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DSP BASED ENERGY MONITORING WITH ONLINE DAQ SYSTEM

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Abstract: This work manifests a low-cost three phase digital signal processing (DSP) based energy monitoring with online data acquisition (DAQ) system. In this endeavor, multifarious parameters are measured. All these parameters are displayed on the TFT LCD of the microcontroller in the real-time domain. Along with the measurement of miscellaneous parameters from the microcontroller, these parameters are directed over the internet via Wi-Fi module. On the internet, there is a succinct, vivid and pithy data log of these measured parameters which show their respective instantaneous values and accumulates them on the internet. This data log interprets energy monitoring over a period of the day, week, month or year. This energy meter can measure voltage (RMS), current (RMS), apparent power (S), real power (P), frequency, displacement factor, distortion factor and total harmonic distortion (THD) of current and voltage using a STM32F429 microcontroller.
Keywords: three phase energy monitoring, thin film transistor, digital signal processing, online monitoring, load duration curve

INTRODUCTION

The measurement of electrical energy plays an essential role in monitoring the usage of electricity. Electric supply companies usually set up an electric meter to measure electrical energy. These companies usually collect data at the end of the month and deliver the bills to consumers. But still, in the modern age, there is a possibility of error in it. There might be the possibility of electricity theft. For these possible errors, there needs a device that will keep the record of the consumer's usage of electricity, from which a consumer can compare his utilization or can improve his electrical energy consumption habits. There should be a device that collects all the data and store it and whenever consumer want to go through it is available.

In the modern age, almost everything is executed online, the energy is also measured online for this purpose. Digital signal processing technique is one of the most frequently used technique nowadays. Mathematical manipulations are usually used in this technique. The measuring algorithms like digital filtering and Fourier transform [1] require the very frequent use of mathematical operation. Furthermore, daily life physical signals can be transformed into digital form through an analog to digital converters (A/D). The voltage and current signals are transformed to digital form and are used for energy measuring purpose. So, there must be an asunder A/D for the measurement of voltage and current. Moreover, this device is portable, can easily communicate, can display results on LCD & the internet and of low-cost.

Online energy measuring instruments are usually characterized by their data processing time. Data processing time usually depends on adopted algorithms and processors. One of the best things to implement all these applications is a microcontroller which has A/D, timers and all the necessary things which are required. Due to the presence of a non-linear load in power system, it affects the power quality of system especially power factor by producing harmonics in current waveform. So, it is necessary to measure the degree of harmonics which causes the distortion of current waveform [2]. For this various power, quality monitors developed.

In power system, various parameters play the very important role that effects the power quality. For measuring these parameters fluke meter is used which measures power factor, three phase voltages and current, THD etc. But, it is quite expensive on an academic level. In this paper microcontroller based energy meter, with online DAQ system is bestowed. Other than regular quantities that traditional meters measure, it also has an apex importance to measure energy quality factors.

WORK GOALS

This meter is used to measure three phase voltages, current, power factor, real and reactive power, frequency, THD of current & voltage, displacement factor and distortion factor. All the measured parameters are shown in real time on the TFT LCD of the microcontroller along with this all the parameters are also sent on the internet, where the graphs showing the energy consumption patterns are displayed. Using this meter, the status of energy consumption can be known worldwide by accessing only the internet. If energy consumption in any building exceeds the allowable limit then the alarm will ring on the mobile or laptop on which energy consumption pattern is monitoring.

This meter can be installed in homes or in any commercial building. Energy consumption of a day, week, month or a year can be easily analyzed. This meter is entirely based on digital signal processor (DSP) in which signal computations are done to achieve work goals.

SYSTEM ARCHITECTURE

This meter is composed of the three-phase voltage sensor, current sensor comprising of three CTs having a ratio of 450:5 Amps and zero crossing detector. Along with this the small and valuable circuitry named "signal conditioning circuit" is also present, which plays a vital role in signal computations in the hardware. This signal conditioning circuit is composed of 1-volt D.C shift. The microcontroller used in this meter is STM32F429-Disco with TFT LCD. In this energy meter built in A/D of the microcontroller is used. Online monitoring uses the ESP8266 Wi-Fi module to send data over the internet. All energy consumption patterns are seen on the website thingspeak.com.

