

Power factor improvement for a three-phase system using reactive power compensation

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ABSTRACT

For all industrial and distribution sites, the lagging power factor of electrical loads is a common problem. In the early days, it was corrected manually by adding the capacitor banks of certain values in parallel. Automatic power factor correction (APFC) using a capacitor bank helps to make a power factor that is close to unity. It consists of a microcontroller that processes the value of the power factor to enable the system and monitor the power factor if it falls below (0.77) from the specified level. This paper presents the automatic correction of the power factor by adding the capacitors banks automatically of the desired value in a three-phase system in the form of binary coding (0-7). The main purpose of this system is to maintain the power factor as close as to unity, for the experimental case, it is set to (0.93) which helps to decrease the losses and ultimately increase the efficiency of the system.

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1. INTRODUCTION

Power factor (PF) is defined as the cosine of angle between the voltage and current. Most of the loads have low PF due to inductive nature in them. And due to low PF the current of the system increases. To reduce the current, this PF should be as close to as unity. The analysis of power factor can be made by drawing power triangle as shown in Figure 1. Due to this low PF the equipment will require larger no of rating, copper losses, conductor size and would result in poor handling capacity of the system. The PF of the system can be improved by adding the capacitor in parallel with the load, since it will provide the leading current I_c which neutralizes the lagging current I drawn by the system as shown in the Figure 2. The resultant current I' have the less magnitude as compared to I .

Other's methods to improve the PF are using phase advancers and synchronous condensers. The capacitor current I_c cancels the lagging reactive component of load current. Capacitance of capacitor to improve PF from $\cos \theta_1$ and $\cos \theta_2$.

$$X_c = \frac{V}{I_c} = \frac{1}{\omega C} \quad (1)$$

An automatic power factor control method proposed for the both inductive and resistive loads [1]. Power quality is a big issue these days due to an increase in the inductive loads. Power quality can be

improved by appropriately monitoring the load PF. Whenever the load power factor decreases than the certain value, line current increases which ultimately leads to a higher voltage drop and line losses.

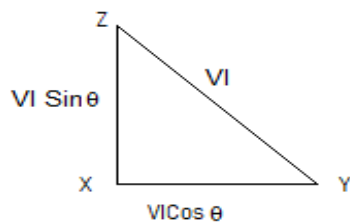


Figure 1. Power triangle

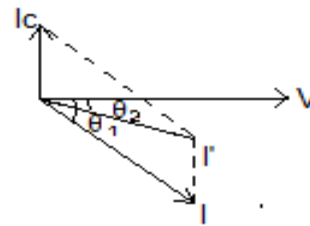


Figure 2. Phasor representation of currents

Where,

$XY = VI \cos \theta$, the active power in kilo Watts

$XZ = VI \sin \theta$, the reactive power in kilo VAR

$YZ = VI$, the apparent power in kilo VA

An automatic power factor control method presented Microcontroller based capacitor bank switching [2]. If the value of the PF goes below the predetermined value of PF, specified value of the capacitance will be required to achieve the desired value using (1) [3]. The phase difference generated due to the low PF is proportional to the signal strength of the pulse width. A Microcontroller is being used to monitor the power factor and it is automatically switch on the capacitors of the required capacity [4]. A comparative analysis using the solid state relay to improve the PF is used in [5] which uses a relay to detect the value of the power factor and compares it with a pre-set value. After the comparison, if the pre-set value comes out to be less the calculated value, then the capacitor is automatically added, by this design [6] Various methods for reactive power compensation are proposed such as series compensation, shunt compensation, static VAR commutator, STATCOM, and synchronous condenser.

Industrial usage of inductive loads is the biggest cause of power loss and power factor lagging [7]. That technique can be used in industries, power systems, and households and it is adding capacitance according to the demand or requirement. In that technique, the power factor was improved from 0.66 to 0.92 value. An automatic power factor compensation (APFC) technique is used for the medical industries in Malaysia and the power factor improved from 0.85 to 0.90 [8]. The APFC contributes to low power loss and more cost-efficient. The APFC technique is beneficial is coping with the challenge of limited energy resources that may arise under the situation, when there is high power demand. An automatic power factor correction using Arduino uno technique is used to improve the power factor by using OR Gates [9].

