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Design, Construction and Evaluation of a Power Factor Monitoring and Correction System

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As a measure of how efficiently an electrical power is converted into useful output, power factor (PF) is a special requirement of every electrical load. A poor power factor is usually the result of a significant phase difference between the voltage and current at the load terminals, high harmonic content or a distorted current waveform. With advancement in research and manufacturing, various techniques have been adopted in the development of power factor correction equipment and power optimizers. This work develops a sophisticated system that measures and corrects the power factor of a given load. The system's development includes circuit design algorithm, embedded software programming, embedded web server/application development, and hardware implementation. A high-end technology built around a 32-bit ARM Cortex M3 microcontroller is employed to provide high precision in power factor measurement and supplies the required reactive power (kVAr) to correct the phase difference between the current and the voltage of a given electrical load. The corresponding load voltage and current before and after correction is displayed on an LCD for user interaction. Also, an on-board web server developed, provides interaction between the system and a personal computer over a Wi-Fi network. The measured parameters are plotted on a web browser when connected. The system operates in accordance with the design specifics, driving the PF of a standing fan from 0.1 to 0.32 values.

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1. Introduction

Power Factor (PF) is a measure of how efficiently electrical power is converted into useful work output. A comparatively small improvement in power factor can bring about a significant reduction in losses since losses are proportional to the square of the current. When the power factor is less than one, the 'missing' power is known as reactive power which unfortunately is necessary to provide a magnetizing field required by motors and other inductive loads to perform their desired functions [1] Reactive power can also be interpreted as wattless, magnetising or wasted power and it represents an extra burden on the electricity supply system and on the consumer's bill.

The amount and complexity of household electrical equipment has increased tremendously over the last few years. Air conditioners, computer monitors, electronic ballast lighting and several other electrical items are welcome additions to our homes but come with additional burdens. One of these is on the electricity grid, as these appliances draw a large amount of currents and generate more signal harmonics. The energy distribution companies in Nigeria have been operating at deficit due to poor power factor of consumers' load. The Nigerian NERC (National Electricity Regulatory Commission) billing methodology offsets 18% and 10% of the total energy consumed by the energy distribution companies to account for technical and commercial losses respectively [2]. The need to improve the overall efficiency of electrical grid is something worth looking into, if we want our power utility companies to be sustained. The energy efficiency is hence one of the central issues that smart homes and smart grids have to face.

Developers have been making efforts to implement systems for automatically correcting power factor as to improve power quality. Many methods for power factor correction control had been proposed. These include Automatic Power

Factor Improvement by Using Microcontroller [3], where many small rating capacitors are connected in parallel and a reference power factor is set as standard value into the microcontroller IC. In a work by [4], an automatic power factor controlling system using Programmable Interface Controller (PIC) microcontroller was presented. The microcontroller measures power factor from the load, determine and trigger sufficient switching capacitors to compensate demand of excessive reactive power locally. An automated project which involves measuring the power factor value and correcting microcontroller and the load to be controlled by using GSM was proposed by [5]. The objective is to improve the power quality by continuously monitoring the load power factor.

Recent technological advancements allow for cost, miniaturization, efficiency improvements and additional features to the already developed systems. This work thus, develops and evaluates a new sophisticated system that measures and corrects the power factor of a given load.

2. Methodology

The development of this system includes circuit design algorithm, embedded software programming, embedded web server/application development, and hardware implementation. Figure 1 represents the functional block diagram of the system.

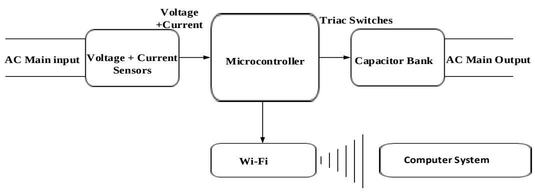

Figure 1. Functional Block Diagram of the Power Factor Monitoring and Correction System

2.1 Operation of the System

As depicted in Figure 1, the major function of this system is to measure the active power and apparent power drawn by the connected load, compute the power factor, correct the power factor by selecting suitable capacitor bank to supply the required reactive power to the load, and print the result on a liquid crystal display (LCD) and also plot it on a PC when requested by the user. The on-chip analog-to-digital converter (ADC) is used to continuously sample the load voltage and current through voltage and current transducers. Active and apparent power values are calculated from the samples and power factor is calculated with the result. The microcontroller (MCU) selects a suitable capacitor bank by switching the corresponding TRIAC switches. The result is printed on an alphanumeric LCD. Additionally, the MCU establishes a Wi-Fi network through a Wi-Fi module to enable web clients to display the result in a more detailed form. The embedded web application provides a real-time plot of the result.

2.2 Circuit Design

This section presents the hardware design stage by stage, and also provides the circuit diagram for each unit in detail.

