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Automatic control of load power factor

By

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Abstract:

This paper focuses on the design and implementation of an automatic control system based on microcontroller that enhances the load power factor (PF) in real time. The system is designed to detect the load power factor and improve it automatically. The system is composed of several elements; the main is microcontroller which compares between the measured load power factor that is received from the energy metering integrated circuit (ADE7763) and a pre-stored value "PF = 0.95". Based on the calculated difference in power factor, the microcontroller drives the power switches (relays circuit) through an interface circuits to choose the appropriate capacitor bank that is required to improve the power factor. Furthermore, the system is able to send the system power factor data in real time to clients either by a Short Message Service (SMS) through an integrated GSM module or by the World Wide Web (internet) through an integrated Ethernet module.

Keywords:

Microcontroller, power factor, power switches, GSM, EATHERNET.

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1.1- Introduction:

This paper presents the background information, method, and results from an eighteen month long pilot project designed to determine the economic feasibility of power factor correction as a method for improving efficiency and reducing losses on the electric utility system. Power factor correction will be analyzed in multi-family dwellings (apartments), single family residences, commercial buildings and industrial buildings. As power factor correction is not a new concept, the project had four objectives. For all phases of the project, our first objective was to measure the power factor in the different environments for many loads. This involved creating data bases to simplify handling of the data being collected. Second, we wanted to gain a better understanding of the reactive loads in the different environments. That understanding includes the age of the appliances or equipment discharging the reactive power and the types of installations involved. Our third objective was to correct the power factor in the most cost effective manner possible. Our final objective was to measure the effect of our installation and determine the cost versus benefit of the installations beside determine the value of capacitors required for improve the system power factor.

1.2- Background:

Power Factor is the ratio of the power needed to do the work within customer premises to the power delivered by the utility. The power needed by customer premise equipment to operate is measured in Kilowatts (KW). The amount of power delivered by the utility is measured in Kilovolt Amperes (KVA). KW divided by KVA is the power factor. A power factor of 1.0 is ideal (unity). Appliances and machinery within customer premises discharge reactive power, measured in Kilovolt Amperes Reactive (KVAR). More KVAR present on the utility system results in a lower power factor, and higher currents (I) present on the wires. Because thermal losses on the wires are proportional to the square of the current, a 12 % increase in current will result in a 25% increase in thermal losses related to the increased current. (1.12 x 1.12=1.25). Similarly, a 10% current reduction will result in a 19% drop in thermal losses and provide the corresponding energy savings (0.9 x 0.9 = 0.81).

Historically, utilities have implemented power factor correction at their substations by installing banks of capacitors. The substations are where the utilities reduce the voltage (usually greater than 110,000 volts) from the transmission wires to lower voltages (4,100 volts or 13,000 volts) for distribution throughout the service area. The voltages are further reduced to the range of 208 volts to 480 volts at the transformers on the utility poles or in underground vaults located near the customer premises. The problem with implementing power factor correction at the substations is that the reactive power present on the distribution system, not serviced by those capacitors, is inducing thermal losses. Furthermore, the distribution system, with its lower voltages and higher currents, already accounts for the majority of the losses on the system. In addition, more thermal losses occur on the customer side of electric meter, within the customer premises. On the Transmission and Distribution System, 50% of the energy lost and almost 75% of the "Accounted For" energy losses occur on the lower voltage Distribution Portion of the system. This is not including losses from reactive load that occur after the customer meters. While the utility does not bill for reactive power in most cases, excess thermal losses after the meter caused by reactive load would be measured in watts and would be billed. The losses, while relatively small for any single location, are very significant.

1.3- Objectives of this project :

- Enhance equipment operation by improving voltage
- Reduce Line Losses in distribution systems
- Eliminate Power Factor Penalties
- Increase System Capacity
- Conserve Energy
- Improve voltage stability
- Increase equipment life
- Save on utility cost
- Improve energy efficiency

1.4- Why do we care about Power Factor?

