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Automatic Power Factor Correction Using Capacitor Banks

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Abstract: The thirst for new sources of energy is unquenchable, but we seldom realize that we are wasting a part of the electrical energy everyday due to the lagging power factor in the inductive loads we use. Hence, there is an urgent need to avoid this wastage of energy. Before getting into the details of Power Factor Correction, let us just brush our knowledge about the term ―power factor‖. In simple words, power factor basically states how far the energy provided has been utilized. The maximum value of power factor is unity. So the closer the value of power factor to unity, better is the utility of energy or lesser is the wastage. In electrical terms, power factor is basically defined as the ratio of active power to reactive power or it is the phase difference between voltage and current. Active power performs useful work while reactive power does no useful work but is used for developing the magnetic field required by the device. Most of the devices we use have power factor less than unity. Hence, there is a requirement to bring this power factor close to unity. Here we are presenting a prototype for automatic power factor correction using the 8-bit AVR microcontroller "Atmega328" as Arduino Uno. Power factor correction using capacitor banks reduces reactive power consumption which will lead to minimization of losses and at the same time increases the electrical system's efficiency. Power saving issues and reactive power management has brought about the development of single phase capacitor banks for domestic applications. The development of this project is to enhance and upgrade the operation of single phase capacitor banks by developing a micro-processor based control system. The control unit will be able to control the individual capacitors in the capacitor bank and will operate in steps based on the variation in power factor. Current transformer and a Voltage transformer are used for sampling of the circuit current and voltage, so as to determine the power factor. The intelligent control using this micro-processor control system ensures even utilization of capacitor steps, minimizes number of switching operations and optimizes power factor correction.

Keywords: Power factor, Capacitor banks, Compensation, Microcontroller (Arduino uno).

I. INTRODUCTION

Power Factor

Power factor is the ration between the KW and the KVA drawn by an electrical load where the KW is the actual load power and the KVA is the apparent load power. It is a measure of how effectively the current is being converted into useful work output and more particularly is a good indicator of the effect of the load current on the efficiency of the supply system.

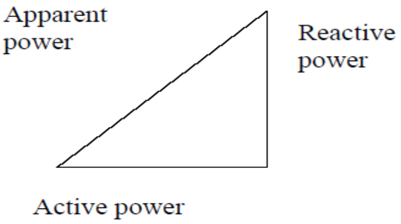

Fig.1. Power triangle

All current will cause losses in the supply and distribution system. A load with a power factor of 1.0 result in the most efficient loading of the supply and a load with a power factor of 0.5 will result in much higher losses in the supply system.

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 an inductive load such as an induction motor, power transformer, lighting ballasts, welder or induction furnace. A poor power factor due to an inductive load can be improved by the addition of power factor correction, but, a poor power factor due to a distorted current waveform requires a change in equipment design or expensive harmonic filters to gain an appreciable improvement.

Power Factor Correction

Capacitive Power Factor correction is applied to circuits which include induction motors as a means of reducing the inductive component of the current and thereby reduce the losses in the supply. There should be no effect on the operation of the motor itself.

An induction motor draws current from the supply that is made up of resistive components and inductive components.

The resistive components are:
(i) Load current
(ii)Loss current

The inductive components are:
(i) Leakage reactance
(ii) Magnetizing current

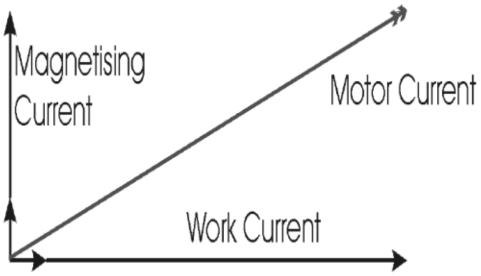

Fig. 2. Ideal running condition of motor

The current due to the leakage reactance is dependent on the total current drawn by the motor, but the magnetizing current is independent of the load on the motor. The magnetizing current will typically be between 20% and 60% of the rated full load current of the motor. The magnetizing current is the current that establishes the flux in the iron and is very necessary if the motor is going to operate.

The magnetizing current does not actually contribute to the actual work output of the motor. It is the catalyst that allows the motor to work properly. The magnetizing current and the leakage reactance can be considered passenger components of current that will not affect the power drawn by the motor, but will contribute to the power dissipated in the supply and distribution system.

