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Research Article

Design of a Cost Effective Optimized Power Factor Measurement Device for Nonlinear Single Phase Home Appliances

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Abstract: Optimized sampling technique to capture the harmonic distortion is the key for power factor measurement of nonlinear loads. Nowadays the power utilities and appliances are fully nonlinear in nature and thus the distortion of harmonics plays an important role and impacts the accuracy of many power factor measurement circuits and instruments. This study provides a cost effective design with a prototype hardware setup with the major components and specifications. Also describes, an optimized computation to calculate the Total Harmonic Distortion based on Discrete Fourier Transform and power quality parameter measuring fundamentals with flowcharts. This prototype is tested for accuracy and consistency and compared the performance with two different commercial equipments with different types of nonlinear home appliances loads with different instances. The results are proved that the prototype is at par with the standard leading commercial equipments, but cheaper by cost wise. This design can be extended further to achieve better cost effective power factor correction.

Keywords: MSP430, nonlinear home appliance loads, optimized technique, power factor correction, power factor measurement, total harmonic distortion

INTRODUCTION

To achieve the efficiency of the power system, the Power Factor (PF) should be in desired level. PF is a measure states how effectively the electricity is getting used. Most of the industrial loads are inductive in nature which has an inherently low PF. If the PF is low, which means the demand of current is much more than the theoretically calculated. This excess current, usually wattles current overloads the power system design. So, it's a must to keep the PF in control with desired limits for the same the measurement is important. In practical, the PF is far from unity which needs to be corrected. Unless we measure it, we can't correct. So the correct measurement of PF is important for any power system.

For any alternate current power system power quality parameters, PF is one of the primary factors which is simply defined as the ratio of real power in kW with apparent power in kVA. Ideally the real power is equal to apparent power which is there for pure resistive loads. So, the PF value is unity for pure resistive loads which describes in other way as it's a 100% efficient electrical power network system.

The PF is influenced by many factors which are predominantly caused by the non linear loads such as Motor Drives, Inert Gas Lightings; Micro Controller based Digital Appliances, Home Appliances, Temperature Controlled Furness, Heating Elements and Personal Computers etc. So the power factor varies which is required to be maintained to our desired level. So the measurement of the PF is very critical especially for nonlinear loads. Nonlinear loads are usually non sinusoidal and with high mix of noises, surges & other disturbances. The world now is merely with non linear loads, complex and thus the measurement of PF is known as critical due to the presence of harmonic frequencies along with the fundamental.

Measuring the harmonics is the real challenging for any power appliances where it depends on the approximations, estimations and do a math to compute. The alternate power system is symmetric in nature and so the even harmonics will get cancelled each other, but the odd harmonics will have a big impact, so which is one of the critical power quality parameter of the power system. Figure 1 shows the amplitude of Fundamental, Odd and Resultant Harmonics.

For a simple power distribution system served by 'Trapezoid' shape AC current, the harmonic spectrum up to 50^{th} order is shown in Fig. 2 (Shah, 2013). This gives further clear understanding about the impact in resultant amplitude by the presence of odd order harmonics.

There is no instrument that measure PF directly but derived mathematically from measured quantities such as voltage, current and phase angles in terms of time relationship. Therefore the correct determination of PF

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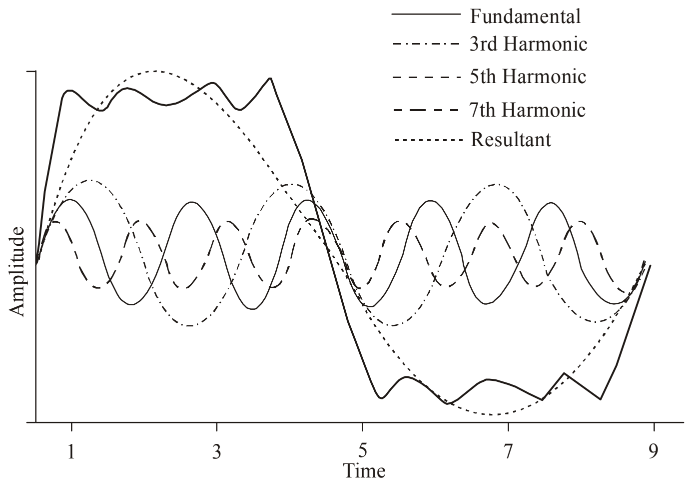

Fig. 1: Representation of fundamental, odd and resultant harmonics

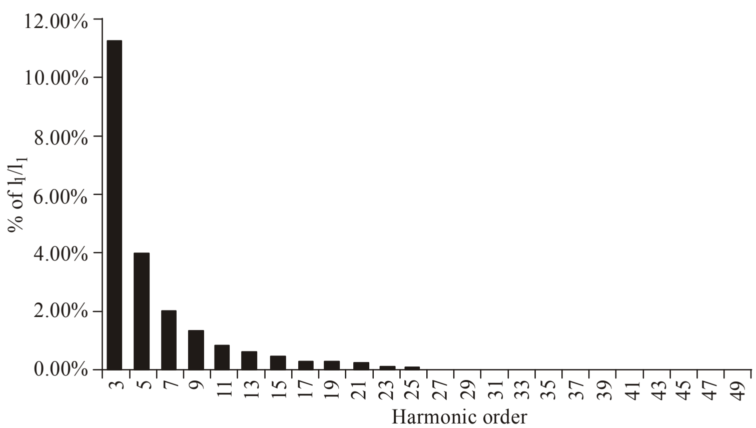

Fig. 2: Representation of fundamental, odd and resultant harmonics

requires accurate measurement of time relationship in terms of proficient mathematics along with voltage and current measurement.