- In Industrial Facilities, Mostly Induction Motor loads
- Energy Efficient Motors not optimized for PF
- Low power factor is caused by oversized or lightly loaded induction motors
- Low power factor results in:
    - Poor electrical efficiency - Higher utility bills
    - lower system capacity
    - On the Supply Side, Generation Capacity & Line Losses

Power Factor Correction Capacitors (PFCC) provide an economical means for improving energy utilization.

1.5- Causes of low power factor:

A poor power factor can be the result of either a significant phase difference between the voltage and current at the load terminals or it can be due to a high harmonic content or distorted/discontinuous current waveform. Poor load current phase angle is generally the result of Poor load current phase angle is generally the result of an inductive load such as an induction motor power transformer, lighting ballasts, welder or induction furnace, Induction generators Wind mill generators and high intensity discharge lightings.

1.6 Distortion power factor

The distortion power factor describes how the harmonic distortion of a load current decreases the average power transferred to the load.

$$\text{distortion power factor} = \frac{1}{\sqrt{1+\mathrm{THD}_i^2}} = \frac{I_{1,\,\mathrm{rms}}}{I_{\mathrm{rms}}}$$

THD_i is the total harmonic distortion of the load current. $I_{1,\mathrm{rms}}$ is the fundamental component of the current and I_{rms} is the total current – both are root mean square-values (distortion power factor can also be used to describe individual order harmonics, using the corresponding current in place of total current). This definition with respect to total harmonic distortion assumes that the voltage stays undistorted (sinusoidal, without harmonics). This simplification is often a good approximation for stiff voltage sources (not being affected by changes in load downstream in the distribution network). Total harmonic distortion of typical generators from current distortion in the network is on the order of 1–2%, which can have larger scale implications but can be ignored in common practice.

The result when multiplied with the displacement power factor (DPF) is the overall, true power factor or just power factor (PF):

$$\mathrm{PF} = \mathrm{DPF}\frac{I_{1,\,\mathrm{rms}}}{I_{\mathrm{rms}}}$$

1.7 Power factor correction in non-linear loads:

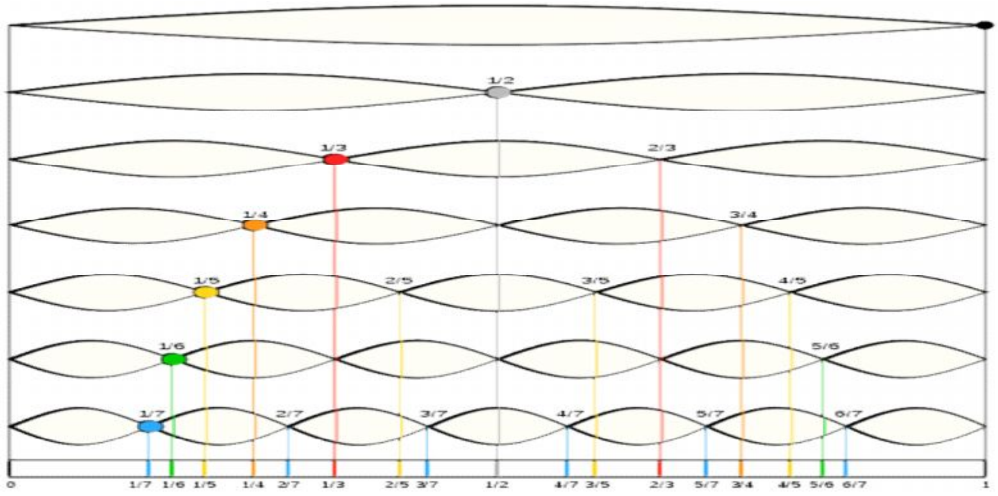
The simplest way to control the harmonic current is to use a filter: it is possible to design a filter that passes current only at line frequency (50 or 60 Hz). This filter reduces the harmonic current, which means that the non-linear device now looks like a linear load. At this point the power factor can be brought to near unity, using capacitors or inductors as required. This filter requires large-value high-current inductors, however, which are bulky and expensive.