A. Voltage Sensor

It consists of three voltage transformers (VTs) and each VT is used for one phase. It steps down 230 volts A.C to 13 volts. These 13 volts are not the in range of A/D converter which is 0 to 3.3 volts [3] until these 13 volts are passed through the potential divider to get 0.619047 volts across the resistor and this voltage is further used to measure voltage. In this sensor, such low value of the voltage is used to be measured by the microcontroller because if transient occurs in the three-phase system then the voltage taken by the microcontroller will not exceed 3.3 volts [3]. Figure 1 shows the schematic of the voltage sensor's connection.

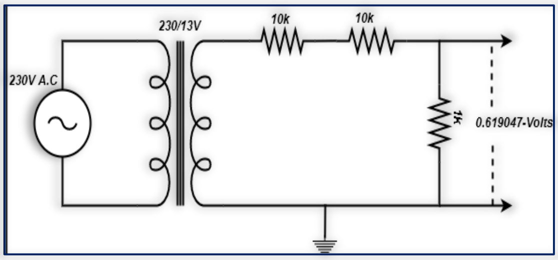

Figure 1. Schematic of voltage sensor's connection

B. Current Sensor

This sensor is composed of three current transformers (CTs). It steps down the current at a ratio of 450:5 amps. The burden used for this CT is 0.47 ohms. The current is passed through the CT and to measure this current, voltage is taken across the burden. The CT used in the sensor is shown in figure 2 and how this sensor is deployed in the hardware is shown in figure 3.

Figure 2. Current transformer (CT)

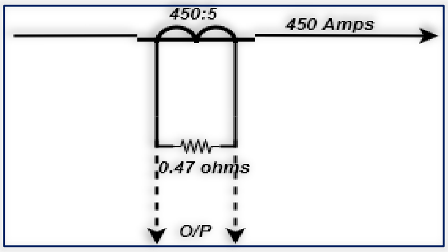

Figure 3. Schematic of current sensor's connection

C. Zero Crossing Detector

System frequency is measured by using zero crossing detector. In this circuit, 230 volts AC is stepped down to 13 volts and after passing through the potential divider it is sent to zero-crossing IC LM358 which gives digital logic on the output, working as a comparator. When the sinusoidal waveform falls below the zero axis it gives high logic and when sinusoidal waveform goes above zero axis then afore-said IC gives low logic and this output is given to the micro-controller and the frequency is measured using the timer interrupt. The output waveform of zero-crossing is shown in fig 5.