There is a mathematical relationship between PF and harmonics. And as per IEEE Std 739 (1995), if the displacement PF ignored, harmonic currents of 20% relate to a power factor will just get by over 98% and harmonic distortion of 5% requires a PF of over 99.8%.

At present, there is no commercial equipment or instrument available for measuring the PF alone. Rather than measuring there are plenty of solutions to correct the PF to unity. PF correction is required by obvious, but the measurement is a must for any analysis to understand the poor quality power. And, there are Energy Management Devices, Solutions available which measures the PF as one of the Power Quality Parameters, but the cost of those equipments are very high which is quiet unnecessary for any domestic single phase home appliances. Those devices will do complete energy monitoring along with the PF which may not be the interest for any house owner to install such a higher end, high cost device for every appliances to monitor the power quality parameters. Also the lower end devices will not help beyond the certain extent as the measurement accuracy is not as good as the expected level. So there's a need to have a PF measurement device for nonlinear type of single phase home appliances as a cost effective solution, but in the same time the measurement should be optimized to accurate.

This study fills this need by providing a suitable design of a cost effective optimized power factor measurement device as a solution for nonlinear single phase home appliances. Here, effective utilization of the microcontroller for only the necessary and sufficient computation to derive and obtain the PF from the basic measurable power quality parameters is considered as optimization. The better optimization technique allows going for general multipurpose microcontroller itself which saves cost considerably when comparing with the other specially made energy management microcontrollers.

Definitions: IEEE Std 1459 (2010) provides the definitions of power quality parameters and also the

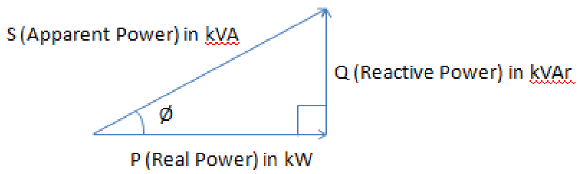

Fig. 3: Vector relationship of real, reactive and apparent power

guidelines for designing the instrument for measuring the same including Power and Energy. From Fig. 3, the fundamental relationship between Real, Reactive and Apparent Powers of any linear type loads. PF (CosØ) which is defined simply by Eq. (1) and (3). Basically this is caused due to the displacement angle Ø, so it's called as Displacement Factor (DPF):

$$DPF = \frac{P_{rms}}{S_{rms}} = Cos\ Ø \tag{1}$$

$$S_{rms} = V_{rms} * I_{rms} \tag{2}$$

So Eq. (1) becomes (3), by implementing S_{rms}:

$$DPF = \frac{P_{rms}}{V_{rms} * I_{rms}} \tag{3}$$

PF tells the amount of reactive power in kVAr involved in any power system. The reactive power is an amount of energy which do not dissipate but consumed by reactive loads such as inductors, capacitors etc.

For nonlinear type loads, there are harmonics and so the power gets distorted. So there is a Distortion Factor (DF) which is measured in terms of Total Harmonic Distortion (THD). Based on IEEE Std 1459 (2010), the THD is defined as Eq. (4) and the same is related with DF at Eq. (5) and (6) the PF is derived for nonlinear loads (Grady and Gilleskie, 1993):

$$THD = \frac{\sum_{k=2}^{\infty} P_k}{P_1} = \frac{\sum_{k=2}^{\infty} V_k}{V_1} = \frac{\sum_{k=2}^{\infty} I_k}{I_1} \tag{4}$$

where,
P_1 = Real Power in kW at Fundamental Frequency
P_k = Real Power in kW at k^{th} harmonic Frequency
V_1 = RMS Voltage in Volts at Fundamental Frequency
V_k = RMS Voltage in Volts at k^{th} harmonic Frequency
I_1 = RMS Current in Ampere at Fundamental Frequency
I_k = RMS Current in Ampere at k^{th} harmonic Frequency:

$$DF = \frac{1}{\sqrt{1 + THD^2}} \tag{5}$$

$$PF = DPF * DF \tag{6}$$

So, the product of Displacement Factor and Distortion Factor will give the Power Factor for nonlinear loads, but the challenge lies with the accurate capturing of Distortion Factor measured in terms of Total Harmonic Distortion. Measuring THD needs to use an application with high speed digital computing techniques to measure the power parameters by sampling the wave forms using better sampling theories. The relation of Harmonics and Power Factor is described in Grady and Gilleskie (1993).

The Fourier Transform converts a waveform from time domain to frequency domain. From the basic measurements as per IEEE Std 1459 (2010) for non-sinusoidal power components by Fourier analysis (Mansour and Chengning, 2013), the time domain waveform is defined. The Current value of harmonic is defined in Eq. (7) as:

$$I_k = \sum_{n=0}^{N-1} I_n e^{\frac{-j.2\pi kn}{N}} \tag{7}$$

where,
I_k = Complex Number includes amplitude and phase value of the current signal at k^{th} order harmonic frequency
N = Number of Samples
I_n = Measured RMS Current of nth sampling instance

The Eq. (7) can be converted into Real Part and Imaginary Part as Eq. (8) and (9):

$$Amp\ |I_k| = G_i * \sqrt{2} * \frac{\sqrt{Re\{I_k\}^2 + Im\{I_k\}^2}}{N} \tag{8}$$

$$Phase\ I_k = tan\left(\frac{Im\{I_k\}}{Re\{I_k\}}\right) \tag{9}$$

where,
G_i = Scaling Factor (based on Current Transducer)