2.2.1 Voltage and Current Measurement

The circuit diagram for voltage and current sensing unit is provided in Figure 2. The a.c mains is coupled to MCU's on-chip 12-bit ADC through a voltage attenuator to achieve a suitable voltage level for ADC measurement. The voltage attenuation for the network in Figure 2 is calculated as follows:

$$dB_V = 20log\frac{V_o}{V_{in}} \qquad (1)$$

Where

dB_V = Voltage attenuation in decibels

V_{in} = Input Voltage

V_o = Output Voltage

But

$$\frac{V_o}{V_{in}} = \frac{R_{16}}{R_{13}+R_{14}+R_{15}} \qquad (2)$$

Therefore:

$$dB_V = 20log\frac{1000}{(100+100+100)\times 1000}$$

$$= 20log\frac{1}{300} \cong -50\text{dB}$$

Attenuation of -50 dB corresponds to 1/300, and this is suitable for the 12-bit ADC which measures approximately 2.33 V_{RMS}. R_{11} and R_{12} serve to accommodate both upper and lower half cycles, while C_1 provides dc bias. GPIOA_0 is the MCU's ADC1 channel 0.

Also, for current measurement, a high-power choke resistor (R_{17}) was used in series with load to sense load current. R_{17} has a very low resistance of 0.1Ω, so as not to alter the current being measured. R_9, R_{10}, and C_2 are similar to R_{11}, R_{12}, and C_1, but used on the current side. GPIOA_1 is the MCU's ADC1 channel 1.

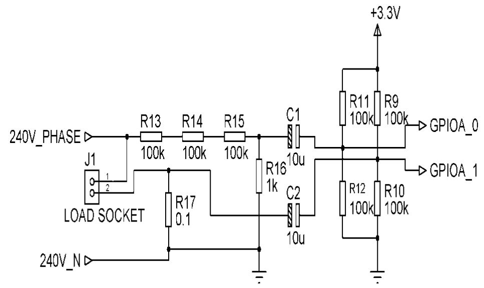

Figure 2. Voltage and Current Sensing Unit

2.2.2 Capacitor Selection Circuit

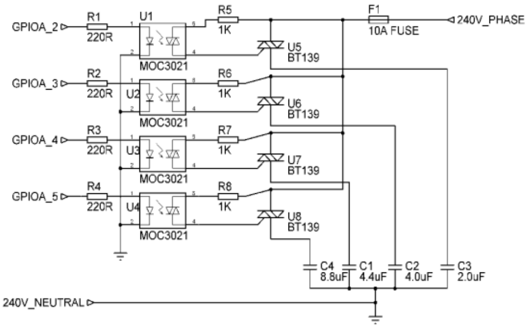

Figure 3. Capacitor Bank Switching Circuit

In Figure 3, C_1 through C_4 is a bank of power capacitors used to correct the load power factor as close to unity as possible. Each capacitor is selected through a TRIAC switch BT139 [6] (U_5 through U_8) accordingly. U_1 through U_4 are opto-couplers used in switching the TRIACs. R_1 through R_4 are current-limiting resistors for opto-couplers' LED. GPIOA_2 through GPIOA_5 are input/output (I/O) pins used for switching the opto-couplers. F1 is a 10-Ampere fuse for protection.

2.2.3 The Wi-Fi Module

The ESP8266-01 [7] is an IEEE 802 [8] compliant Wi-Fi module used to establish an HTTP [9] communication between a web client and the on-board web server. The picture and circuit connection of this module are shown in Figure 4 (a) and (b) respectively.

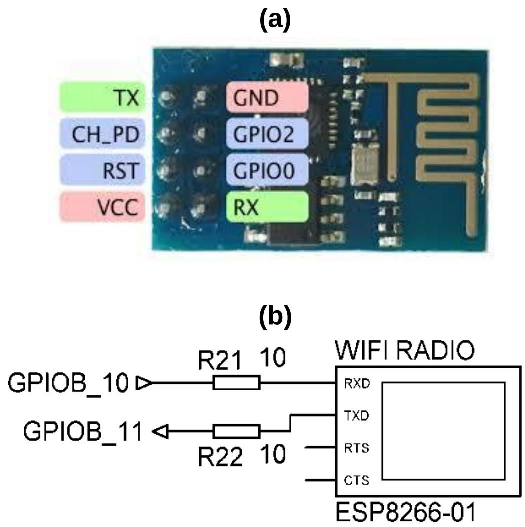

Figure 4 (a). ESP8266-01 Wi-Fi Module and **(b).** ESP8266-01 Wi-Fi Module Connection

2.2.4 SD Card Interface

A memory card (micro SD-card) was used as off-chip ROM (Read-only memory) to store the web pages for display purposes. It was also used for logging, i.e. to store the result and load parameters at some time interval. Figure 5 depicts the schematic of the SD card interface.

