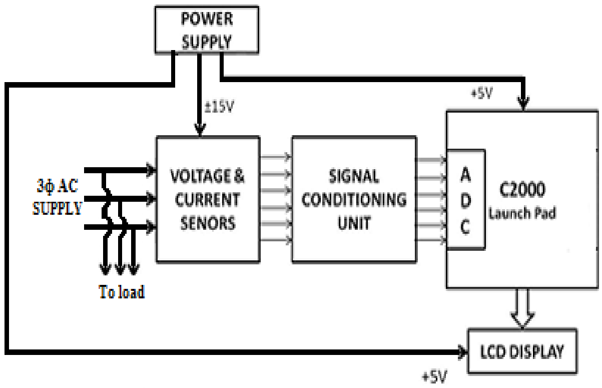


Fig.2. Functional block diagram

Description for Sub-Systems

1. Voltage & Current Sensor:Two voltage and two current sensors are used to sense the three phase balanced system.
2. Signal Conditioning Unit:Two Signal Conditioning circuits (Unipolar) each have two channels
3. C2000 Launch Pad:Evaluation Module from Texas Instruments is used as a controller
4. LCD Display:Sharp Memory LCD Booster pack for displaying output parameters.
5. Power Supply:It supplies
   a. Signal conditioner (±5V)
   b. Current Sensor (±15V)
   c. LCD (+5V)
6. Load:
   Three cases of load are considered
   a. Three phase wye connected Resistive load
   b. Three phase Inductive load
   c. Three phase diode bridge rectifier fed Resistive load.

Voltage Sensor-

Incoming AC voltage is stepped down using potential transformer (230V/3V) and is sent to signal conditioning circuits. In fig.3 we have a normal potential transformer which is used as the voltage sensor.

Fig.3. Potential Transformer

Current Sensors-

LA 25P 711290 Current transducer is used as the current sensor. The current transducer steps down the current in the ratio 1000:1. The stepped down current in terms of voltage is measured across a resistor. In fig.4 is the general current transducer which is being used as the current sensor.

Fig.4. Current Transducer

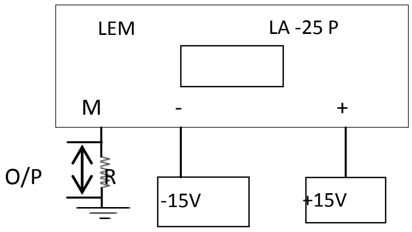


Fig.5. Current Sensor circuit

In fig.5 we can see that a dual supply of 15V is given to the current transducer. Then across the resistor the output is taken. The resistor employed here is 100ohm.

Advantages of current transducer-

1. Excellent accuracy
2. Very good linearity
3. Low temperature drift
4. Optimize response time
5. No insertion loss

Signal Conditioning Unit-

Outputs of Voltage and Current sensors are sent to signal conditioning unit where Bipolar Signals are transformed to unipolar signal using a clamper circuit. Two non-inverting amplifiers are used to limit the gain of the signal. Amplifier and clamper circuits are made using Texas Instruments Operational amplifier LM2902. The signal conditioning output is fed to ADC unit of C2000 micro-controller.
In the fig.6 gives us the general block diagram of the signal conditioning circuit which consist of an amplifier to amplify the input signal and clamper to clamp the signal when it goes beyond the desired value the signal is also shifted to make it unipolar and then buffer is used to maintain the given signal.