The Real value and Imaginary value of Eq. (7) is derived as Eq. (10) and (11):

$$Re\{I_k\} = \sum_{n=1}^{N} I_n * cos\left(\frac{2\pi kn}{N}\right) \tag{10}$$

$$Im\{I_k\} = \sum_{n=1}^{N} I_n * sin\left(\frac{2\pi kn}{N}\right) \tag{11}$$

LITERATURE REVIEW

The energy meter based on microcontroller to measure the power quality parameters by transducers and communicating by USB to a host personal computer is briefed in Gallo *et al.* (2010). The Digital Signal Processing (DSP) based approach using Fast Fourier Transform (FFT) for computing THD is followed using the chip STM32F103RB of ARM family. Since the sampling rate followed is low as 256/sec, the measured values will not be accurate. The low cost solutions for measuring power quality parameters from D'Apice *et al*. (2007), Minosi *et al*. (2003) and McEachern and Eberhard (2009) are considered to understand their effective utilization of the microcontroller. The microcontroller is the one has the complete control of the solution with various computations, sampling logics and algorithms etc. So, the various similar measurement solutions based on different types, makes of the microcontroller is studied carefully and analyzed in detail. In Wattanayingcharoen *et al*. (2012), it describes the harmonics measurement based on IEEE Std 1459 (2010) standard using Cortex-M3, a high performance 32 bit microcontroller, where the results comparison didn't provide the complete picture of the new instrument as it's not compared with commercial equipment statistically.

Monitoring of power quality parameters of s substation is attempted by Thiyagarajan and Palanivel (2010) using Atmel AVR microcontroller. Nothing about harmonics is addressed and rather their application notes Atmel AVR1631 (2012) did. MSP430 from Texas Instrument (TI) is used in Qiang *et al*. (2013) for power quality monitoring. But the same is using another customized Integrated Circuit (IC) ATT7022E which has the power quality parameters computations already. It's really not required to use two ICs for this requirement. TI's C6711 prototype board is used for the similar solution but with DSP Implementation (Gherasim *et al*., 2004). ATMEGA16, which is an 8 bit RISC micro controller is used in Bhatti and Asati (2012) with Phase Lock Loop (PLL) and Discrete Fourier Transform (DFT) for Harmonic Detection, but limited only with 3rd Order. In Basciftci and Hatay (2010), PIC 18F452 is used for reactive power measurement and tried PF correction for a refrigerator load by proper utilization of capacitor loading, but not by PF measurements. Energy Metering ICs as ADE7763, ADE7880 from Analog Devices, CS5463 from Cirrus Logic and TMS320C2000 from TI are straight away measures the values of certain power quality parameters, but when in harmonics, they will get only the magnitude, i.e., the real value, but the imaginary value need to be obtained from the phase information which need to be computed. And moreover, these are costly and higher end ICs when compared with MSP430 series from TI.

The limits of THD are described in IEEE Std 519 (2014). However typically, the harmonics are measured up to 25^{th} order, but in critical applications, those are measured up to 50^{th} or 100^{th} order (Shah, 2013). From the harmonic spectrum in Fig. 2, it's figured out as 80% of resultant harmonic impact is obtained within 7^{th} order itself. And further 90% is achieved by 13^{rd} Order, 98% by 25^{th} Order and 99.8% by 39^{th} Order.

For harmonic computation from waveform sampling, FFT and DFT techniques are used widely and in many references. The Discrete Wavelet Transform (DWT) by Pham and Wong (1999) and Gaouda *et al*. (2002) and also the Goertzel Algorithm by Goertzel (1958) also other computation techniques described, but not efficient. The most commonly used harmonic estimation method is by DFT. The instrument described in IEC 61000-4-7 (2009) is based on this method only and the DFT algorithm is known as standard and recommended by the power quality standards (Radil and Ramos, 2011).

So, the proposed design is made using MSP430 series and developed a cost effective PF measurement for home appliances. Based on the definitions, principles and guidelines from IEEE Std 1459 (2010) and IEC 61000-4-7 (2009) the design and optimized computation is made to achieve the solution.

PROPOSED DESIGN AND OPTIMIZED COMPUTATION TECHNIQUE

The microprocessor from TI, MSP430 power series is already with sigma-delta ADC and suitable for all our power related math and sampling calculations. There are few functions in built will support and meet our requirements upfront. And the same can be enhanced further for power factor correction application also in future. For the accurate measurement lies with the sensors to pick up the voltage and current from even distorted power and ripples. So carefully chosen the transducers from Honeywell, LEM and they are linked with Microcontroller by Analog to Digital Converters. The suitable filters and zero crossing detectors are provided to capture the exact distorted non-sinusoidal waveform of current and voltage as it is to the microcontroller for proper computation and further measurement calculations. Standard cost effective Flip-Flops, Op Amps are also used for the above purpose. The output is fed to computer by simple USB interface and the data can be either getting stored, so that it will be available to export into excel to see the graph with respect to time or view the live graph using an interface software, called 'iobridge' which is available for free download from the website "www.iobridge.com/interface".

The design is made for measuring the power of domestic home appliances which is rated less than 1000 W, operating at 230 V, 50 Hz frequency. The block diagram of the proposed optimized power factor measurement is shown in Fig. 4.