An automatic power factor metering using Arduino is used in, power systems, and households and it is adding capacitance according to the demand or requirement [10]. In that technique, the power factor was improved from 0.68 to 0.90 value. Automatic power factor correction techniques along with energy monitoring system is proposed consist of a power supply that runs at 230V at 50 Hz frequency and then to control the voltage use step down transformer and bridge rectifie [11]. Voltage sensors and current sensor circuits are used for the observation of these quantities. Microcontroller and liquid crystal display (LCD) are being used for monitoring and relay drivers are used for the implementation of commands [12]. There are various methods of power factor correction unit, one of the old methods of low power factor correction includes the installation of fixed capacitors for the compensation of active power [13].

Nowadays efficient methods of power distribution are becoming very important because of the demand for electricity in every sector (industrial, residential, commercial). In this scenario we learn about the technique of load sharing of transformer and improve power factor automatically [14]. As the power factor decreases, it causes electrical losses in a system which is due to increase in the size of conductor. For economical operation, a PF correction unit allows the device to restore its PF close to unity. Reduced power system losses, enhanced load carrying capacities, enhanced voltages for the benefits of power factor correction [15]. The foremost reason for this work is to develop an automatic power factor correction (APFC) system capable of tracking the power consumption of a system and enhancing its PF routinely.

In industry induction motors are used commonly due to the low cost and robustness and removes the penalty factor [16], [17]. For mining purposes, it acts as a prime mover. At no-load condition, the induction motor is a low power factor. Algorithms are designed to improve power factor for three-phase induction motors using programmable system on chip (PSoC3) [18]. A three-leg rectifier-inverter introduces which

works as both boost converter and buck converter. A technique for enhancing the capacity of synchronous generators at the distant ends of rural distribution where the power factor was small and the line resistance was high. These methods have been proposed only for the inductive loads [19], [20]. If the power factor is lagging, the system starts consuming more power from utility and the extra power utility gives a penalty [21]. Our first and foremost priority of industries make power factor nearer to unity [22]. Ideally power factor must be near to unity it makes voltage stability, minimize power losses and also increase the power system efficiency [23], [24].

The earlier power factor was 0.65 before adding the reactive power in this paper, and the power factor has been enhanced to 0.93. In order to achieve that, the capacitor of 22uF has been mounted. Conclusively, an enhanced power factor of 0.28 has been achieved. Another research on APFC technique has been carried out in the paper automatic power factor correction utilizing reactive power compensation for three phase systems [2].

In this paper the power factor has been improved by using the capacitors banks and by using microcontroller for three phase systems. Before the system automatic power factor correction utilizing reactive power compensation for three phase systems the conclusion was per year payment before corrected is 12.59\$ and per year payment after power factor corrected is 9.27\$ and annual savings is 3\$ [7]. After the design of systems the conclusion was per year payment before corrected is 13.12\$ and per year payment after power factor corrected is 9.12\$ and annual savings is 4\$. The annual savings is to increase in the design, so automatic power factor correction utilizing reactive power compensation is better than the previous design.

2. BLOCK DIAGRAM OF SYSTEM

Complete block diagram of the system is shown in Figure 3. Three phase supply is used (phase to neutral 230V). CT is connected to source in series to (A6). PT is connected to source parallel to (A8). Phase difference or zero crossing can be measured by voltage and current divider circuit. Microcontroller ATmega2560 is used to operate relay and relay operates capacitor banks which is connected in strings.