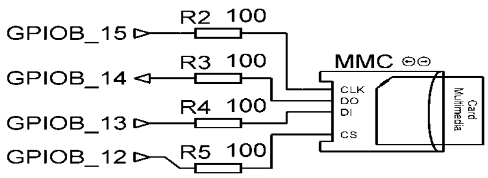

Figure 5: SD Card Connection

2.2.5 Power Supply

A switching regulator was used to provide a regulated dc supply to the circuit from a rectified mains voltage. The power supply is capable of delivering constant dc current of 3 A. The power supply schematic shown in Figure 6 was adopted from [10] and used to provide the required stabilized 5V.

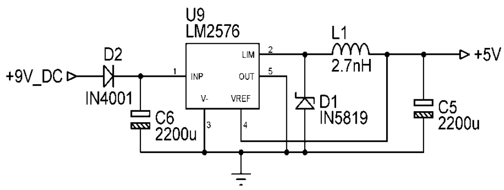

Figure 6. Power Supply Circuit [10].

2.2.6 Microcontroller Unit (MCU)

The MCU used in this work is a 32-bit ARM Cortex M3 microcontroller [11]. It is programmed to manage all the circuit peripheral hardware and also use its on-chip ADC to capture data from voltage and current sensors. Voltage zero cross detection is accomplished by the use of the MCU's external interrupt. It manages the Wi-Fi network established by the Wi-Fi module. Figure 7 shows the picture of this module.

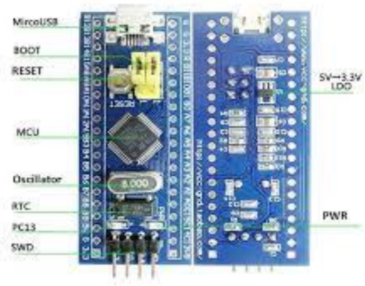

Figure 7. STM32F103C8T6 Module [11].

2.2.7 Power Calculations

Once the voltage and current signals are sampled by the microcontroller device, it is time to calculate the instantaneous power that is being consumed by the device under test. The power supplied by the distribution company is known as complex power 'S'. Complex power can be expressed by the vectorial sum of the real or active power 'P', plus the imaginary or reactive power 'Q'

$$S = P + jQ \qquad (3)$$

Real power is given by:

$$P = \frac{1}{T}(\int V(t) \times I(t)dt \qquad (4)$$

Which can be expressed in terms of the root-mean-square (RMS) values of the current (I) and the voltage (V), where 'θ′ is the phase delay between V(t) and I(t).

$$P = V_{RMS} \times I_{RMS} \times Cos(\theta) \qquad (5)$$

Equally, the reactive power 'Q' that is the energy that flows back and forth in an inductive or capacitive load can be written in a similar way:

$$Q = V_{RMS} \times I_{RMS} \times Sin(\theta) \qquad (6)$$

As the complex power 'S' is the vectorial sum of 'P' and 'Q', then:

$$S = V_{RMS} \times I_{RMS} \qquad (7)$$

Finally, the power factor 'PF' is defined as:

$$PF = Cos(\theta) = \frac{P}{(|S|)} \qquad (8)$$

For the common user, the valuable magnitudes are the real power 'P' and the power factor 'PF'. The voltage and current is extra information that can also be useful. Hence, for calculating the power factor, considering (8), complex power 'S' and real power 'P' have to be determined. The complex power can be calculated attending to (7).

The RMS value is defined as:

$$V_{RMS} = \sqrt{\frac{1}{T}\int v(t)^2 dt} \qquad (9)$$

Moreover, the microcontroller device that sense the current and the voltage will be working in the discrete time domain, instead of the continuous time domain, as an ADC is the responsible of sensing these magnitudes. Therefore, the equivalent discrete time equation for (9) would be (10)

$$V_{RMS} = \sqrt{\frac{1}{N}\sum_{n=0}^{N-1} v(n)^2} \qquad (10)$$

Where 'N' is the number of samples and 'n' the current sample. The same procedure can be applied for the current.

With (10) and the equivalent equation for the current, the complex power 'S' can be calculated using (7). To resolve the Power Factor 'PF' with the equation (8) the real power 'P' must be estimated. This formula in (11) [1] could be used:

$$P = \frac{1}{N}\sum_{n=0}^{N-1} v(n) \times i(n) \qquad (11)$$

This concise theory should be enough to be able to develop a program for the microcontroller device that calculates the real power 'P' and the power factor 'PF'. Other relevant information to be derived from the voltage and current information are the cumulative energy consumption, frequency, and the amount of capacitance needed to force the power factor to a value closed to unity.