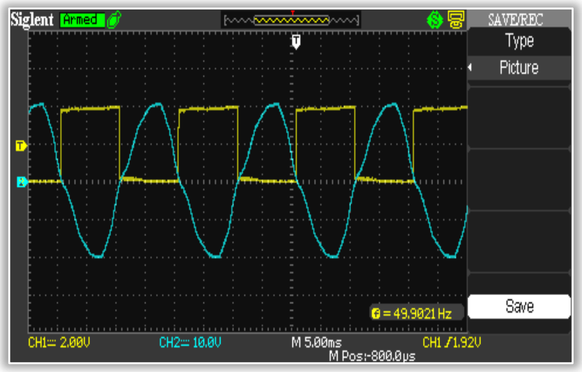

Figure 4. Output of zero crossing detector

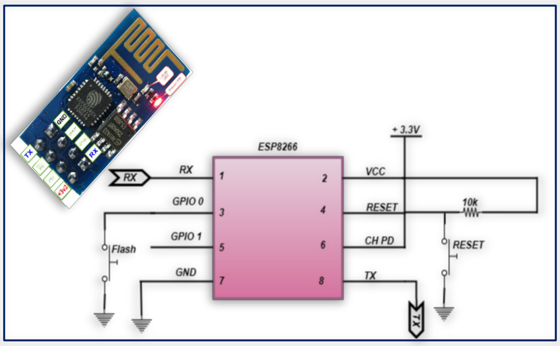

Figure 5. Schematic of ESP8266 Wi-Fi module

D. Wi-Fi Module

The critical part is the design of the data log system for the acquisition of AC parameters. Although the understandable GUI on the TFT LCD of STM32F429 is developed for the instant monitoring purpose of electrical power being used. But this data log will enable to draw a load duration curve on the daily, monthly, weekly or annual basis. For this, IOT Module ESP8266 is used, it is a Wi-Fi operated the device. It accepts commands to work. There are some sites that give free space to view data sent by ESP8266 to the Internet. To make ESP8266 work properly with a microcontroller, it is very necessary to match their baud rates. The module is configured in station mode and has nearby Wi-Fi access to facilitate data transmission and reception. Figure 5 shows the circuit diagram of ESP8266 Wi-Fi module.

E. Signal Conditioning Current

This is the smallest but very important part of the meter. This meter works on the STM32F429IZ-Disco microcontroller while the A/D of this microcontroller is unipolar but our signals are bipolar. The microcontroller is unable to read these bipolar signals. For this purpose, signal conditioning circuit is designed to adapt the signal which gives DC offset to the voltage and current signal so that these signals are centered across 1 volt. The voltage and current signals are passed through signal conditioning circuit [4] to give them a shift of 1 volt to make all signals within the range of A/D which is 0 to 3.3 volts [3]. All these shifted signals are then sent to the microcontroller for further progress.

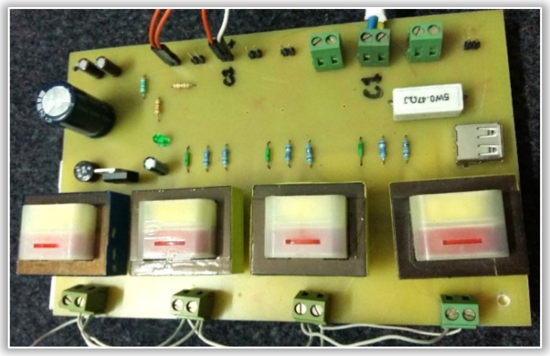

Figure 6. Voltage sensor's hardware PCB

SOFTWARE IMPLEMENTATION

The below list shows some of the major techniques of software implementations.

A. External Memory (SDRAM)

Define To store all the data external SDRAM of 64-Mbit is used. Which consists of 4-banks of 16 Mbit each. The bank consists of 4096 rows with 256 columns and 16 bits. This external SDRAM has different modes of operation comprising of auto-refresh, power-saving and power-down. In this, the values are captured on the positive edge of the clock signal.

The DMA controller has direct access to memory and can trigger transactions such as peripheral to memory, memory to peripheral and memory to memory.

In this energy meter, six independent channels of the ADC-3 are used for power system and is attached with APB-2. The default frequency of ADC-3 is 90 MHz but the prescalar is accordingly set in such a way that frequency of the ADC-3 becomes 45 MHz, which is the sampling frequency of ADC. In this, samples are taken at the timer interrupt and the frequency of this timer interrupt is 25.6 kHz. Therefore, in the end, the sampling frequency of this energy meter becomes 25.6 kHz in which 512 samples are taken in one cycle for signal computation.

All these samples are stored in the internal buffer and when the internal buffer is near to its full capacity all this data is immediately transferred to address in the external memory through DMA. Samples are taken without any loss and the better accuracy is obtained by using this technique. When the DMA is in the mode of data transfer, reading or writing, microcontroller performs other calculations.

B. System's Algorithm

In this ADC is configured in an independent mode with five-cycles and two sampling delay. For the acquisition of samples, a timer interrupt of 25.6 KHz is introduced which collects 512 samples in a 50Hz AC cycle. Samples are stored in the memory space using direct memory access (DMA) to avoid data loss. After the collection of 512 samples, RMS of the signal is calculated using given formula and this signal is the shifted signal obtained after the addition of 1-volt DC shift. The flowchart showing all the steps of software implementations is shown in figure 7.