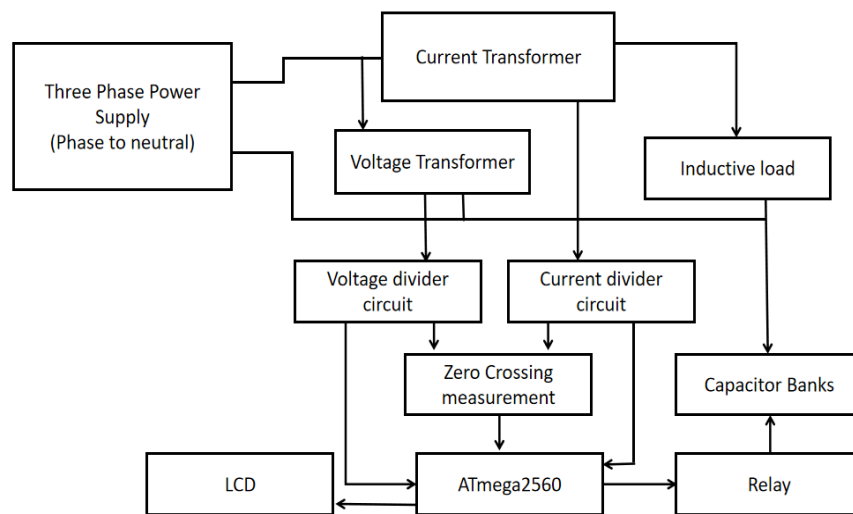


Figure 3. Block diagram

3. SYSTEM FLOW CHART

- Step-1: Initially voltage and current signal is sensed as input signal by microcontroller (Arduino Mega2560).
- Step-2: Calculation and display of voltage, current, power factor and apparent power.
- Step-3

$$Q = \sqrt{S^2 - P^2} \tag{2}$$

- Step-4: Phase shift is measured between voltage and current signal.
- Step-5: If PF>0.95 applied Phase A inductive load is on. If PF≤0.95 allied Phase A and Phase B inductive loads are on. If PF<0.95 applied Phase A, B and C inductive load are on. Figure 4 parades the flow chart of the system.

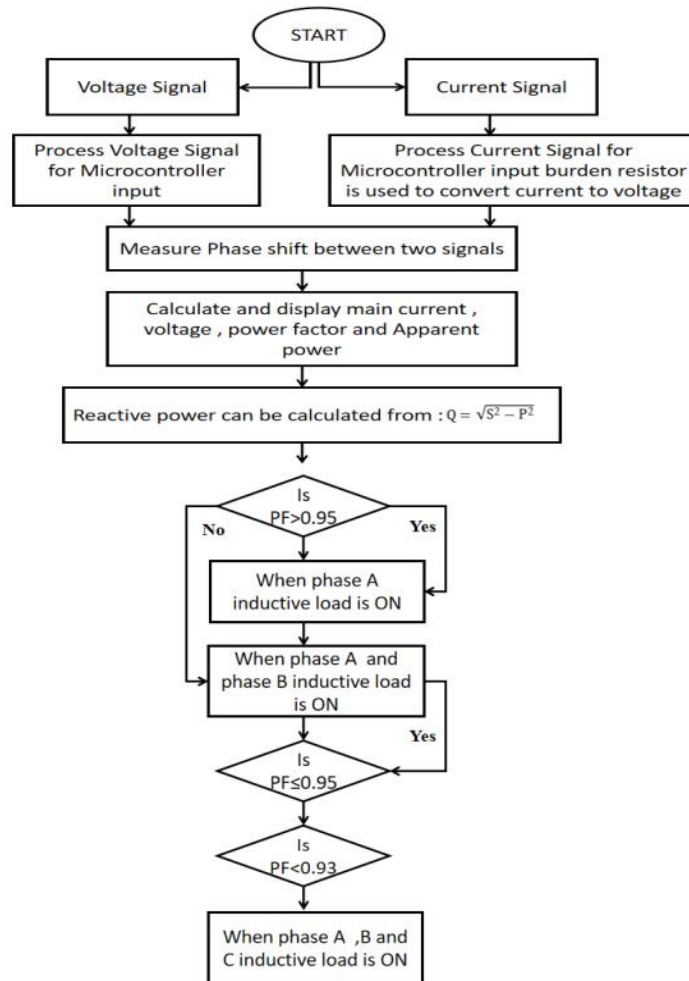


Figure 4. Flow chart

4. RESULTS AND DISCUSSIONS

4.1. Simulation results

Three phase supply is used and the power factor of each phase was improved. Each phase is connected with potential transformer (PT) and current transformer (CT). Voltages of each phase measured by PT and step down to 5V through using potential divider for making appropriate voltages for microcontroller [25]. Similarly, Current is measured through CT. Each phase is connected with four capacitor bank string and these four capacitor bank strings are used to compensate reactive power. Each phase has 6 capacitors (When phase A, B and C inductive load is on) and total 18 capacitor are used for 3-phase for minimizing the reactive power. Figure 5 show proteus simulation circuit. Results are displayed on LCD 20 × 4.