Taking an example, a motor with a current draw of 100 Amps and a power factor of 0.75 the resistive component of the current is 75 Amps and this is what the KWh meter measures. The higher current will result in an increase in the distribution losses of (100 x 100) / (75 x 75) = 1.777 or a 78% increase in the supply losses.

In the interest of reducing the losses in the distribution system, power factor correction is added to neutralize a portion of the magnetizing current of the motor. Typically, the corrected power factor will be 0.92 - 0.95 some power retailers offer incentives for operating with a power factor of better than 0.9, while others penalize consumers with a poor power factor. There are many ways that this is metered, but the net result is that in order to reduce wasted energy in the distribution system, the consumer will be encouraged to apply power factor correction.

Power factor correction is achieved by the addition of capacitors in parallel with the connected motor circuits and can be applied at the starter, or applied at the switchboard or distribution panel. The resulting capacitive current is leading current and is used to cancel the lagging inductive current flowing from the supply. Capacitors connected at each starter and controlled by each starter are known as "Static Power Factor Correction"

Static Correction

As a large proportion of the inductive or lagging current on the supply is due to the magnetizing current of induction motors, it is easy to correct each individual motor by connecting the correction capacitors to the motor starters. With static correction, it is important that the capacitive current is less than the inductive magnetizing current of the induction motor.

When the motor is connected to the supply, the capacitors are also connected providing correction at all times that the motor is connected to the supply. This removes the requirement for any expensive power factor monitoring and control equipment. In this situation, the capacitors remain connected to the motor terminals as the motor slows down. An induction motor, while connected to the supply, is driven by a rotating magnetic field in the stator which induces current into the rotor. When the motor is disconnected from the supply, there is for a period of time, a magnetic field associated with the rotor. As the motor decelerates, it generates voltage out its terminals at a frequency which is related to its speed. The capacitors connected across the motor terminals, form a resonant circuit with the motor inductance. If the motor is critically corrected, (corrected to a power factor of 1.0) the inductive reactance equals the capacitive reactance at the line frequency and therefore the resonant frequency is equal to the line frequency. If the motor is over corrected, the resonant frequency will be below the line frequency. If the frequency of the voltage generated by the decelerating motor passes through the resonant frequency of the corrected motor, there will be high currents and voltages around the motor/capacitor circuit. This can result in severe damage to the capacitors and motor. It is imperative that motors are never over corrected or critically corrected when static correction is employed.

Static power factor correction should provide capacitive current equal to 80% of the magnetizing current, which is essentially the open shaft current of the motor. The magnetizing current for induction motors can vary considerably. Typically, magnetizing currents for large two pole machines can be as low as 20% of the rated current of the motor while smaller low speed motors can have a magnetizing current as high as 60% of the rated full load current of the motor. It is not practical to use a "Standard table" for the correction of induction motors giving optimum correction on all motors. Tables result in under correction on most motors but can result in over correction in some cases. Where the open shaft current cannot be measured, and the magnetizing current is not quoted, an approximate level for the maximum correction that can be applied can be calculated from the half load characteristics of the motor.

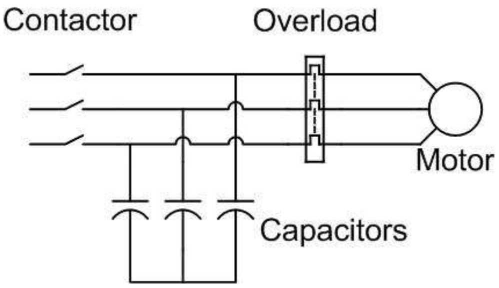

Fig.3: Static correction

Static correction is commonly applied by using one contactor to control both the motor and the capacitors. It is better practice to use two contactors, one for the motor and one for the capacitors. Where one contactor is employed, it should be up sized for the capacitive load. The use of a second contactor eliminates the problems of resonance between the motor and the capacitors.

II. SUPPLY HARMONICS

Harmonics on the supply cause a higher current to flow in the capacitors. This is because the impedance of the capacitors goes down as the frequency goes up. This increase in current flow through the capacitor will result in additional heating of the capacitor and reduce its life.