A passive PFC requires an inductor larger than the inductor in an active PFC, but costs less.

This is a simple way of correcting the nonlinearity of a load by using capacitor banks. It is not as effective as active PFC. One example of this is a valley-fill circuit.

- Active PFC

An *active power factor corrector* (active PFC) is a power electronic system that changes the wave shape of current drawn by a load to improve the power factor. The purpose is to make the load circuitry that is power factor corrected appear purely resistive (apparent power equal to real power). In this case, the voltage and current are in phase and the reactive power consumption is zero. This enables the most efficient delivery of electrical power from the power company to the consumer.



1.8 - Why do we install capacitors?

In this example, demand was reduced

to 8250 kVA from 10000 kVA as shown in figure 1.

- 1750KVA Transformer Capacity Release.
- The power factor was improved from 80% to 97%

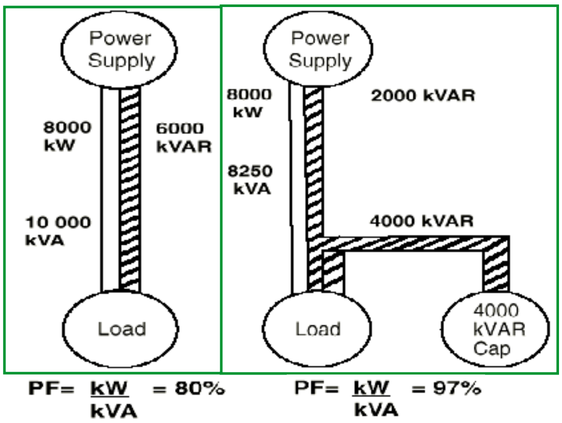


Fig 1 The reactive power

1.9- Benefits

- To counteract the undesirable effects of electric loads that create a power factor that is less than one.
- To improve the stability and efficiency of transmission network.
- Monitoring the power factor changes using AVR and LCD in real time basis.
- Demand side management
- Automation in power factor improvement
- Reduced Power Costs: Since Capacitors supply reactive power, you don’t pay the utility for it and You can calculate the savings
- Off-load transformers: Defer buying a larger transformer when adding loads
- Reduce voltage drop at loads :Only if capacitors are applied at loads (minimal benefit at best)

2 - System Implementation

A large part of the project involved choosing the appropriate hardware components to measure the power factor and provide a wireless link. The initial idea was to search for an all-in-one solution that would have all the components integrated, allowing for the smallest size possible. Initially it was thought that a simple circuit could be built and attached to a microprocessor (microcontroller) to sample the voltage and current measurements. After doing active and reactive power calculations, many calculations were stumbled upon, such as power factor.

Equipment located in customer premises emits reactive power that lowers the power factor. There are devices that can be attached to the loads to raise the power factor and reduce the amount of energy lost as heat on the wires in buildings and on the electrical distribution system.

It was decided that designing a simple circuit, such as a voltage divider, would not be enough, and would provide inaccurate readings. The following sections describe the research process as well as the implementation of these integrated circuits, and we will explain each components of the system as follow.

2.1 System design

Power measurement was the basic task of this project. To be able to detect the active and reactive power there were three fundamental options. A System-On-Chip (SOC) that would be fully integrated and would be an all-in-one solution and how to implement either a System- On-Chip or an Analog Front-End with a microcontroller.
Another option was to use an Analog Front-End (AFE) chip attached to a microprocessor

through SPI bus ports to make a comparison.
The last option was to assemble a circuit to adequately obtain the power factor by a microcontroller.
Out of these options, the most appropriate and most accurate would be monitor and control the system in the real time

2.2 Power Measurement:

After further reviewing for integrated chips, it was realized that there was an extensive programming requirement to implement power measurement calculations using a chip abandoned and have an Analog Front- End. After reviewing several different manufacturers, the Analog Devices ADE7763 chip was chosen for its easy accessibility and its integration of SPI bus. Using SPI would allow for easy communication between the microcontroller and the Analog Front-End chip. A large amount of the AFE chips reviewed did not contain an SPI communication bus, but rather had a counter, which was mainly used for the older utility power meters.