The microcontroller MSP430F47197 is a 16 MHz device and has seven Analog to Digital Converters (ADCs) which are 2^{nd} order Sigma-Delta architecture and supports for energy measurement application even for three phase system. This is a cost effective and ultra low power microcontroller from Texas Instruments, operates at 3.3 V DC. All the 16 bit ADCs will collect the sample of instantaneous voltage and current by

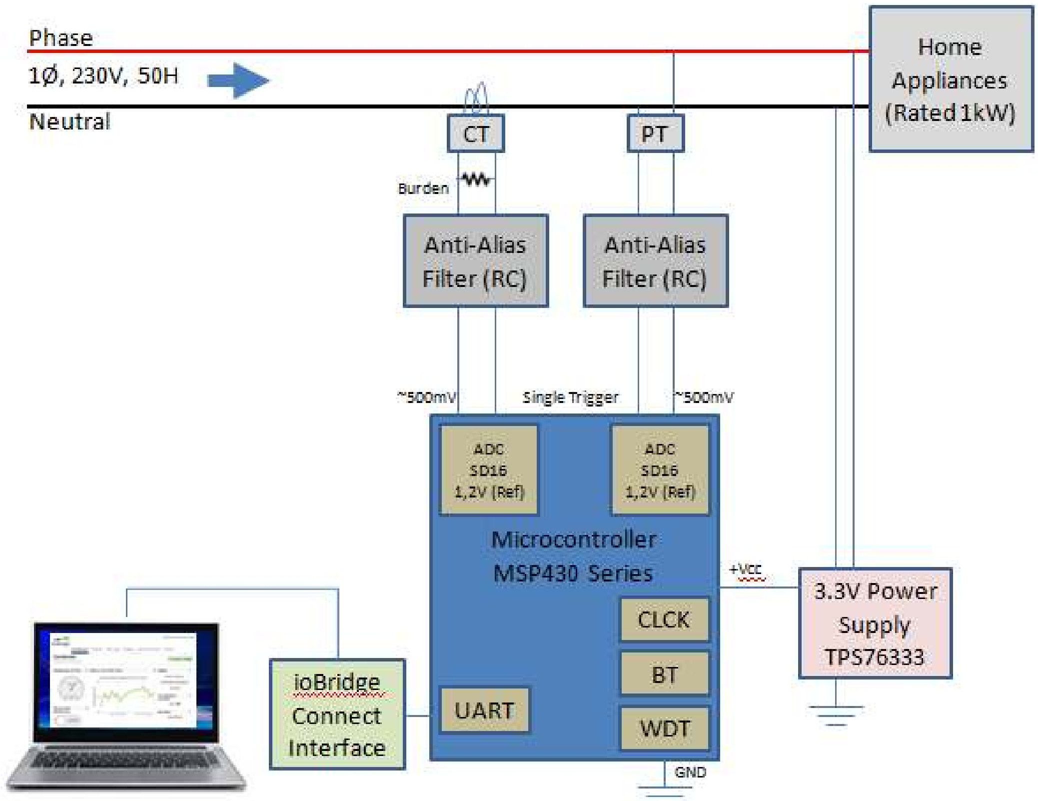

Fig. 4: Block diagram with various modules of the proposed design

single trigger. The Oversampling Ratio (OSR) is chosen to be 256 and the modulation frequency f_M as 1 MHz gives the sampling frequency as 4096 Hz. The Basic Timer is set with 1 sec interrupt precisely (Underwood *et al*., 2009). TPS76333 Low Dropout (LDO) regulator from TI is used to provide the required +3.3 V regulated DC voltage to power up the microcontroller MSP430F47197. The dropout voltage is typically 300 mV at 150 mA and with 5 terminals SOT-23 IC package. There are many existing designs available for the +3.3 V power supply using this IC TPS76333 and here the reference design from Underwood *et al*. (2009) is followed.

A +3.3 V, ~10 A rated current transducer with the accuracy of +0.25% is chosen from the market and with suitable burden resistor and anti-aliasing filter, connected with the microcontroller. A simple resistive based voltage divider is used as a voltage transducer to bring down the supply voltage to a 500 mV range. Necessary protection components, anti-aliasing filters are provided.

As per IEEE Std 519 (2014) guidelines, at any Point of Common Coupling (PCC), the measured THD should not exceed 5%. So, typically measuring up to 25th order harmonic distortion will give a clear indication about the nonlinear load. But considering the fact about the microcontroller processing time for the Sin and Cosine calculation will take more time. Since the same in embedded system is done iteratively using Tylor or Maclaurin series which makes the processor relatively slow (Bacurau *et al*., 2014). So, it's better to limit the harmonic calculations up to 13th Order itself which is above 90% of capturing the harmonic impact alone, but in total the measurement covers 98.5% of the data. For the typical home appliances, this accuracy is more than sufficient to control the THD within specified limits of IEEE Std 519 (2014).

Based on the sampling rate and the optimization derived, the basic formulas are fine tuned to more precise as in Eq. (12) and (13):

$$V_{rms} = G_v * \sqrt{\frac{\sum_{n=1}^{4096} V_n^2}{4096}} \quad (12)$$

$$I_{rms} = G_i * \sqrt{\frac{\sum_{n=1}^{4096} I_n^2}{4096}} \quad (13)$$

where,
G_v = Scaling Factor (based on Voltage Transducer)
G_i = Scaling Factor (based on Current Transducer)

By substituting the sampling rate N = 4096, Eq. (7) becomes (14) and accordingly the other Eq. (8) to (11) also get varied:

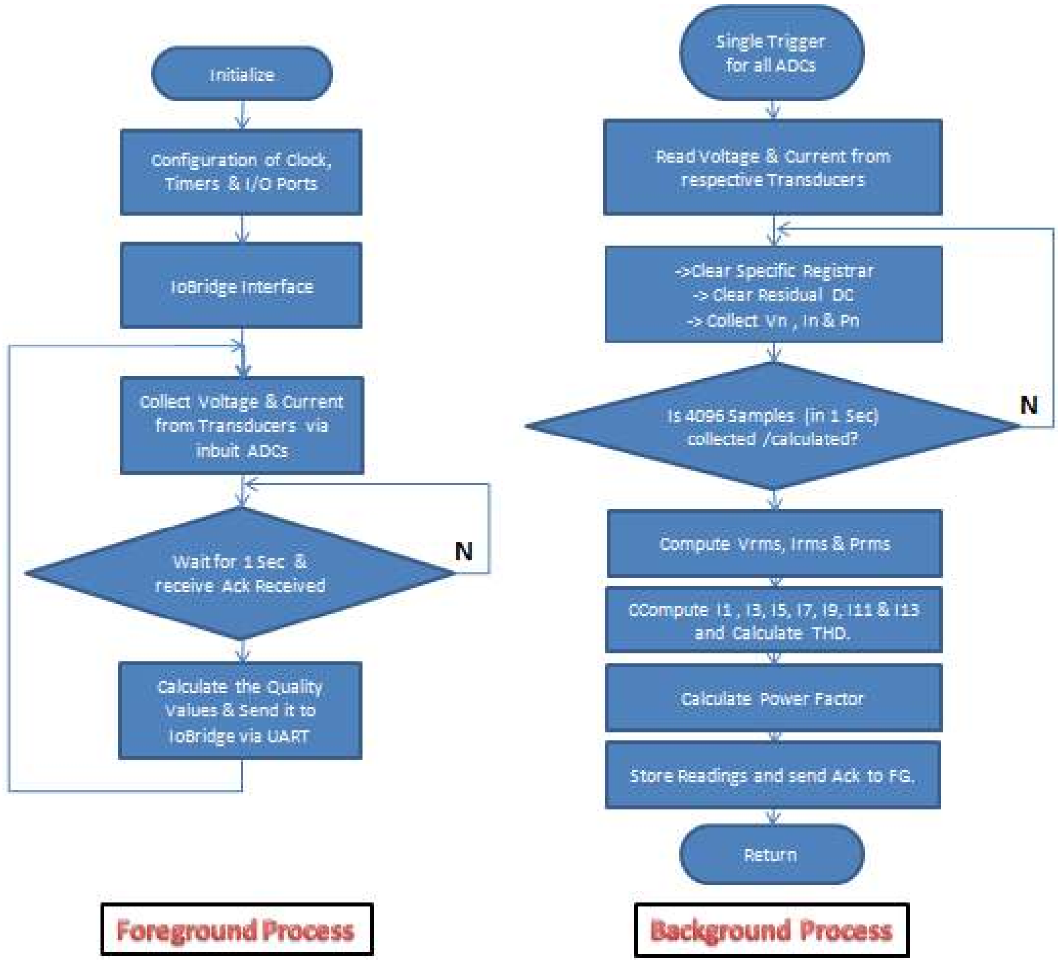

Fig. 5: Flow charts for program

Table 1: List of materials used for prototype

Description	Manufacturer
Microcontroller	MSP430F47197 from TI
LDO regulator	TPS76333 from TI
Current transducer	Multisource
Varistors	Multisource
Actives components	Multisource
Pasive components	Multisource
PCB_general purpose	Multisource
Interfacing com. cable	FCI
Lead wires	Multisource
Protection relays	Omran
Consumables	Multisource

$$I_k = \sum_{n=0}^{4095} I_n e^{\frac{-j.2\pi kn}{4096}} \quad (14)$$

The Eq. (4) is optimized up to 13th order only and removed the even order harmonics as the waveform is symmetric in nature, so Eq. (4) becomes (15) as below:

$$THD = \frac{I_3+I_5+I_7+I_9+I_{11}+I_{13}}{I_1} \quad (15)$$

Finally, substituting Eq. (4) and (5) in (6) we get PF as Eq. (16):

$$PF = \left(\frac{P_{rms}}{V_{rms} * I_{rms}}\right) * \left(\frac{1}{\sqrt{1+THD^2}}\right) \quad (16)$$

Figure 5 is the flow chart of the programming flow based on the sequences of calculations and measurements.

In order to prove the concept, the proto is prepared and tested on bench at lab. For preparing the proto, the components are purchased from online traders and proto type suppliers which are basically at higher prices, so there’s a scope to have further better final price for this proposed model. The is the Table 1 lists the Bill of Material of proto type without any enclosure and mechanical supports. Based on the estimation of this proposed device cost, it’s calculated as it’s cheaper by at least 40% when comparing with the existing solutions.

RESULTS AND DISCUSSION

In instrumentation, every assembled meter has an error of the same magnitude in its range of tolerance. No two meters will give same results on same

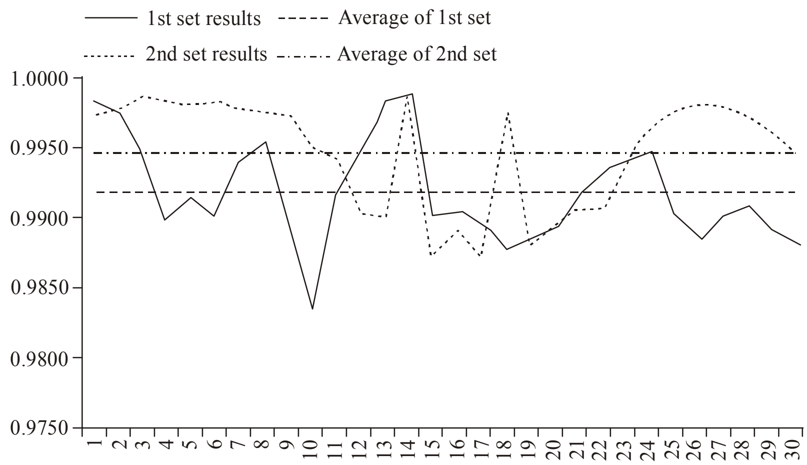

Fig. 6: Observation of variation of two consecutive set of measurements

Table 2: Set of PF measurements of incandescent bulb to check accuracy

Test No.	Measured value	Expected value	Diff in (%)
1	0.9921	1.0000	-0.79
2	0.9924	1.0000	-0.76
3	0.9919	1.0000	-0.81

measurement, unless it's calibrated. The best traditional way of calibration is to measure the parameters using new instrument from known accurate calibrated source of those parameters and align the measurement from the instrument to match the values of source. Here, the prototype is connected with the calibrated power source which supplies 230 V, 50 HZ to a 1 A linear load. Now, the measurements are matched with to the exact source value by adjusting the scaling factor G_i and G_v represented in Eq. (8), (12) and (13). In order to ensure proper calibration, the same procedure is repeated with another set of different reading and validated by measuring the third set of readings.