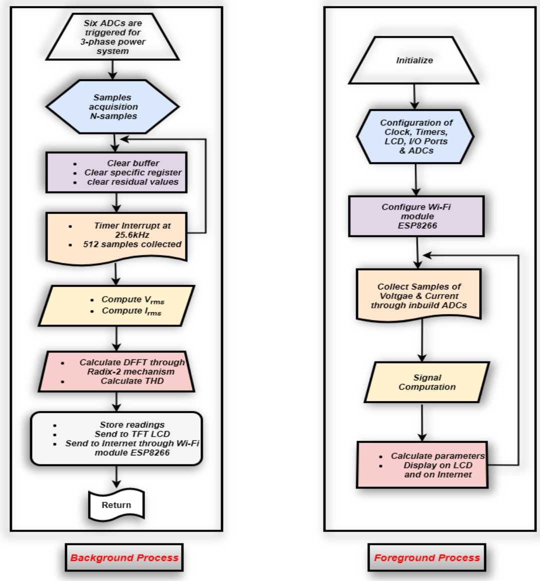

Figure 7. Flow chart of software implementation

$$V_{rms,shifted\ a.c} = \sqrt{\frac{\sum_{i=1}^{n}(X_i)^2}{n}} \quad (1)$$

$$I_{rms,shifted\ a.c} = \sqrt{\frac{\sum_{i=1}^{n}(X_i)^2}{n}} \quad (2)$$

n = number of samples X_i= Instant sample

The number of samples is calculated by using the given formula as described below:

$$\text{Number of samples} = \frac{\text{Timer frequency}}{\text{A.C signal frequency}}$$

$$\text{Number of samples} = \frac{25.6\ \text{KHz}}{50\ \text{Hz}} = 512\ \text{samples}$$

In this case, n = 512 samples.

The average value of the shifted signal having DC shift of 1-volt is calculated by using following formula:

$$V_{mean,shifted\ signal} = \frac{\sum_{i=1}^{n}(X_i)}{n} \quad (3)$$

$$I_{mean,shifted\ signal} = \frac{\sum_{i=1}^{n}(X_i)}{n} \quad (4)$$

n = number of samples X_i= Instant sample

The RMS value of AC signal excluding the DC shift is calculated as:

$$AC^2 = RMS^2 - DC^2 \quad (5)$$

$$AC = \sqrt{RMS^2 - DC^2} \quad (6)$$

$$V_{rms,ac} = \sqrt{V^2_{rms,shifted\ ac} - V^2_{mean,shifted\ ac}} \quad (7)$$

$$I_{rms,ac} = \sqrt{I^2_{rms,shifted\ ac} - I^2_{mean,shifted\ ac}} \quad (8)$$

For the calculation of apparent power, following formula is used

$$S = V_{rms} * I_{rms} \quad (9)$$

Since load can be unbalanced on all three phases, so apparent power of each phase must be calculated separately. Total apparent power will be the sum of apparent power of all three phases such as

$$S_{total} = S_a + S_b + S_c \quad (10)$$

Similarly, the real power is also calculated for each phase. The real power is average utilized power over a complete cycle as

$$P = \frac{\sum_{i=1}^{N}(V_i * I_i)}{N} \quad (11)$$

The input displacement factor (IDF) is:

$$IDF = \frac{P}{S} = \frac{\text{Real Power}}{\text{Apparent Power}}$$

While the true power factor becomes:

$$PF = \text{Input Displacement factor} * \text{Distortion Factor}$$

The distortion in the signal is calculated using Fast Fourier Transform (FFT) technique [5]. With the help of FFT, different frequency components are calculated using the radix-2 algorithm. Radix-2 is the fast process for the calculation of FFT. In this method samples are divided into two parts of equal number of samples then these resulting samples are present in two parts and each part consists of the same number of samples as the other part then each part is further divided into equal number of samples and this process goes on until we get each part which has 2 samples then FFT of such number of samples is trivial and can easily be calculated. For example, when we have eight number of samples then it is divided into two FFT's of size 4 and then this is divided into four FFT's of size 2 and then it is easy to find the FFT's of size two through the radix-2 mechanism. This mechanism for eight number of samples is also shown below in figure 9.