4.1.1. Simulation calculation

Proteous simulation results are shown in Table 1. When all three phases inductive loads are on, the number of capacitors is on 18 automatically and its binary number is (10010). At no load power factor is 0.78 and with load power factor is 0.93 (targeted value of PF) to improve the efficiency of three phase system. The load use in design is 41.82 KW.

Table 1. Software calculation results

| Sr. | Voltage (V) | Current (A) | Apparent power (KVA) | Reactive power (KVAR) | Capacitor ON | PF |
|-----|-------------|-------------|----------------------|-----------------------|--------------|------|
| 1 | 139V | 20.67A | 54.31KVA | 34.65VAR | 00 | 0.78 |
| 2 | 220V | 8.91A | 44.96KVA | 667VAR | 18 | 0.93 |

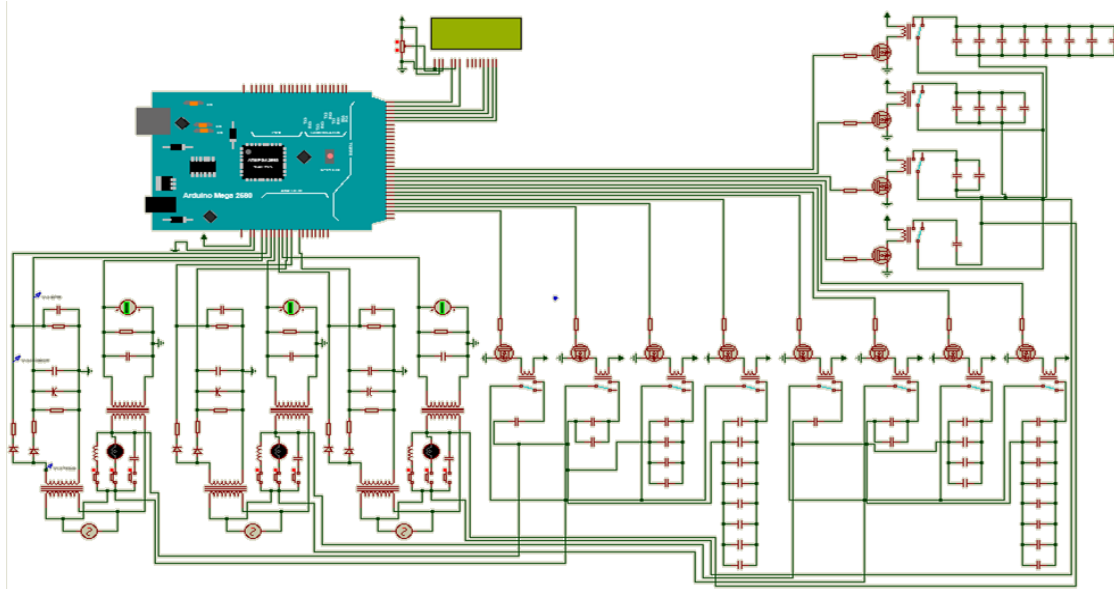


Figure 5. Proteus simulation

4.1.2. Simulation LCD display results 20×4

LCD 20×4 display the results of low value of power factor (0.78) and improve value of power factor (0.93). Switching of capacitor are done automatically and hence we improve the power factor. Figure 6 shows the low and improve power factor results.



Figure 6. Simulation results LCD display

4.1.3. Voltage divider circuit

Step down transformer is used to step down voltages up to 16.148 V and then potential divider is used to step down further voltages. After designing the circuit and voltages are step down up to 2.34 V. Design of potential divider is given in Figure 7.