The harmonics are caused by many nonlinear loads; the most common in the industrial market today, are the variable speed controllers and switch mode power supplies. Harmonic voltages can be reduced by the use of a harmonic compensator, which is essentially a large inverter that cancels out the harmonics. This is an expensive option. Passive harmonic filters comprising resistors, inductors and capacitors can also be used to reduce harmonic voltages. This is also an expensive exercise. In order to reduce the damage caused to the capacitors by the harmonic currents, it is becoming common today to install detuning reactors in series with the power factor correction capacitors. These reactors are designed to make the correction circuit inductive to the higher frequency harmonics. Typically, a reactor would be designed to create a resonant circuit with the capacitors above the third harmonic, but sometimes it is below.

Adding the inductance in series with the capacitors will reduce their effective capacitance at the supply frequency. Reducing the resonant or tuned frequency will reduce the effective capacitance further. The object is to make the circuit look as inductive as possible at the 5th harmonic and higher, but as capacitive as possible at the fundamental frequency. Detuning reactors will also reduce the chance of the tuned circuit formed by the capacitors and the inductive supply being resonant on a supply. harmonic frequency, thereby reducing damage due to supply resonance amplifying harmonic voltages caused by non linear loads.

III. SUPPLY RESONANCE

Capacitive Power factor correction connected to a supply causes resonance between the supply and the capacitors. If the fault current of the supply is very high, the effect of the resonance will be minimal, however in a rural installation where the supply is very inductive and can be high impedance, the resonance can be very severe resulting in major damage to plant and equipment.

To minimize supply resonance problems, there are a few steps that can be taken, but they do need to be taken by all on the particular supply.

1) Minimize the amount of power factor correction, particularly when the load is light. The power factor correction minimizes losses in the supply. When the supply is lightly loaded, this is not such a problem.
2) Minimize switching transients. Eliminate open transition switching - usually associated with generator plants and alternative supply switching, and with some electromechanical starters such as the star/delta starter.
3) Switch capacitors on to the supply in lots of small steps rather than a few large steps.
4) Switch capacitors on o the supply after the load has been applied and switch off the supply before or with the load removal.

Harmonic Power Factor correction is not applied to circuits that draw either discontinuous or distorted current waveforms.

IV. CALCULATION OF CAPACITANCE REQUIRED

In order to calculate power factor correction for your installation, you should follow the steps below:
Step 1– Calculate Actual Load (kW)
(Load) Power kW = Volts V **x** $\sqrt{3}$ x Current **I** x Power factor (Pf)

Step 2– Calculate Required Power Factor Correction (kVAr)

Power Factor Correction kVAr = Power kW **(**TanΦi – TanΦd**)**

Φi = Cos^{-1} Initial Power Factor Pf

Φd = Cos^{-1} Required Power Factor Pf

Step 3**–** Calculate Actual Power Factor Correction [kAVr].

Actual Power Factor Correction Pf = Cos**(**Tan^{-1} **(**TanΦi **–** Correction kVAr **/** Power kW **))**

V. CIRCUIT FOR SENSING CURRENT AND VOLTAGE

Circuit for Sensing Current

To connect a CT sensor to an Arduino, the output signal from the CT sensor needs to be conditioned so it meets the input requirements of the Arduino analog inputs, i.e. **a** positive voltage between 0V and the ADC reference voltage**.** This can be achieved with the following circuit which consists of two main parts:

1. The CT sensor and burden resistor
2. The biasing voltage divider (R1 & R2)

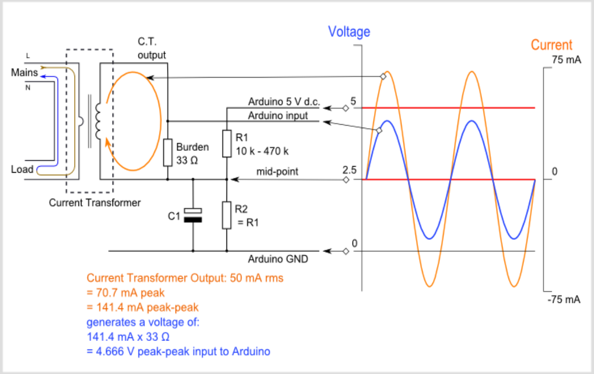

Fig 4. Current sensing circuit

Calculating a Suitable Burden Resistor

If the CT sensor is a "current output" type the current signal needs to be converted to a voltage signal with a burden resistor. If it is a voltage output CT you can skip this step and leave out the burden resistor, as the burden resistor is built into the CT.

1) Choose the current range you want to measure

The CT has a current range of 0 to 5 A. For this example, let's choose 5 A as our maximum current.