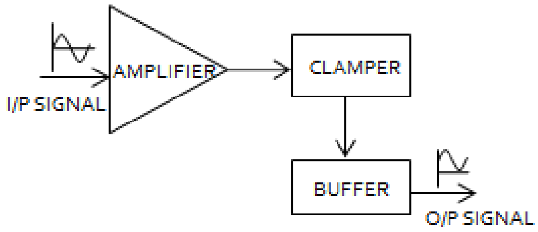


Fig.6. Block diagram of signal conditioning

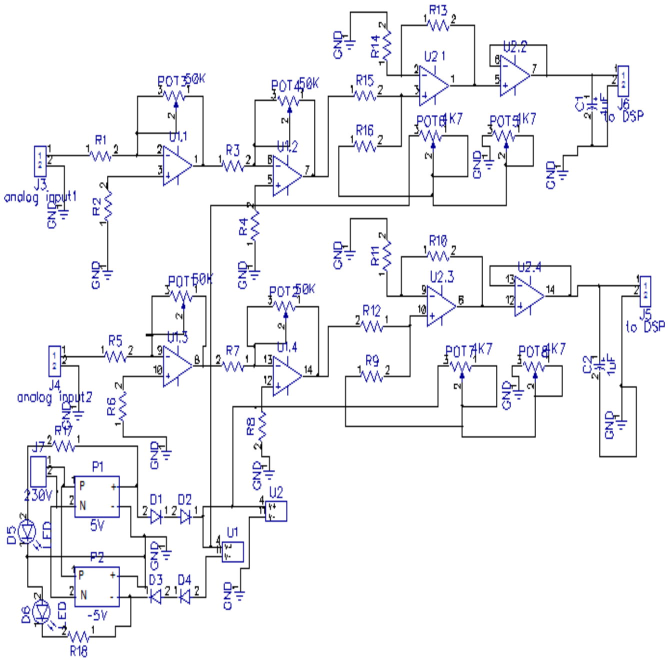


Fig.7 .Signal Conditioning Circuit

Fig. 7. gives the circuit diagram of the signal conditioner in which we use LM2902 quad op-amp, resistors of 10Kohm & 470ohm, pre-set value pot of 50Kohm and 4.7Kohm, 1N4007 diodes, capacitor of 1uF and LED.

Features of LM2902:

- Internally frequency compensated for unity gain.
- Large DC voltage gain 100dB.
- Wide Bandwidth (1Mhz).
- Very low supply drain current
- Low input biasing current

Advantages of LM2902:

- Four internally compensated op-amps in a single package.
- Power drain suitable for battery operation.
- Vout goes to GND
- Direct sensing near GND etc

C2000 Launch Pad

1. High-Efficiency - Three 32-Bit CPU timers
   a. 60 MHz (16.67-ns Cycle Time)
2. Low Cost
3. 48-Pin PT : Low-Profile Quad Flatpack (LQFP)
4. Serial Port Peripherals
   a. SCI (UART) Module
   b. SPI Module
   c. Inter-Integrated-Circuit (I^2C) Bus
5. Peripheral Interrupt Expansion (PIE)
6. Independent 16-Bit Timer in Each ePWM-module
7. Code-Security Module : 128-Bit Security Key/Lock
8. Analog-to-Digital Converter (ADC)

In fig.8 we have the c2000 launch pad microcontroller which is the heart of the LCPQA. The coding's embedded in the processor using Code Composing Studio software.

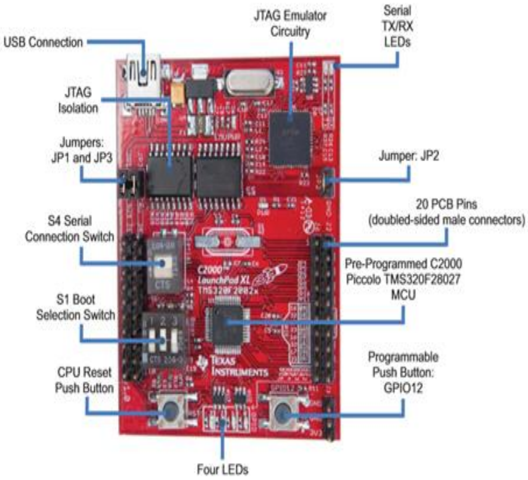


Fig.8. C2000 Microcontroller

Features of C2000 Launch Pad –

1. The F2802x Piccolo family of microcontrollers
2. provides the power of the C28x™ core coupled with highly integrated control peripherals in low pin-count devices.
3. This family is code-compatible with previous C28x- based code, as well as providing a high level of analog integration.
4. An internal voltage regulator allows for single-rail operation. Enhancements have been made to the HRPWM module to allow for dual-edge control (frequency modulation).
5. Analog comparators with internal 10-bit references have been added and can be routed directly to control the PWM outputs. The ADC converts from 0 to 3.3-V fixed full-scale range and supports ratio-metric VREFHI/VREFLO references.
6. The ADC interface has been optimized for low overhead and latency.