Now, the calibrated prototype of the proposed design is tested for their Accuracy, Consistency and compared the results with two other commercial branded equipments.

The accuracy is the degree to which the measurement conforms to the correct value or standard value. The PF is standard for the pure resistive load. So, the incandescent light bulb load is measured for its PF by the calibrated proto type and found the results as below.

And, the same test is continued for every 2 min and collected 30 measured results for 1st h. The variations are observed to see the repeatability of the measurements to judge the consistency. To ensure, the test is repeated for another hour and collected 2nd set of 30 measured results (Table 2).

The unit is designed for domestic application and so the two most common non linear home appliances (Television and Water Pump Motor) in India are considered and compared the measured values of the prototype with two standard and branded commercial equipments (Agilent and Yokogawa). All three measuring devices are connected with to the load such that the measurements of all are taken at the time with same common operating conditions of source as well as the load. Only the PF value is measurement taken for 30 times as a set for every instance. The Capacitive and Inductive load, basically will influence the PF by voltage fluctuations due to the variation in current. So the tests are carried for two loads at two voltage conditions which give 4 test instances. Thirty readings per equipment for one instance, gives total 360 readings which are shown in Table 3 with the mean, max and min values.

Performance analysis: The values of PF when measured for unity PF load, the difference is seen as <1% from the Table 2 and same is plotted in graph, shown in Fig. 6. It's also noticed that the value is not crossed the unity and only third decimal is varying. It meets the standard 2% accuracy of market level.

From the continuous measurements of 2 sets of 30 readings shows the average which are accurate by two decimal. The statistic analysis of two set of readings are shown in Fig. 7 and 8 from where the values are concentrated within very narrow range of PF. The prototype can provide almost the same result consistently with +1% of variation.

The comparison results from Table 3, indicates that the prototype measures the value at par with the other two commercial equipments and provides similar results within the range of its tolerances (Fig. 9 and 10).

So, the performance of the prototype can be consolidated as its measurements are >98% accurate, consistent with +1% variation and at par with the commercial measuring equipments.

Table 3: Comparison of PF measurements of home appliances of proto type with commercial equipments

Nature of nonlinear load	Description of load	Voltage condition	By proposed prototype			By key sight 6800 (formerly Agilent 6800)			By Yokogawa WT210		
			Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.
Capacitive	LCD TV	@240V	0.6960	0.7085	0.6821	0.71	0.73	0.66	0.6895	0.7012	0.6826
Capacitive	LCD TV	@210V	0.6756	0.6871	0.6587	0.68	0.70	0.66	0.6707	0.6814	0.6606
Inductive	0.5HP motor	@240V	0.4169	0.4248	0.4106	0.42	0.43	0.41	0.4134	0.4208	0.4113
Inductive	0.5HP motor	@210V	0.4012	0.4086	0.3932	0.41	0.42	0.38	0.4003	0.4077	0.3963