2) Convert maximum RMS current to peak-current by multiplying by √2.

Primary peak-current = RMS current × √2 = 5 A × 1.414 = 7.07A

3) Divide the peak-current by the number of turns in the CT to give the peak-current in the secondary coil.

The CT has 1000 turns, so the secondary peak current will be:

Secondary peak-current = Primary peak-current / no. of turns = 7.07 A / 100= 0.0707A

4) To maximise measurement resolution, the voltage across the burden resistor at peak-current should be equal to one-half of the Arduino analog reference voltage. (AREF / 2)

If you're using an Arduino running at 5V: AREF / 2 will be 2.5 Volts. So the ideal burden resistance will be:Ideal burden resistance = (AREF/2) / Secondary peak-current = 2.5 V / 0.0707 A = 35.4 Ω 35 Ω is not a common resistor value. The nearest values either side of 35 Ω are 39 and 33 Ω. always choose the smaller value, or the maximum load current will create a voltage higher than AREF.

Here are the same calculations as above in a more compact form:

Burden Resistor (ohms) = (AREF * CT TURNS) / (2√2 * max primary current)

Adding a DC Bias

If you were to connect one of the CT wires to ground and measure the voltage of the second wire, relative to ground, the voltage would vary from positive to negative with respect to ground. However, the Arduino analog inputs require a positive voltage. By connecting the CT lead we connected to ground, to a source at half the supply voltage instead, the CT output voltage will now swing above and below 2.5 V thus remaining positive. Resistors R1 & R2 in the circuit diagram above are a voltage divider that provides the 2.5 V source .Capacitor C1 has a low reactance **-** a few hundred ohms **-** and provides a path for the alternating current to bypass the resistor.

Choosing a suitable value for resistors R1 & R2:

Higher resistance lowers quiescent energy consumption.

Circuit for Sensing Voltage

An AC voltage measurement is needed to calculate real power, apparent power and power factor. This measurement can be made safely (requiring no high voltage work) by using an AC to AC power adaptor. The transformer in the adapter provides isolation from the high voltage mains. The main objective for the signal conditioning electronics detailed below, is to condition the output of the AC power adapter so it meets the requirements of the Arduino analog inputs**:** a positive voltage between 0V and the ADC reference voltage (5V).The output signal from the AC voltage adapter is a near-sinusoidal waveform. If you have a 9V (RMS) power adapter the positive voltage peak be 12.7V, the negative peak -12.7V. However, due to the poor voltage regulation with this type of adapter, when the adapter is un-loaded (as in this case), the output is often 10-12V (RMS) giving a peak voltage of 14-17V. The voltage output of the transformer is proportional to the AC input voltage. The signal conditioning electronics needs to convert the output of the adapter to a waveform that has a positive peak that's less than 5V and a negative peak that is more than 0V. So we need to:

1. Scale down the waveform.
2. Add an offset so there is no negative component.

The waveform can be scaled down using a voltage divider connected across the adapter's terminals, and the offset (bias) can be added using a voltage source created by another voltage divider connected across the Arduino's power supply (in the same way we added a bias for the current sensing circuit).

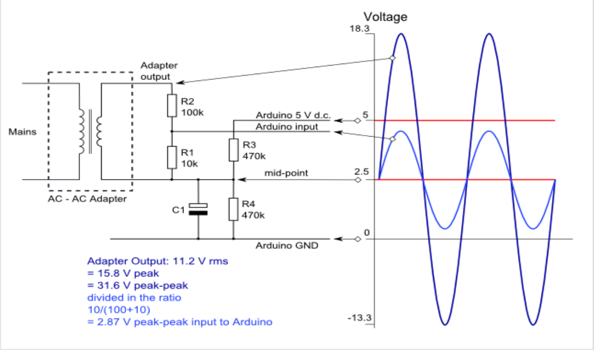

Fig. 5. Voltage sensing circuit

Resistors **R1** and **R2** form a voltage divider that scales down the power adapter AC voltage. Resistors **R3** and **R4** provide the voltage bias. Capacitor **C1** provides a low impedance path to ground for the AC signal. The value is not critical, between 1 µF and 10 µF will be satisfactory. R1 and R2 need to be chosen to give a peak-voltage-output of ~1V. For an AC-AC adapter with an 9V RMS output, a resistor combination of 10k for R1 and 100k for R2 would be suitable:

peak_voltage_output = R1 / (R1 + R2) x peak_voltage_input = 10k / (10k + 100k) x 12.7V = 1.15V