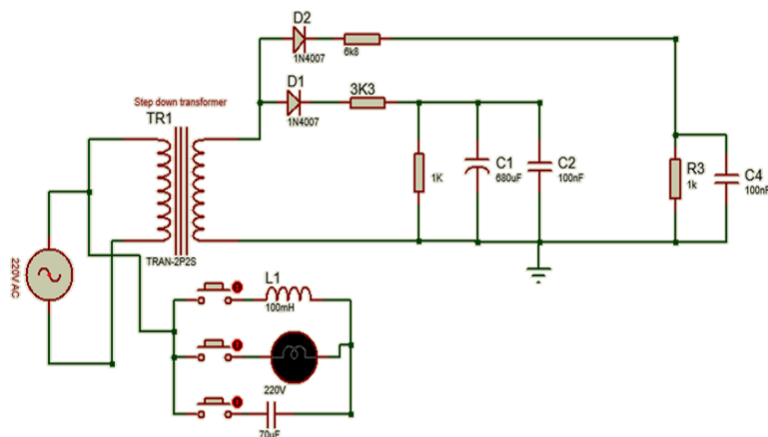


Figure 7. Voltage divider circuit

Calculation of the voltage division is calculated as;

$$V_{\text{acrossarduino}} = \frac{V_{\text{acrossPTonSecondaryside}} \times R_2}{R_1 + R_2} \quad (3)$$

$$V_{\text{acrossPTonSecondaryside}} = 16,1487$$

$$R_1 = 3.3k, R_2 = 1k$$

Putting values in (3)

$$V_{\text{acrossarduino}} = \frac{(16.1487 \times 1)K}{(1 + 3.3)K} \quad (4)$$

$$V_{\text{acrossarduino}} = 3.75V \text{ (ADC 767 number Arduino pin } A_1)$$

4.1.4. Current divider circuit

CT is connected to the source in series to measure the current. Further current division circuit is used to convert current into voltages because Arduino Mega2560 detect voltages in terms of binary coding. Design of current divider is given in Figure 8.

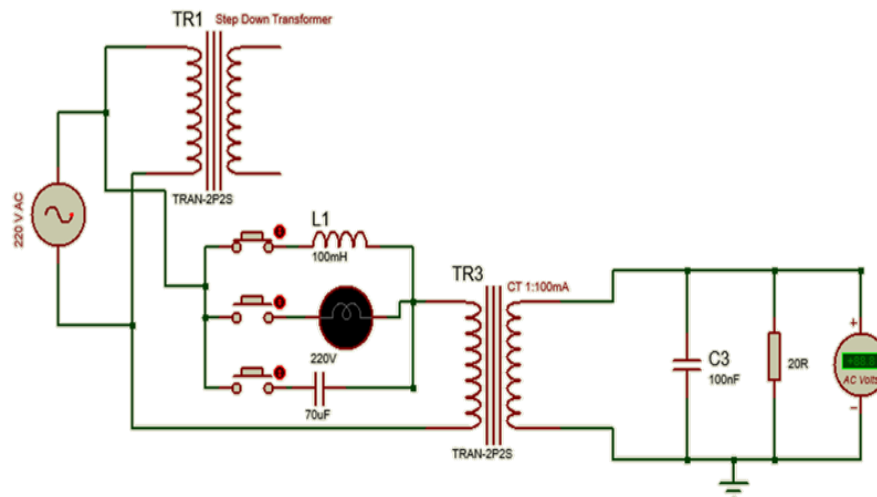


Figure 8. Current divider circuit

Calculation of Current Divider circuit is as follows;

$$V = IR \quad (5)$$

Putt values in (5)

$$V = (100mA) (25ohm)$$

$$V = 2.5V \text{ (ADC number is 511) in Arduino pin } A_0$$

4.1.5. Capacitor calculations

For the designing of the circuit of capacitors, active, reactive and apparent power is calculated. All these powers of each phases are calculated separately. After performing all these calculations capacitors of $22\mu F$ is selected design of capacitance circuit is given in Figure 9.