Load-

Three cases of load are considered

a. Three phase wye connected Resistive load

Fig.9. Resistive load

b. Three phase Inductive load

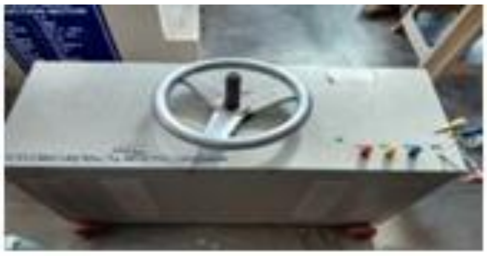


Fig.10. Inductive Load

c. Three phase diode bridge rectifier fed Resistive load.

Fig.11.Three phase diode bridge rectifier

For load we have considered three cases here fig.9, fig.10, Fig.11 are the various loads. These loads are connected and the power quality is monitored.

B. Software Implementation

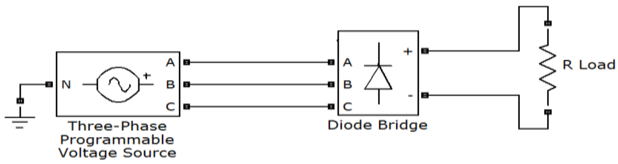


Fig.12. Simple Three-Phase Diode Bridge Rectifier – RLoad

Above in fig.12 we have the simple three-phase diode bridge rectifier which is used for simulation purpose.

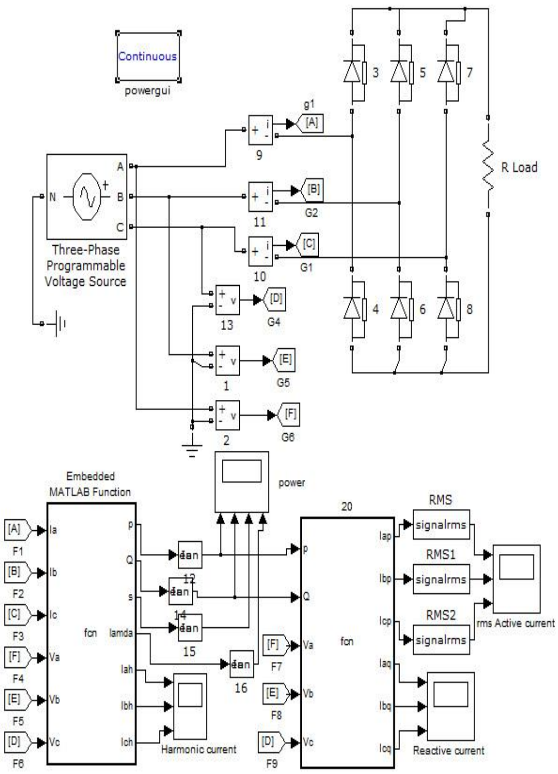
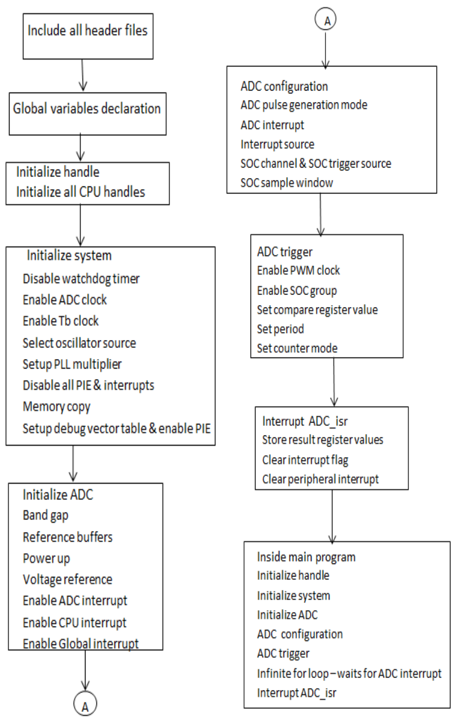