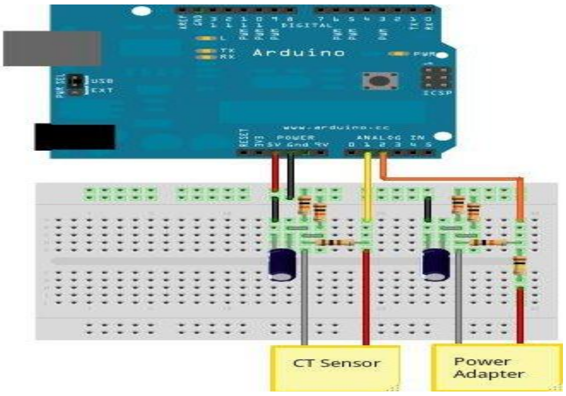

Fig. 6. Circuit to sense current and voltage

Calculating Power Factor

To calculate the power factor, we need to sense instantaneous current and voltage and calculate real and apparent power, from the relation of power factor with real and apparent power we can calculate power factor.

VI. INSTANTANEOUS VOLTAGE AND CURRENT

As the name suggests, AC Voltage and current continually alternate. If we draw a picture of the voltage and current waveform over time, it will look something like the image below. Depending on the type of load consuming power, the current waveform - blue in the diagram below - is what you get if you look at a typical laptop computer power supply. (There's an incandescent light bulb present, as well). The image was made by sampling the mains voltage and current at high frequency, which is exactly what we do on the emontx or Arduino. We make between 50 and 100 measurements every 20 milliseconds. 100 if sampling only current. 50, if sampling voltage and current. We're limited by the Arduino analog read command and calculation speed.

Each individual sample is an instantaneous voltage or current reading.

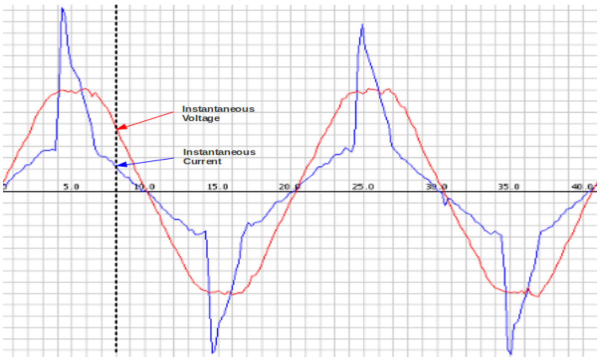

Fig. 7. Instantaneous voltage or current reading

VII. CALCULATING REAL POWER ON AN ARDUINO

VIII.

Real power is the average of instantaneous power. The calculation is relatively straight forward.

First we calculate the instantaneous power by multiplying the instantaneous voltage measurement by the instantaneous current measurement. We sum the instantaneous power measurement over a given number of samples and divide by that number of samples:

```
for (n=0; n<number_of_samples; n++)
{
 // inst_voltage and inst_current calculation from raw ADC input goes here

 inst_power = inst_voltage * inst_current;
```

```
 sum_inst_power += inst_power;
}

real_power = sum_inst_power / number_of_samples;
```

Root-Mean-Square (RMS) Voltage:
The root-mean-square is calculated in the way the name suggests. First we square the quantity, then we calculate the mean and finally, the square-root of the mean of the squares, this is how its done:

```
for (n=0; n<number_of_samples; n++)
{
  // inst_voltage calculation from raw ADC input goes here.
  squared_voltage = inst_voltage * inst_voltage;
  sum_squared_voltage += squared_voltage;
}
mean_square_voltage = sum_squared_voltage / number_of_samples;
root_mean_square_voltage = sqrt(mean_square_voltage);
```

Root-Mean-Square (RMS) Current:
Same as the RMS voltage calculation:

```
for (n=0; n<number_of_samples; n++)
{
  // inst_current calculation from raw ADC input goes here.
  squared_current = inst_current * inst_current;
  sum_squared_current += squared_current;
}
mean_square_current = sum_squared_current / number_of_samples;
root_mean_square_current = sqrt(mean_square_current);
```

Apparent Power

```
apparent_power = root_mean_square_voltage * root_mean_square_current;
```