Calculation for capacitors is as;

$$S_{\text{old}} = \frac{P}{PF} = \frac{41.82}{0.65} \quad (6)$$

$$S_{\text{old}} = 64.33KVA$$

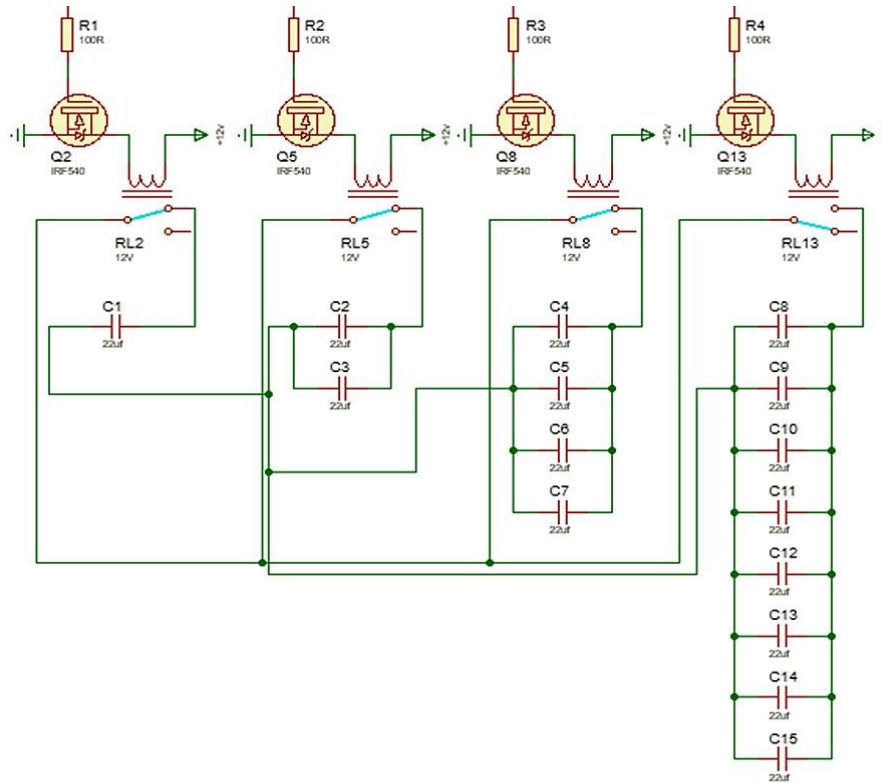


Figure 9. Capacitance circuit

The reactive power is calculated as;

$$Q_{old} = \sqrt{S^2 - P^2} \tag{7}$$

Putting values in (7)

$$Q_{old} = \sqrt{64.33^2 - 41.82^2} \tag{8}$$

$$Q_{old} = 48.88 \text{KVAR}$$

$$S_{new} = \frac{P}{PF} = \frac{41.82}{0.93} \tag{9}$$

$$S_{new} = 44.96 \text{KVA}$$

$$Q_{new} = \sqrt{S^2 - P^2} \tag{10}$$

Putting values in (9)

$$Q_{new} = \sqrt{44.96^2 - 41.82^2} \tag{11}$$

$$Q_{new} = 16.507 \text{KVAR}$$

$$Q_{required} = Q_{old} - Q_{new} \tag{12}$$

Putting values Q_{old} and Q_{new} in (12)

$$Q_{required} = 48.88 - 16.507$$

$$Q_{required} = 32.373 \text{KVAR}$$

Reactive power required of each phase;

$$Q = \frac{32.373}{3} \quad (13)$$

$$Q = 10.79A$$

Total current before capacitor added;

$$S_{\text{new}} = V_{\text{rms}} \times I_{\text{rms}} \quad (14)$$

Re-arrange (14)

$$I_{\text{rms}} = \frac{S_{\text{new}}}{V_{\text{rms}}} \quad (15)$$

Putting values in (15)

$$I_{\text{rms}} = \frac{44.96}{221} = 203A \quad (16)$$

$$\text{Active Component of current} = I_{\text{active}} = I_{\text{rms}} \cos \phi \quad (17)$$

$$I_{\text{active}} = 203 \times 0.65 = 131.95A$$

Reactive component of current

$$I_{\text{old reactive}} = I_{\text{rms}} \sin \phi \quad (18)$$

$$\phi = \cos^{-1} 0.65 = 49.45$$

$$\sin 49.45 = 0.7598$$

$$I_{\text{old reactive}} = I_{\text{rms}} \sin \phi \quad (19)$$

Putting values in (19)

$$= 203 \times 0.7598 = 154A$$

New reactive component is;

$$I_{\text{new reactive}} = I_{\text{rms}} \sin \phi \quad (20)$$

Putting values in (20)

$$I_{\text{new reactive}} = 203 \times \sin 21.56 = 74.59A$$

The capacitive value of current is calculated by the difference in old reactive current and new reactive current component and capacitor is added in star sequence.