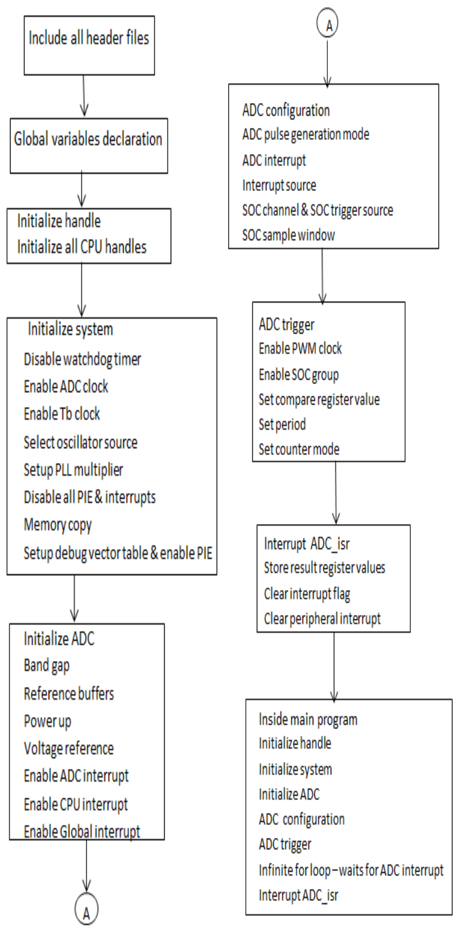
Fig.13.Matlab Simulink model of three-phase diode bridge rectifier



The algorithm for the development of LCPQA is derived from instantaneous PQ theory and is simulated using Matlab/ Simulink environment. And fig.13 gives the complete circuit model of three-phase diode bridge rectifier fed R-Load.

ADC Flowchart: Features & Functions of the ADC module .

The core of the ADC contains a single 12-bit converter fed by two sample-and-hold circuits. The sample-and-hold circuits can be sampled simultaneously or sequentially. It consists of 13 analog input channels. The converter can be configured to run with an internal band-gap reference to create true-voltage based conversions (or) a pair of external voltage references (V_{REFHI}/V_{REFLO}) to create radiometric-based conversions. The basic principle of operation is centered on the configurations of individual conversions, called SOCs .Full range analog input: 0 V to 3.3 V fixed.



The digital value of the input analog voltage is derived by

1. Internal Reference (V_{REFLO} = V_{SSA}. VREFHI must not exceed VDDA when using either internal or external reference modes.)

$$\text{Digital Value} = 0, \qquad \text{when input} \leq$$

$$\text{Digital Value} = 4096 \times \frac{\text{Input Analog Voltage} - V_{REFLO}}{3.3} \qquad \text{when } 0\text{ V} < \text{i}$$