2.3 The ADE7763 :(figure 2)

Features:

ADCs and fixed function Digital Signal Processor (DSP) for "high accuracy over large variations in environmental conditions and time." It incorporates two second-order, 16-bit ∑- Δ ADCs, a digital integrator, reference circuitry, a temperature sensor, and all the signal processing required to perform active and apparent energy measurements, line-voltage period measurements, and root-mean squared (RMS) calculation on the voltage and current channels/ports of the chip. The selectable on-chip digital integrator provides direct interface to di/dt current sensors such as Rogowski coils, which could be used as an interface to sample the current. The basic functional block diagram is shown in figure 2.2. This chip is a Single-Phase Active and Apparent Energy Metering IC. It contains two Programmable Gain Amplifiers (PGA) and two Analog-to-Digital Converters (ADC) that achieve the basic sampling functionality of the chip. The values calculated by the internal DSP are stored in registers, which can be accessed through SPI communication.

Fig 2 The ADE7763

2.4 AVR microcontroller(ATmega32) (figure 3)

In an embedded system, the Microcontroller is the heart of the system. Hence it must be selected correctly according to the application of the system. There are many families of microcontrollers available such as ATMEL, ATMEGA, and PIC etc. In this work ATmega32 microcontroller was chosen for doing the proposed application. The following are the criteria through which a microcontroller could be selected for a particular system.
It is the main brain of the system which all the components are take orders from it (status, commands…..), connect all parts together , make all the calculations needed for the power factor ,and Calculate the value of the capacitors (capacitor banks are switched according to the output) needed for the system in KVAR.

Fig 3 ATMEGA32

Also do the following:

- Read the Analog Values From the ADE Chip
- Calculate Value of Power factor
- Show System information on the LCD
- Find out the exact values of the capacitors needed
- Handle the communication with the external world using GSM
- Read Inputs used to Configure the System
- Capacitor banks are switched according to the output of AVR.

Features:

High-performance, Low-power Atmel®AVR® 8-bit High Endurance

Non-volatile Memory Segments, Advanced RISC Architecture:

- 131 powerful instructions – most single - clock cycle execution
- 32*8 general purpose working registers
- Fully static operation
- Up to 16 mips through put at 16 MHZ
- Handle the communication with the external world using GSM
- On chip 2- cycle multiplier
- Low power consumptions
- High operating speed , good interrupt capability.
- A single 5V source is required for programming.

2.5 GSM Modem (figure 4)

Fig 4 GSM modem

A GSM (Global System for Mobile Communication, originally from Group Special Mobile) modem is a wireless modem that works with a GSM wireless network. A wireless modem behaves like a dial-up modem, except the main difference between them is that a dialup modem sends and receives data through a fixed telephone line, while a wireless modem sends and receives data through radio waves. Like a GSM mobile phone, a GSM modem requires a SIM card from a wireless carrier in order to operate. A GSM modem can be an external unit or a PCMCIA card (also called PC Card). An external GSM modem is connected to a PC through either a serial cable or a USB cable or Bluetooth or Infrared.

GSM is the most popular standard for mobile phones in the world. It is used by over 3 billion people across more than 212 countries and territories. Its ubiquity makes international roaming very common between mobile phone operators, enabling subscribers to use their phones in many parts of the world.

GSM digitalize both signals and speech channels and thus is considered as a second generation mobile phone system. This has also meant that data communication was easy to build into the system.

In our System it’s used for sending every critical Power factor change over SMS Also it can receive a configuration SMS from a mobile to Configure the system or Request the Current Status of the System in order to Monitor and Control it.