$$I_c = I_{\text{old reactive}} - I_{\text{new reactive}} \quad (21)$$

$$I_c = 154 - 74.59 = 79.41A$$

$$C = \frac{I_c}{2 \times 3.14 \times f \times V_{\text{ph}}} \quad (22)$$

Putting values in 22

$$C = \frac{79.41}{2 \times 3.14 \times 50 \times 220 \times \sqrt{3}}$$

$$C = 66\mu F$$

$$C = \frac{66\mu F}{3} = 22\mu F$$

Each capacitor value is 22uF.

4.1.6. Per year cost before correction

$$S_{old} = 64.33 \text{KVA}$$

$$\text{Per Month Payment} = 0.017\$ \times 64.33 = 1.0937\$/\text{month}$$

$$\text{Per Year Payment} = 1.0937\$ \times 12 = 13.12\$/\text{year}$$

4.1.7. Per year cost after correction

$$S_{new} = 44.96 \text{KVA}$$

$$\text{Per Moth Payment} = 0.017\$ \times 44.96 = 0.76\$/\text{month}$$

$$\text{Per Year Payment} = 0.76\$ \times 12 = 9.12\$/\text{year}$$

$$\text{Saved dollar (\$)} = \text{Per year payment before corrected} - \text{per year payment after corrected}$$

$$\text{Saved dollar (\$)} = 13.12\$ - 9.12\$ = 4\$$$

The compiled data is shown in Table 2.

Table 2. Savings after correction of power factor

| No | Status | Dollar (\$) |
|----|-----------------------------------|-------------|
| 1 | Per year payment before corrected | 13.12(\$) |
| 2 | Per year payment after corrected | 9.12(\$) |
| 3 | Saved dollar (\$) | 4(\$) |

4.1.8. Simulation results low PF

Figure 10 shows the waveform of low power factor (Phase A, Phase B and Phase C). In Phase A $V_{rms} = 212\text{V}$, Peak Volage is $V_p = 299\text{V}$ and Peak Current is $I_p = 8.71\text{A}$ and average voltage is $V_{avg} = 190\text{V}$ and Rms value of current is $I_{rms} = 6.16\text{A}$. In Phase B $V_{rms} = 213\text{V}$, Peak Volage is $V_p = 301\text{V}$ and Peak Current is $I_p = 8.69\text{A}$ and average voltage is $V_{avg} = 191\text{V}$ and Rms value of current is $I_{rms} = 6.17\text{A}$. In Phase C and Rms value of current is $I_{rms} = 6.17\text{A}$ $V_{rms} = 212\text{V}$, Peak Volage is $V_p = 300\text{V}$ and Peak Current is $I_p = 8.72\text{A}$ and average voltage is $V_{avg} = 191\text{V}$.

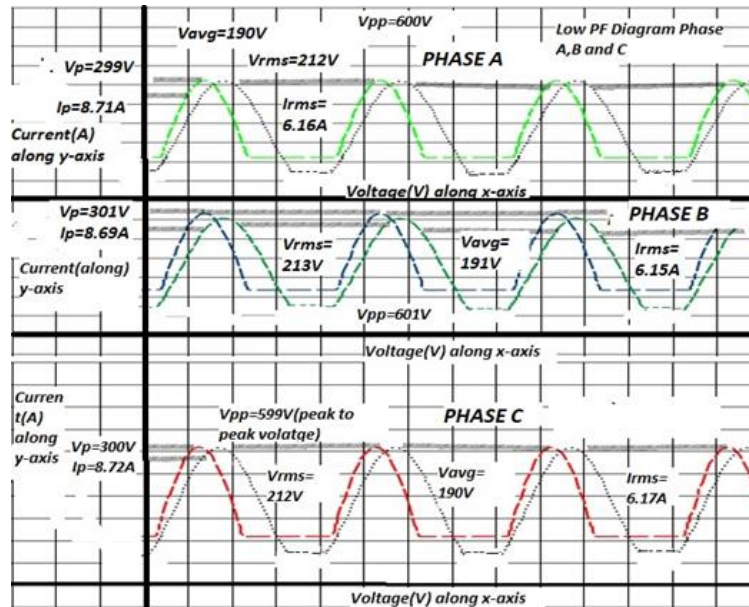


Figure 10. Simulation results (at low pf) when Phase A, B and C inductive loads are ON