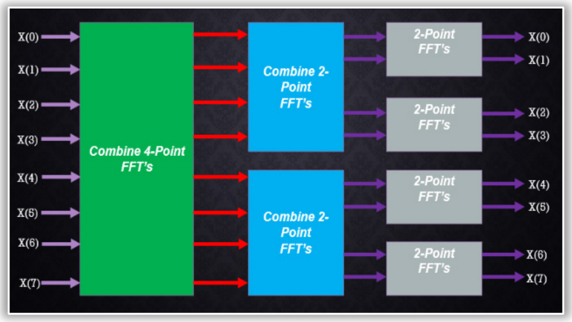

Figure 8. Radix-2 mechanism of FFT

For the calculation of THD factor first, thirteen frequency components are taken. Distortion factor and total harmonic distortion are calculated for each phase using the formula:

$$THD_F = \sqrt{\frac{V_2^2 + V_3^2 + V_4^2 + \cdots + V_n^2}{V_1^2}} \quad (12)$$

$$THD_F = \sqrt{\frac{I_2^2 + I_3^2 + I_4^2 + \cdots + I_n^2}{I_1^2}} \quad (13)$$

$$\text{Dist. fact. in } V_a = \frac{V_1}{V_{rms}} \quad (14)$$

where V_1 is the first harmonic component in the signal. The power factor for each phase is calculated separately. For the sake of better Information, the average power factor is calculated.

The calculated data is then sent to a website for monitoring and plotting of load duration curve. For this purpose, ESP8266 Wi-Fi module is used. It is configured in station mode and connected to local Wi-Fi. The data is sent to thingspeak.com using internet protocol. USART (Universal Synchronous/Asynchronous Receiver Transmitter) is configured to send AT commands to Wi-Fi module at the baud rate of 115200 bits/second. Along with uploading of data, all measurements are also displayed on a built-in TFT LCD of the microcontroller.

RESULTS AND DISCUSSIONS

This meter is attached with three phase variable supply of 0-300V (10A each phase) and the results are compared with the Yokogawa meter, 2013 model. Figure 9 shows the voltage measurements.

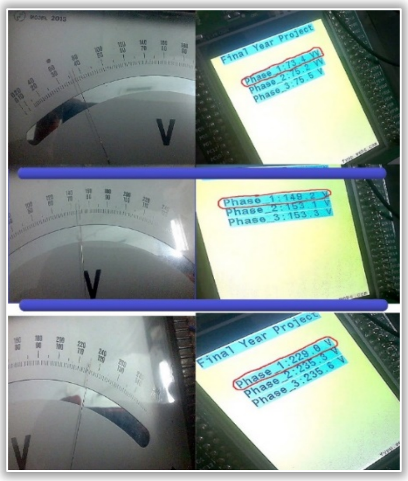

Figure 9. Voltage reading on microcontroller

The graph of voltage reading is shown in figure 10.

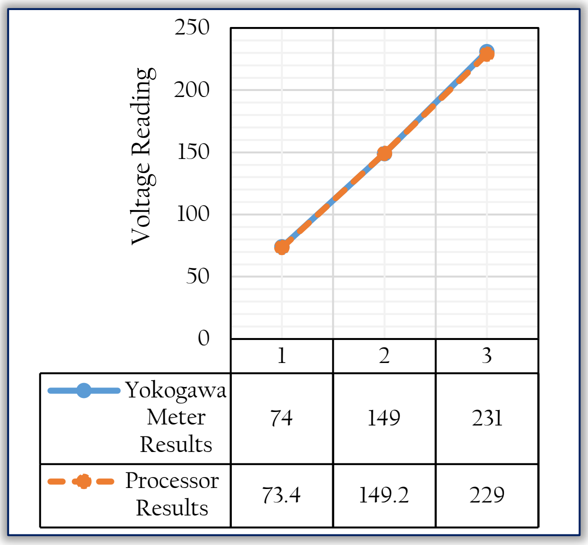

Figure 10. Voltage comparison between microcontroller and meter reading

For the measurement of the current non-linear load is connected and the results are compared with the Yokogawa current meter. Figure 11 shows the results of current measurement.