As RMS voltage is generally a fixed value such as: 230V (+10% -6% in the UK). It's possible to approximate apparent power without making a voltage measurement by setting the RMS voltage to 230V. This is a common practice used by commercially available energy monitors.
Power Factor

```
power_factor = real_power / apparent_power;
```

VIII. INTERFACING OF CAPACITOR BANK

Capacitors are connected in parallel to the load circuit, so they are designed such as to be connected in parallel to load. Capacitance of capacitors add when connected in parallel, they are connected in parallel with the relay switch board. Below figure shows the connection of capacitor bank. Capacitors are connected in parallel to the load circuit, so they are designed such as to be connected in parallel to load. Capacitance of capacitors add when connected in parallel, they are connected in parallel with the relay switch board.

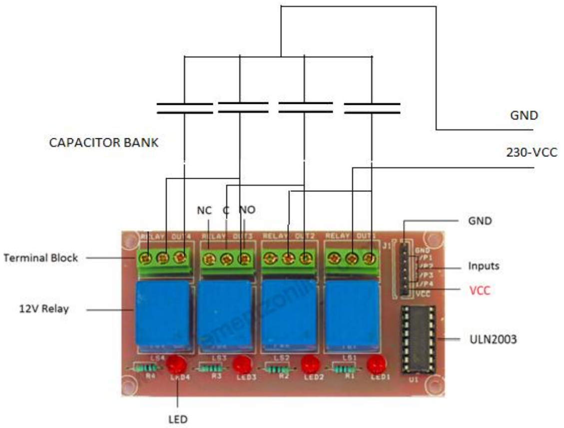

Fig. 8. connection of capacitor bank.

IX.DESIGN OF POWER CIRCUIT

The power circuit provides the Power factor circuit and the microcontroller with +5V supply and relay circuit with +12V supply for uninterrupted operation. The following circuit is used for the power circuit. In this circuit the single phase supply of 230 V ac is stepped down to 12 V using a 230/12 V transformer of 1 amp rating. Then after this the 12v A C supply is passed through a bridge rectifier made of 4 p-n junction diode IN4007 which converts the A C supply into D C supply which filtered through a 1000 uF electrolytic capacitor. Below is the circuit-

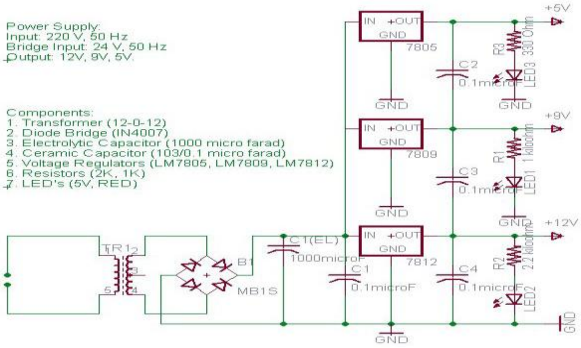

Fig.9. Design of power circuit.