Max.: Maximum; Min.: Minimum

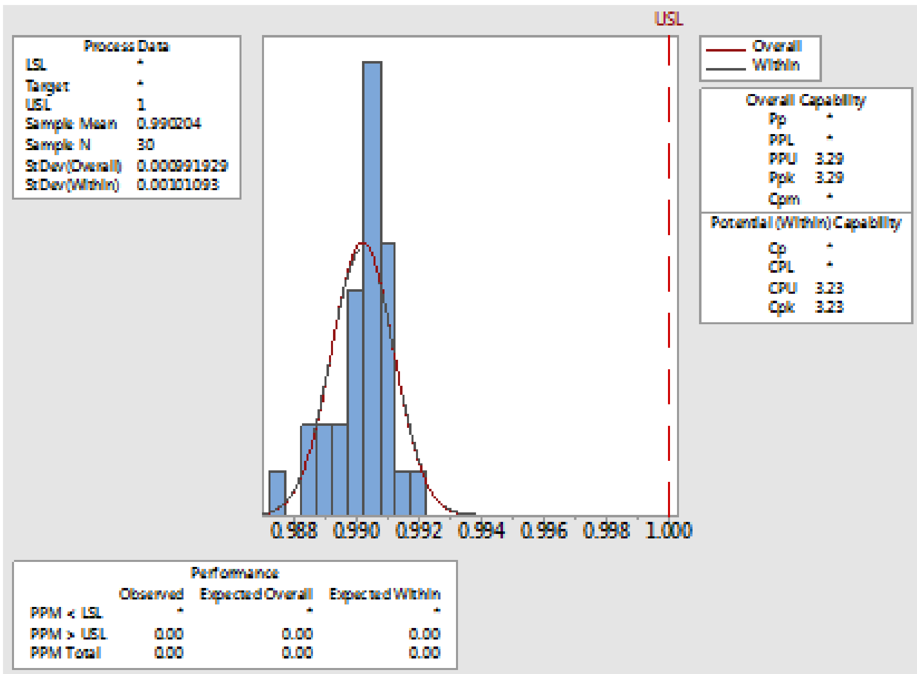

Fig. 7: Statistical curve of 1st set of measurement

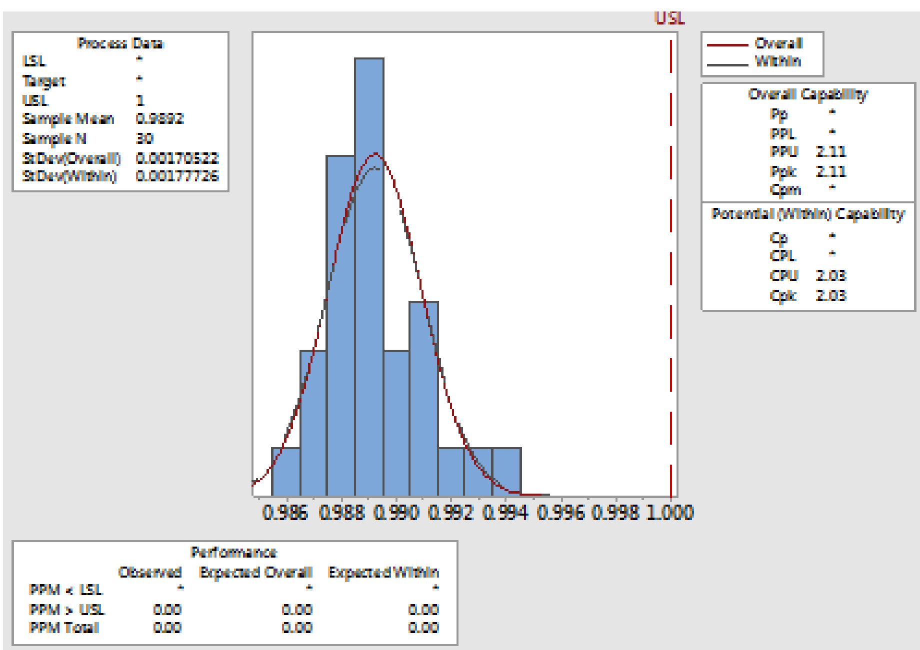

Fig. 8: Statistical curve of 2nd set of measurement

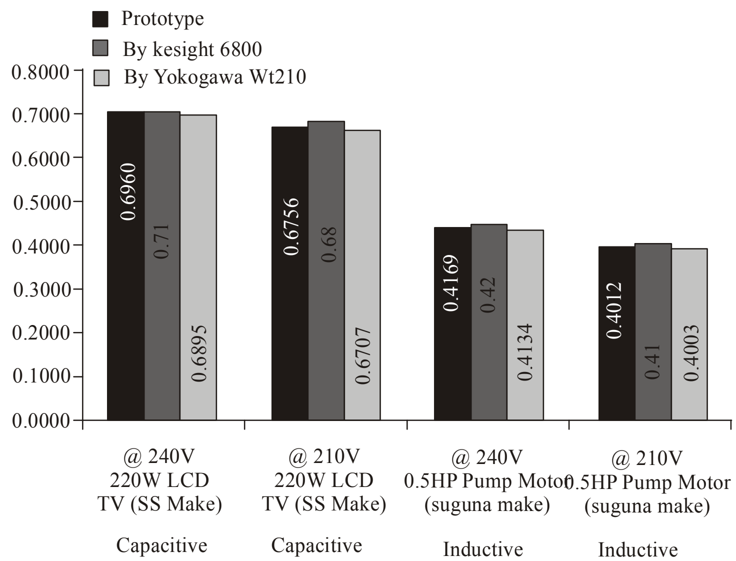

Fig. 9: Graphical view of comparison PF measurements from Table 3

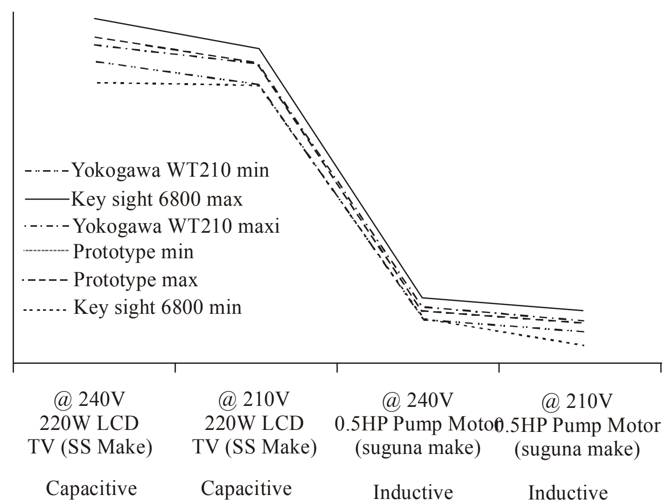

Fig. 10: Pattern observation of all four measurements from three instruments

CONCLUSION

The objective of designing a cost effective Power Factor Measurement device for a single phase nonlinear type home appliances way with necessary optimization is done and the prototype is made. And the same is tested individually and also tested along with the branded commercial instruments for comparison. The performance of the prototype is weighed in terms of accuracy, consistency and comparison. The result of performance analysis states that the prototype is accurate by >98%, consistent by ¬+1% and at par with the commercial equipments. The THD measurements are optimized to cover the max of 98.5% of overall harmonics and the same ensures the THD value of the home appliances to validate against the specified limits of IEEE Std 519 (2014). This optimization relaxed the complexity of processing calculations, speed which doesn't demand for any higher end, high cost microcontroller and supporting peripherals. Thus the cost of this proposed model is estimated at least cheaper by 40%.