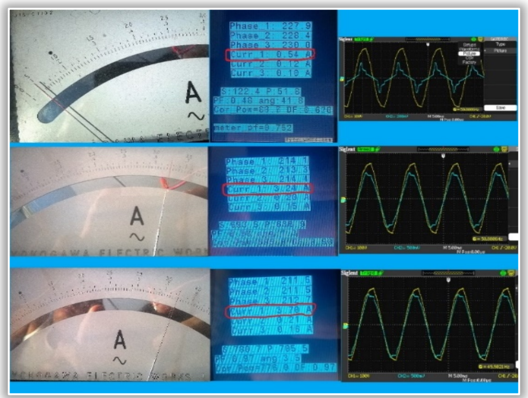

Figure 11. Current Measurement on microcontroller

The graph of current reading is shown in figure 12.

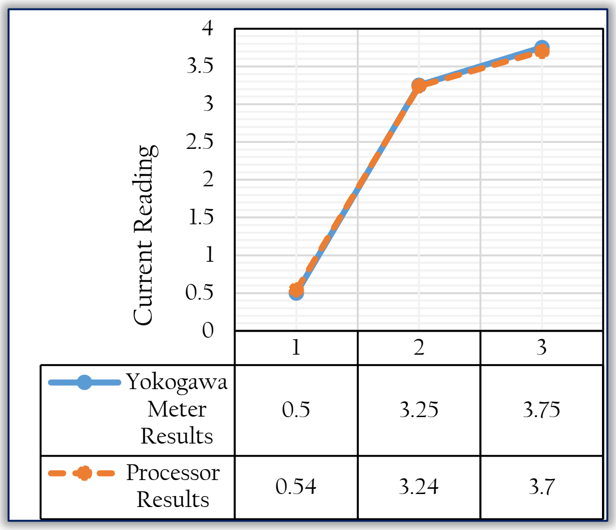

Figure 12. Current comparison between microcontroller and meter reading

Percentage error calculated from these measurements are shown below in figure 13.

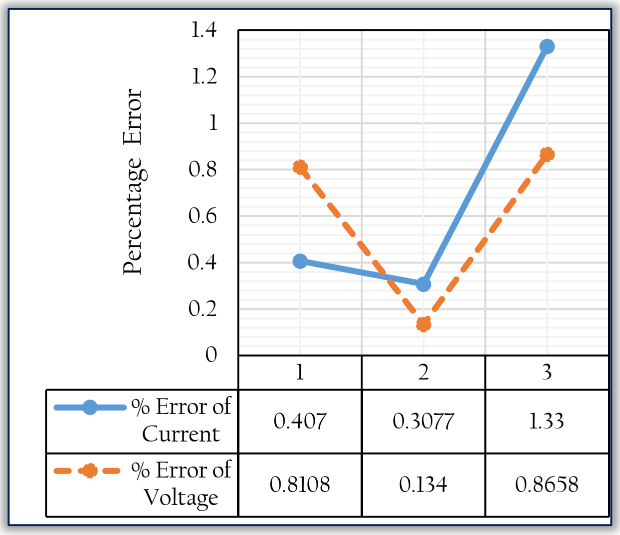

Figure 13. Percentage error of voltage and current readings

In this work, the square waveform is given to the meter with D.C shift of 1 volt. Fourier analysis is performed on the square waveform and Fourier coefficients are calculated from the radix-2 mechanism. These Fourier coefficients are compared with theoretical Fourier coefficients calculated as shown below:

$$V_0(t) = a_0 + \sum_{n=0}^{\infty}[a_n \cos(n\omega_s t) + b_n \sin(n\omega_s t)]$$

$$V_0(t) = \sum_{n=1,3,5,..}^{\infty} [b_n \sin(n\omega_s t)]$$

$$\text{while} \quad \omega = \frac{2\pi}{T_s}$$

$$b_n = \frac{2}{T_s}\int_0^{T_s} V_0(t)\sin(n\omega_s t)\,.\,dt$$

$$V_0(t) = \textstyle\sum_{n=1,3,5,..}^{\infty}[\frac{4V_s}{n\pi}\sin(n\omega_s t)] + a_0 \qquad (15)$$