2.2.8 Software Development

Estimating the power consumed by connected appliances utilizes the samples of the voltage and current waveforms captured using the ADC. This estimation rests on the application of the equation (8).

First, a certain number of samples 'N' of a certain number of wavelengths of the signals of the analog channels are captured. These samples would be $V(n)$ and $I(n)$ in equation (2.8). For each sample 'n', the instantaneous power is estimated. Then all the instantaneous powers are summed and finally this value is divided by the number of samples 'N' taken. The main flow of the code that implements this method is displayed in Figure 8.

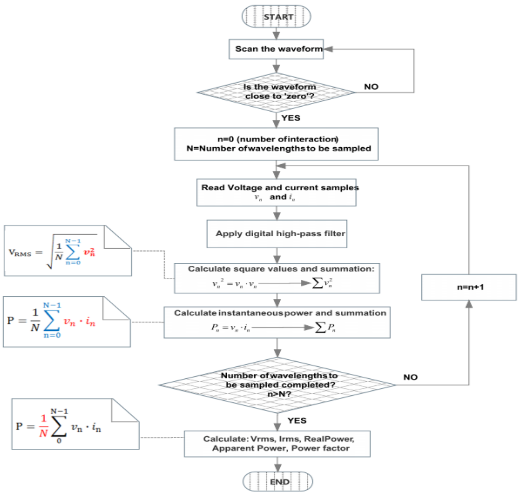

Figure 8: Power calculation subroutine flow diagram

2.2.9 Hardware Production

Hardware production involves wiring and packaging of the designed circuit. This requires arrangement and soldering of various components and sub-circuits that make up the whole system. The snapshots of the hardware are shown in Figure 9.

Figure 9. Hardware Snapshots

2.2.10 Software Testing

After the whole development, the system was used to establish a Wi-Fi network. A PC was connected to the network while a web browser was used to view the result. Figure 10 shows the snapshots of the result.

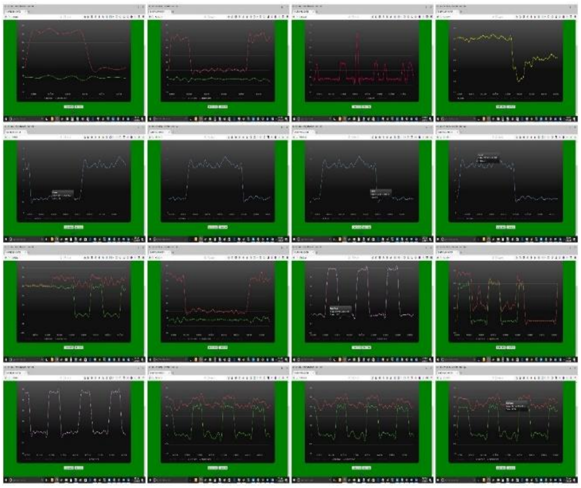

Figure 10. Application View Snapshots

3. Test, Result and Discussion

The system was subjected to series of tests upon completion, results obtained and subsequently discussed.

3.1 General Testing

The system was tested using different loads and recording the power factor with/without the power factor correction enabled. A standing fan, a pressing iron, and a laptop were used to check the PF measurements. Table 1 lists the measurements.

Table 1. Test results for different loads considered

Test No.	Load type	PF before correction	PF after correction
1	Pressing Iron	0.87	0.999
2	Laptop Power Pack	0.25	0.55
3	Fan	0.1	0.32
4	Electric Kettle	0.89	0.999

3.2 Discussion of Results

With reference to Table 1, it is apparent that the system clearly performs power factor correction using the on-board capacitance. The pressing iron and electric kettle were expected to present a PF very close to 1 without correction, but were observed otherwise. An examination of this reveals that the resistive elements in these loads exhibit a mix of both resistive and inductive components, instead of the purely resistive charactersitics expected. Correction of the PF for these two loads showed them approaching unity. The fan used during testing exhibited a very low power factor. This was put down to manufacturing issues. Correcting the PF increased it to the 0.32 mark. Extra capacitance would have taken the PF close to 1, but since it was not present, the PF correction was limited to about 0.3. As for the laptop, the system drive the PF to 0.55 after correction. The PC connected to the wi-fi network established by the model system displays a real-time plot of the result via a web browser. Some of the reported PF correction systems [13] [14] are non-automated and focused on the PF improvement of induction load. The automated PF correction systems developed is an improvement over [2] [5] [7] [15] as it incorporates a wi-fi module for interaction between the system and a PC.

4. Conclusions

The design and assembly of the power factor monitoring correction system was effected in line with the design specifications spelt out in section 2. The design objectives were met with minimal changes to the original hardware design realization, namely, the amount of capacitance that could be employed for correction. The design was deemed succesful based on series of test conducted after system assembly, and the correctness of the test results.

Conflict of Interest

The author declares no conflict of interest.

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