$$\text{Digital Value} = 4095, \qquad \text{when input} \geq$$

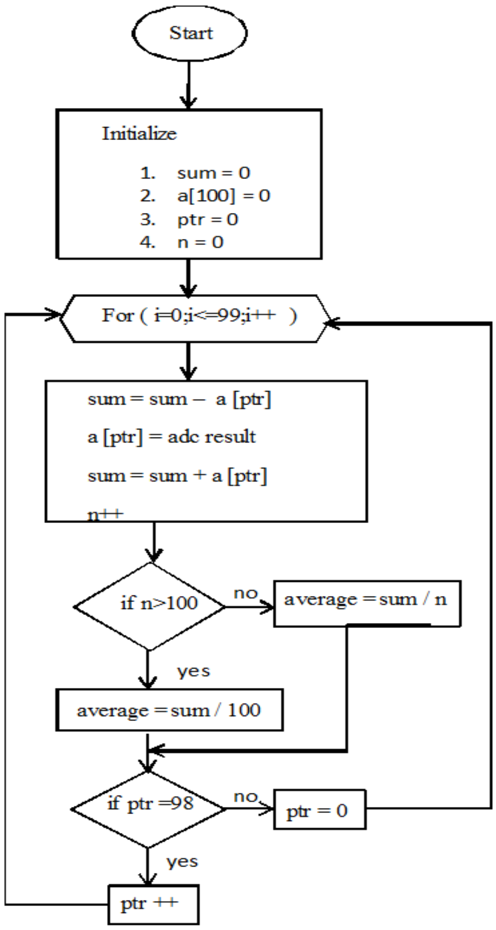
2. External Reference (V_{REFHI}/V_{REFLO} connected to external references. VREFHI must not exceed VDDA when using either internal or external reference modes.)

$$\text{Digital Value} = 0, \qquad \text{when input} \leq 0\text{ V}$$

$$\text{Digital Value} = 4096 \times \frac{\text{Input Analog Voltage} - V_{REFLO}}{V_{REFHI} - V_{REFLO}} \qquad \text{when } 0\text{ V} < \text{input} <$$

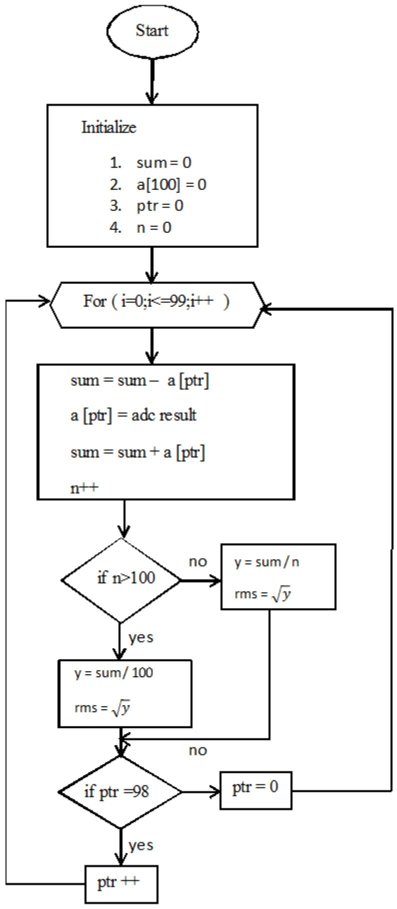
$$\text{Digital Value} = 4095, \qquad \text{when input} \geq V_{REFH}$$

***Moving Average Flowchart*:**



A moving average (rolling average or running average) is a calculation to analyze data points by creating a series of averages of different subsets of the full data set. It is also called a moving mean (mm) or rolling mean and is a type of finite impulse response filter. Variations include: simple, and cumulative, or weightedforms moving average is commonly used with time series data to smooth out short-term fluctuations and highlight longer-term trends or cycles. The threshold between short-term and long-term depends on the application, and the parameters of the moving average will be set accordingly. Viewed simplistically it can be regarded as smoothing the data.

***Moving Window rmsFlowchart*:**



The root mean square is calculated using a moving window. It is calculated for each window of data according to the equation 5:

$$\text{RMS} = \left(\frac{1}{S}\sum_{1}^{S} f^2\,(S)\right)^{1/2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5$$

WhereRMS - Root Mean Square, S - Window Length (Points), f(s) - Data within the Window
According to the equation, the root mean square calculation consists of three steps:

1. Square all of the values in the window
2. Determine the mean of the resultant values
3. Take the square root of the result

ADC Interrupt Service Routine pseudo code:

4. ADC Interrupt Service Routine:
    a. After every ADC conversion an interrupt is being generated and enters the ADC_ISR routine.
5. Various parameters of power quality are being computed in this routine.