2.6 LCD LIQUID CRYSTAL DISPLAY (figure 5)

LCDs are used as numerical indicators; especially in digital watches where there is a much smaller current needed than LED displays (microamperes compared with milliamperes) which prolongs battery life. Liquid crystals are organic (carbon) compounds, which exhibit both solid and liquid properties. The LCD display used in this project consists of many rows. Each row consists of maximum 16 characters.

It is (liquid Crystal Display) it's connected to the MCU to show the information of our system in a user friendly way it can be

- Graphical Mono-color
- Graphical RGB
- Alphanumeric LCD
- Dot matrix liquid crystal display HD44780U is used.
- Can display up to one 8- character line.
- Requires a low power supply.

Fig 5 LCD

2.7 Capacitors Bank Board (figure 6)

This board consists of relays connected to capacitors, switching on/off the relays allow connecting/disconnecting capacitor to/from the AC line ,also it connect the loads which needed to be monitored and controlled.

Fig 6 Capacitor banks

2.8 Power supply board

To supply energy to the measurement side of the project, it was required to design a power supply. A basic design was chosen (figure 2.6) to deliver +5VDC required for the ADE7763 chip , so it need some device to convert the AC voltage To DC and Step it down to 5v and this is the job of the power supply.

2.9 Firmware

The microcontroller is a smart chip but without Programming it's useless piece of silicon. In order to program the microcontroller you have multiple choices, a lot of programming languages used to do this job Such as:

- Assembly
- Basic
- C
- Flow code

C is our choice for these reasons

- It's fast
- Friendly
- Easier than assembly
- Compatible with a lot of microcontrollers
- You can learn it faster than other languages
- It has a wide support over the internet
- It allows a lot of software modularity which is very important

Operation

When the system powered up the microcontroller receive the active and reactive power or power factor for each load are connected the system on relay board which is detected by the ADE chip, after that the MCU calculate the total power factor for the connected load in real time ,then it compare this value by the stored one (0.95)(this value are recommended by the customer),so if the value for the total load is less than the stored one rabidly it determine the value of the capacitor banks need to entered to the system to eliminate the difference between the two value ,furthermore it connect the capacitor banks through the relay board.

When the system reaches the stored value the system will be in steady state to any change of components which side by side change the value of the power factor value and also change the value of the capacitor banks.

It means that the system all the time is on the stored power factor value.
Also all this steps are monitored by the mobile phone to have easy enter to the system through sending an SMS message (GSM module) appear the status of the system and on the LCD inside the place (Show the Power Factor ,Connected capacitor s ,VRMS ,IRMS and Average Real Power)

When the microcontroller starts working it initialize all internal Peripherals then initialize all other Electronic Control Units Connected to the system (LCD – GSM – ADE –Relays) Send commands to Relays Board to connect/ disconnect the capacitor Find out if the Power Factor is critical if so it sends SMS to the Mobile of The System Operator Read if the System Received A new message with some Commands as well as the web page through EATHERNET protocol.

Theoretical equations

Inputs for each device:
Actual (active) Power (P),Reactive Power (Q) ,Power Factor ($COS\ \varphi$) (PF)