This design proposal is made for 1Ø, 230 V, 50 Hz, 1000 W home appliances, but the same can be extended to the industrial usages and three phase systems. Since, the industrial applications are very vast, the design has to be carefully optimized to capture the actual PF measurement. However, we can proceed by providing an option by a soft select switch to choose the application, which basically selects the right optimization at back end. And the hardware setup for measuring the PF is same with the Power Meter. So this can be used for Power and Energy Management applications too.

REFERENCES

Atmel AVR1631, 2012. Single Phase Energy Meter using XMEGA A: 8-bit Atmel Microcontroller. 42039A-AVR-11/2012.

Bacurau, R.M., E.C. Ferreira, L.F.C. Durate and J.A.S. Dias, 2014. Techniques for efficient implementation of firmware in microcontroller's based energy consumption breakdown smart meters. VIVECHAN Int. J. Res., 5(1).

Basciftci, F. and O.F. Hatay, 2010. Microcontroller-controlled reactive power measurement and saving circuit design for residences and small-scale enterprises. Sci. Res. Essays, 5(16): 2312-2317.

Bhatti, J.K. and D. Asati, 2012. Harmonic detection using microcontroller. Int. J. Comput. Technol. Electron. Eng., 2(3).

D'Apice, B., C. Landi, A. Pelvio and N. Rignano, 2007. A multi-DSP based instrument for real-time energy and PQ measurements. Metrol. Meas. Syst., 14: 495.

Gallo, D., G. Ianniello, C. Landi and M. Luiso, 2010. An advanced energy/power meter based on ARM microcontroller for smart grid applications. Proceeding of the 17th Symposium IMEKO TC 4, 3rd Symposium IMEKO TC 19 and 15th IWADC Workshop. Kosice, Slovakia.

Gaouda, A.M., S.H. Kanoun, M.M.A. Salama and A.Y. Chakhani, 2002. Wavelet-based signal processing for disturbance classification and measurement. Proceeding of the IEE Generation, Transmission and Distribution Conference, 149: 310-318.

Gherasim, C., J.V.D. Keybus, J. Driesen and R. Belmans, 2004. DSP implementation of power measurements according to the IEEE Trial-use Standard 1459. IEEE T. Instrum. Meas., 53(4).

Goertzel, G., 1958. An algorithm for the evaluation of finite trigonometric series. Am. Math. Mon., 65(1).

Grady, W.M. and R.J. Gilleskie, 1993. Harmonics and how they relate to power factor. Proceeding of the EPRI Power Quality Issues and Opportunities Conference (PQA '93). San Diego, CA, USA.

IEC 61000-4-7, 2009. Electromagnetic Compatibility (EMC)-part 4-7: Testing and Measurement Techniques-General Guide on Harmonics and Interharmonics Measurements and Instrumentation, for Power Supply Systems and Equipment Connected Thereto. Retrieved from: http://webstore.iec.ch/preview/info_iec61000-4-7%7Bed 2.0%7Den_d.pdf.

IEEE Std 519, 2014. IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems. Institute of Electrical and Electronics Engineers, Power and Energy Society, Piscataway, USA.

IEEE Std 739, 1995. IEEE Recommended Practice for Energy Management in Industrial and Commercial Facilities (Revision of IEEE Std 739-1984). Energy Systems Committee of the Industrial and Commercial Power Systems, Department of the IEEE Industry Applications Society, Recognized as an American National Standard (ANSI), USA.

IEEE Std 1459, 2010. IEEE Standard Definitions for the Measurement of Electric Power Quantities Under Sinusoidal, Nonsinusoidal, Balanced, or Unbalanced Conditions. Institute of Electrical and Electronics Engineers, Piscataway, USA.

Mansour, A. and Z. Chengning, 2013. Measurement of Power Components in Balanced Three-phase Systems under Nonsinusoidal Operating Conditions by Using IEEE Standard 1459-2010 and Fourier Analysis. ICLTEEE.

McEachern, A. and A. Eberhard, 2009. A new, ultra low cost power quality and energy measurement technology: The future of power quality monitoring. Proceeding of the IEEE/PES Power Systems Conference and Exposition (PSCE'09), pp: 1-4.

Minosi, A., A. Martinola, S. Mankan, F. Balzarini, A.N. Kostadinov and A. Prevostini, 2003. Intelligent, low power and low-cost measurement system for energy consumption. Proceeding of the IEEE International Symposium on Virtual Environments, Human-computer Interfaces and Measurement Systems, pp: 125-130.

Pham, V.L. and K.P. Wong, 1999. Wavelet-transform-based algorithm for harmonic analysis of power system waveforms. IEE P-Gener. Transm. D., 146(3).

Qiang, W., P. Zhaolong, M. Jianlin and L. Yingjie, 2013. Design of a power quality monitoring system based on MSP430. Proceedings of the 2nd International Conference on Computer Science and Electronics Engineering (ICCSEE'2013).

Radil, T. and P.M. Ramos, 2011. Methods of Estimation of Voltage Harmonic Components. In: Mr Andreas Eberhard (Ed.), Power Quality. In Tech, ISBN: 978-953-307-180-0.

Shah, N., 2013. Harmonics in Power Systems: Causes, Effects and Control. Siemens Industry Inc., USA.

Thiyagarajan, V. and T.G. Palanivel, 2010. An efficient monitoring of substations using microcontroller based monitoring system. IJRRAS, 4(1): 63-68.

Underwood, S., V. Chan and K. Venkat, 2009. Implementation of a three-phase electronic watt-hour meter using the MSP430F471XX. Application Report, SLAA409A, MSP430 Applications.

Wattanayingcharoen, P., A. Detchrat and S. Chitwong, 2012. Developing harmonic power analyzer based on IEEE 1459-2010 standard. Proceeding of the International MultiConference of Engineers and Computer Scientists (IMECS, 2012). Hongkong, Vol. 2.