6. Moving average of Voltage, Current, real, reactive and apparent powers are being computed.
7. Moving window RMS of voltage, fundamental current and harmonic current are also computed.
8. About 100 samples per cycle of waveform are being taken and ADC trigger is given by PWM pulses.

4. RESULTS

The proposed concept has been well validated using simulation in Matlab/Simulink.

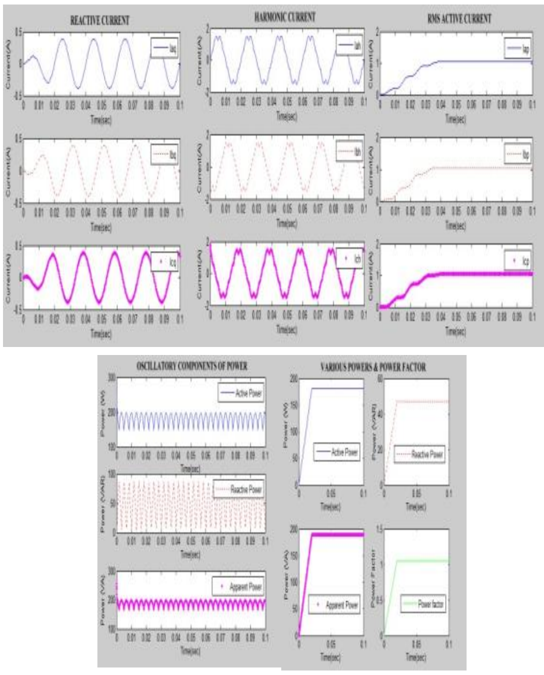


Fig.14.Simulated Waveforms of instantaneous values of extracted components of voltage, current and power using Instantaneous pq theory

Thus, fig.14 gives the simulated results of three-phase diode bridge rectifier fed R load which is done using matlab software

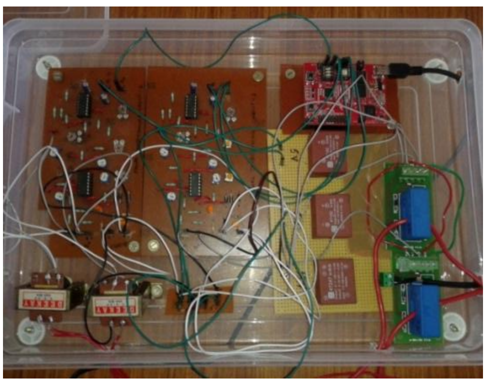


Fig.15. Experimental setup of LCPQA

Here fig.15 gives the complete setup of LCPQA which consist of two voltage sensors, two current sensors, two signal conditioning circuits and c2000 microprocessor.

Fig.16. Complete set up of LCPQA with FLUKE and other loads

In the above fig.16 we can see the complete set of LCPQA with other loads and gives the respective readings which can be viewed in the watch window of Code Composer Studio Software.

VALIDATION OF LCPQA WITH FLUKE 434-II

Benchmarking/Performance Analysis

VOLTAGE (V)		CURRENT (A)	
LCPQA	FLUKE	LCPQA	FLUKE
226	234	3.6	3.4
209	216	2.9	2.7
190	198	2.5	2.3
172	178.4	1.6	1.5
157	160.4	1.4	1.3
132	135.6	1.2	1.2
106	109.5	1.5	1.5
97	98.5	0.94	0.9
165	167	0.86	0.8
81	82.6	0.6	0.6
		0.3	0.3

Table 1: Voltage and Current readings shown in LCPQA and FLUKE (for RL load)

REAL POWER		REACTIVE POWER	
LCPQA (W)	FLUKE (KW)	LCPQA (var)	FLUKE (Kvar)
1451	1.6	1010	1.04
1265	1.35	762	0.80
1210	1.27	632	0.68
1086	1.13	530	0.57
912	0.92	428	0.47
670	0.66	315	0.35
591	0.59	230	0.26
397	0.36	126	0.14
288	0.25	106	0.12
195	0.17	63	0.06