X. PROGRAM SKETCH

```
#include "EmonLib.h"            // Include Emon Library
EnergyMonitor emon1;             // Create an instance
#include <LiquidCrystal.h>
LiquidCrystal lcd(12, 11, 5, 4, 3, 2);
int cap1 = 6; //2.5 micro farad capacitor
int cap2 = 7; //2.5 micro farad capacitor
```

```
int cap3 = 8;//2.5 micro farad capacitor
int cap4 = 9; //2.5 micro farad capacitor

float upf          = -0.90;
float lpf          = -0.01;
float powerFActor;

void setup()
{
  Serial.begin(9600);
  lcd.begin(16, 2);

  emon1.voltage(2, 234.26, 1.7);   // Voltage: input pin,
calibration, phase_shift
  emon1.current(1, 111.1);         // Current: input pin,
calibration.

  pinMode(cap1, OUTPUT);
  pinMode(cap2, OUTPUT);
  pinMode(cap3, OUTPUT);
  pinMode(cap4, OUTPUT);

}

void loop()
{
  getpf();
  delay(5000);
  Serial.print("\tThe current Power factor of the system
is:\t\t\t");
  Serial.println(powerFActor);
   lcd.setCursor(0,0);
   lcd.print("Power Factor =");
   lcd.setCursor(8,1);
   lcd.print(powerFActor);


  if(0.01<powerFActor <0.99 )
{
Serial.print("\tThe load connected is Inductive in nature,
therefore the power factor is inductive in nature:\t\t\t");
digitalWrite(cap1, LOW);
delay(10000);
getpf();
Serial.print("\tThe corrected Power factor ( 1 ) is:\t\t\t");
Serial.println(powerFActor);

if(upf<powerFActor <lpf )
{
Serial.print("\tThe load connected is Inductive in nature,
therefore the power factor is inductive in nature:\t\t\t");
digitalWrite(cap1, HIGH);
delay(10000);
getpf();
Serial.print("\tThe corrected Power factor ( 1 ) is:\t\t\t");
Serial.println(powerFActor);

  if(0.01<powerFActor <0.99 )
{
Serial.print("\tThe load connected is Inductive in nature,
therefore the power factor is inductive in nature:\t\t\t");
digitalWrite(cap2, LOW);
delay(10000);
getpf();
Serial.print("\tThe corrected Power factor ( 1 ) is:\t\t\t");
Serial.println(powerFActor);


  if(upf<powerFActor <lpf)
{
digitalWrite(cap2, HIGH);
delay(10000);
getpf();
Serial.print("\tThe corrected Power factor ( 2 ) is:\t\t\t");
Serial.println(powerFActor);

  if(0.01<powerFActor <0.99 )
{
Serial.print("\tThe load connected is Inductive in nature,
therefore the power factor is inductive in nature:\t\t\t");
digitalWrite(cap3, LOW);
delay(10000);
getpf();
Serial.print("\tThe corrected Power factor ( 1 ) is:\t\t\t");
Serial.println(powerFActor);
if(upf<powerFActor <lpf)
{
digitalWrite(cap3, HIGH);
delay(10000);
getpf();
Serial.print("\tThe corrected Power factor (3) is:\t\t\t");
Serial.println(powerFActor);

  if(0.01<powerFActor <0.99 )
{
Serial.print("\tThe load connected is Inductive in nature,
therefore the power factor is inductive in nature:\t\t\t");
digitalWrite(cap4, LOW);
delay(10000);
getpf();
Serial.print("\tThe corrected Power factor ( 1 ) is:\t\t\t");
Serial.println(powerFActor);

if(upf<powerFActor <lpf)
{
digitalWrite(cap4, HIGH);
delay(10000);
getpf();
```

```
Serial.print("\tThe corrected Power factor (4) is:\t\t\t");
Serial.println(powerFActor);

                        }
                    }
}
}}}}}

    else if(powerFActor=1)
{
Serial.print("\tThe circuit has a resistive load, hence the normal power factor is:\t\t\t");
Serial.println(powerFActor);
}
}
void getpf()
{
  emon1.calcVI (20,2000);         // Calculate all. No. of half wavelengths (crossings), time-out

   power Factor       = (emon1.powerFactor);        //extract Power Factor into Variable
}
```

XI. APPLICATION AND PROPOSED IMPROVEMENT

Application

1. This automatic power factor controller provides an easy and reliable method to monitor and improve power factor of an electrical system.
2. A system with improved power factor will provide the following advantages:

· Reactive power decreases
· Avoid poor voltage regulation
· Overloading is avoided
· Copper loss decreases
· Transmission loss decreases
· Improved voltage control
· Efficiency of supply system and apparatus increases

3. This kind of automatic power factor controller is cost effective, so can be applied to small systems too.

Proposed Improvements

1. Measurement of power factor need to be done with better and accurate potential transformer.
2. Capacitors with quick response are needed which can charge and discharge quickly otherwise, any change in power factor will cause two three cycles of program to run before final correction.
3. More combinations of capacitors are required to be applied so that precise improvement can be done.

XII. CONCLUSION

In this automatic power factor correction system, we are using potential divider circuits instead of traditional zero crossing detector which gives a more stable power factor and the price also get cut down because we do not need to use IC’s.

It can be concluded that power factor correction techniques can be applied to the industries, power systems and also households to make them stable and due to that the system becomes stable and efficiency of the system as well as the apparatus increases. The use of microcontroller reduces the costs. Due to use of microcontroller multiple parameters can be controlled and the use of extra hard wares such as timer, RAM, ROM and input output ports reduces.

Care should be taken for overcorrection otherwise the voltage and current becomes more due to which the power system or machine becomes unstable and the life of capacitor banks reduces.

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BIOGRAPHIES

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