RMS value of fundamental voltage:

$$V_n = \frac{4V_s}{\sqrt{2}\, n\, \pi}$$

$$V_1 = \frac{4(1)}{\sqrt{2}\,(1)\,\pi} = 0.9003163162$$

Harmonics:

$$V_3 = \frac{4(1)}{\sqrt{2}\,(3)\,\pi} = 0.0.3001054387$$

$$V_5 = \frac{4(1)}{\sqrt{2}\,(5)\,\pi} = 0.1800622632$$

$$V_7 = \frac{4(1)}{\sqrt{2}\,(7)\,\pi} = 0.1286166166$$

$$V_9 = \frac{4(1)}{\sqrt{2}\,(9)\,\pi} = 0.1000351462$$

The microcontroller results are shown in figure 14 while the theoretical computations are shows in figure 15.

Figure 14. Harmonics calculations of square waveform on the microcontroller

The theoretical results which calculated from the analysis of square waveform are:

$$V_n = \frac{4\,V_s}{n\,\pi}$$

Theoretical Calculations	*FFT measurement (Microcontroller)*
V_1 = *0.900316316*	*0.913*
V_3 = *0.300105439*	*0.304*
V_5 = *0.180062263*	*0.183*
V_7 = *0.128616617*	*0.13*
V_9 = *0.100035146*	*0.101*

Figure 15. Harmonics of square waveform calculated theoretically

The results which get from the microcontroller are compared with theoretical results as shown in figure 16.

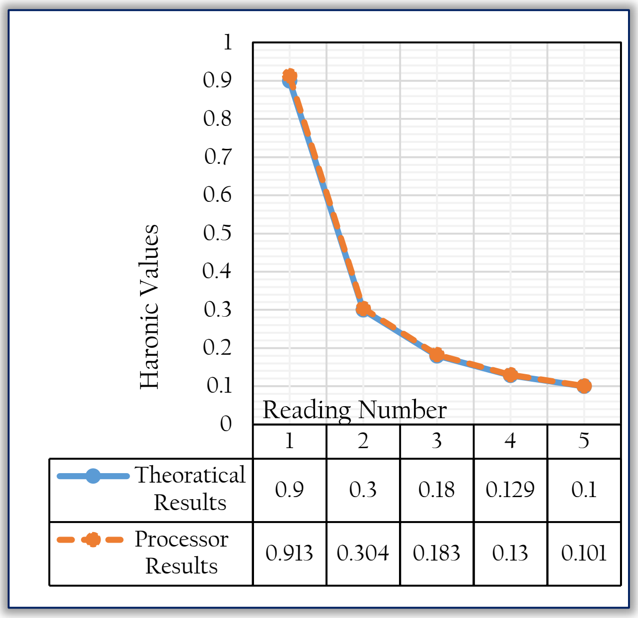

Figure 16. Comparison of harmonics calculation between microcontroller and theoretical results

All data is sent to the internet using Wi-Fi module and how to display data over the Internet is displayed. Figure 17 shows the comprehensive graphical user interface for online monitoring.

Figure 17. GUI for online energy monitoring

CONCLUSION

The development of low-cost DSP based energy monitoring with online data acquisition and its implementation is described in detail. This meter is scrutinized on artificial disturbances and tests are performed on the single and three-phase power system in real time. Therefore, it is culminating for real time monitoring. This is fast, robust, and efficient and gives meticulous results and all the signal computations are totally based on digital signal processing by using STM32F429-disco microcontroller.

This data acquisition will also be very constructive for future researchers and can easily be installed anywhere. It is extremely low-cost, portable and very easy to handle.

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