Table 2: Real and Reactive Power readings shown in LCPQA and FLUKE (for RL load)

APPARENT POWER		POWER FACTOR	
LCPQA (VA)	FLUKE (KVA)	LCPQA	FLUKE
2401	2.36	0.89	0.89
1816	1.76	0.86	0.86
1565	1.52	0.82	0.82
1225	1.20	0.78	0.78
945	0.91	0.69	0.69
736	0.70	0.55	0.55
489	0.48	0.33	0.33
364	0.35	0.25	0.25
224	0.20	0.2	0.2
115	0.11		

Table 3: Apparent Power and Power Factor readings shown in LCPQA and FLUKE (for RL load)

From the above Table 1, Table 2 and Table 3 we can see the various readings of LCPQA vs. FLUKE.

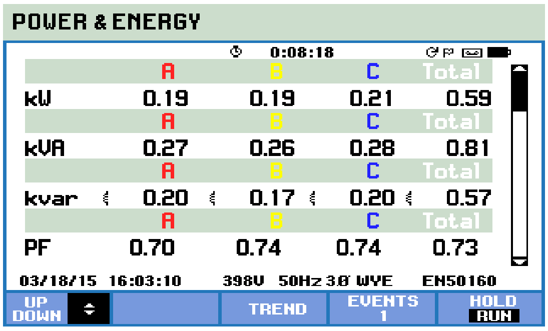


Fig.17. (a)

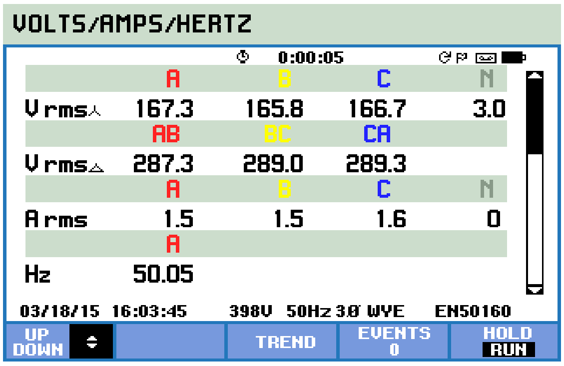


Fig.17. (b)

Expression	Type	Value
(x)= RMS_Voltage	float	165.6024
(x)= RMS_Current	float	1.560346
(x)= Inst_active_power	float	591.2733
(x)= Inst_reactive_power	float	530.7889
(x)= Inst_apparent_power	float	798.8974
(x)= Inst_powerfactor	float	0.7403288

Fig.17. (c)

Fig.17.(a). Various Powers and Power Factor Readings of FLUKE
(b).Voltage and Current Readings of FLUKE
(c).Corresponding Readings Shown in LCPQA

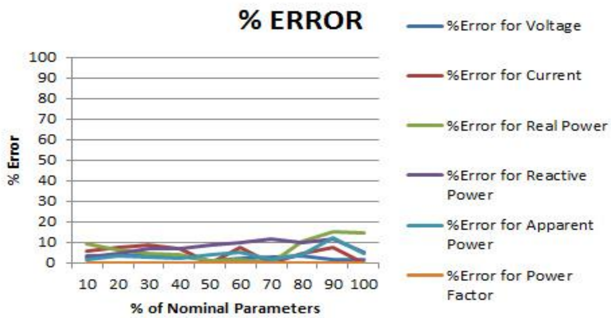


Fig.18. Graph showing the accuracy of the meter at various % of nominal parameters

5. CONCLUSION

The proposed LPQA is expected to meet the high accuracy standards existing market available at a low cost customized to meet the academic needs excluding the waveform display features and data logging features. It is intended to restrict the product cost within 200 USD. For a large scale manufacturing the product cost could be further reduced. Also the LPQA will be calibrated using Fluke 434-II and field tested. A well-defined process will be developed in the due course to convert this prototype to a product.

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