Interested to boost up=95% $\Longrightarrow$ PF_2 = 95 %

$$\varphi = COS^{-1}\ (PF) \quad (1)$$

$$Q = P * \tan \varphi \quad (2)$$

$$Q_T = Q_1 + Q_2 + Q_3 \quad (3)$$

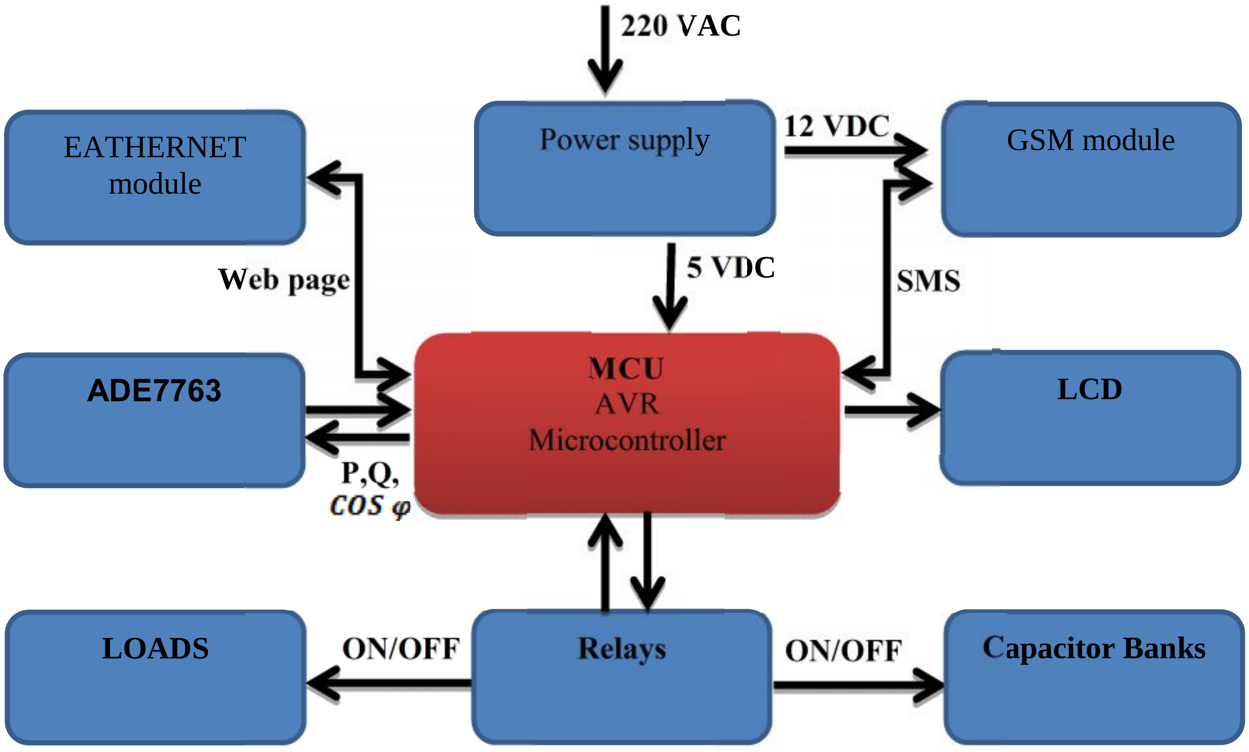
$$P_T = P_1 + P_2 + P_3 \quad (4)$$

$$\varphi_{new} = \tan^{-1} (Q_T / P_T) \quad (5)$$

$$PF_{new} = \cos \varphi_{new} \quad (6)$$

$$Q_c = P_T * (\tan \varphi_{new} - \tan PF_2) \Longrightarrow \text{KVAR} \quad (7)$$

Block diagram of an automatic power factor correction system



Conclusions

The project allows a user to measure the power factor of different devices and obtain the value of the capacitor banks required for improve the power factor whichever the number of loads are connected to the system. These devices connect directly to relay board provided in the project. The VRMS and IRMS values are calculated by an analog front-end integrated circuit and give active and reactive power to the microcontroller. The power factor data is sent wireless to a mobile phone through GSM module which connects the system to a customer. Power consumption data is graphed and shown in a graphical user interface.

Currently data is being transmitted in one second intervals. There are improvements that can be implemented on the project, such as provide a longer distance range for the wireless transmission by using different wireless transceivers, design a more compact power supply, and integrate multiple printed circuit boards (PCB) into one small PCB. This work also facilitates to monitor the power factor changes on LCD in real time basis. this is suitable for applications where manual switching of capacitors is to be replaced by automatic switching.

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Nomenclatures:

φ	Power angle
Q	Reactive power
P	Active power