4.1.9. Simulation results improved PF

Figure 11 shows the waveform of improve power factor (Phase A, Phase B and Phase C). In Phase A $V_{rms} = 220\text{V}$, Peak Volage is $V_p = 311\text{V}$ and Peak Current is $I_p = 4.15\text{A}$ and average voltage is $V_{avg} = 198\text{V}$ and Rms value of current is $I_{rms} = 2.94\text{A}$. In Phase B $V_{rms} = 220\text{V}$, Peak Volage is $V_p = 311\text{V}$ and Peak Current is $I_p = 4.21\text{A}$ and average voltage is $V_{avg} = 197\text{V}$ and Rms value of current is $I_{rms} = 2.98\text{A}$. In Phase C

$V_{rms}=220V$, Peak Voltage is $V_p=311V$ and Peak Current is $I_p=4.16A$ and average voltage is $V_{avg}=197V$ and Rms value of current is $I_{rms}=2.98A$. In improve Power Factor, Power losses of the system is reduced and efficiency is increased.

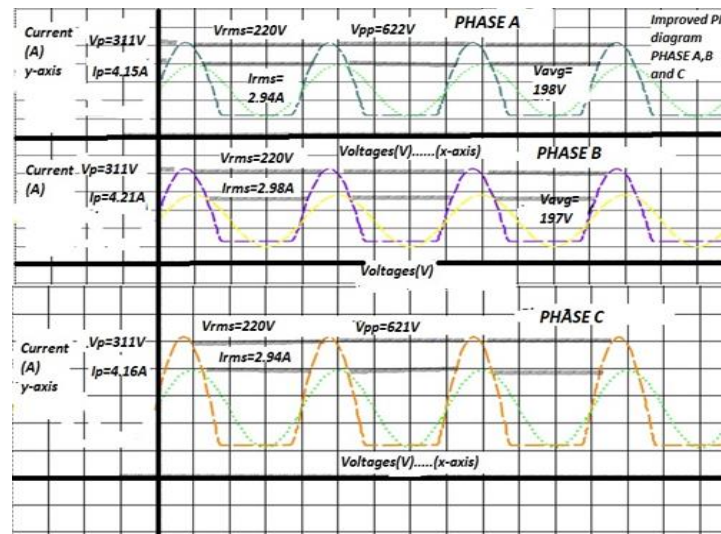


Figure 11. Hardware simulation results (at Improve pf) when Phase A, B and C inductive loads are ON

4.2. Hardware results

CT is connected to source in series to measure current PT is connected to source with parallel to measure voltages. Phase Difference or zero crossing can be measure by Voltage divider circuit and current divider circuit. Metal oxide semiconductor field effect transistor (MOSFET) interfeon regulatory factor (IRF) 540(N-channel) has been used to amplify the voltage. The Gate signal can apply through Arduino Mega 2560pin (41,42,43(Phase C),45,46,47,48(Phase B),49,50,51(Phase A). Adapter is used to step down the voltage from 240V to 12V further buck converter convert voltages from 12 V to 5 V and it's connected with pin 5 of Arduino. There are 15 capacitors are used for each phase and in total 45 capacitors are used for three Phase A, B and C. Design of Hardware is given in Figure 12.

4.2.1. Hardware calculation

Hardware results are shown in Table 3. When all three phases inductive loads are on, the number of capacitors is on 40 automatically and its binary number is (101000). At no load power factor is 0.67 and with load power factor is 0.93 (targeted value of power factor) to improve the efficiency of three phase system. The load use in design is 41.82 KW.

4.2.2. Hardware

LCD display results 20×4. LCD 20×4 displays the results of low value of power factor (0.67) and improved value of power factor (0.93). Switching of capacitor is done automatically and hence we improve the power factor. Low and improve power factor are shown in Figure 13.



Figure 12. Hardware implementation of the system



Figure 13. Hardware LCD display results at low power factor and improved power factor

Table 3. Hardware calculation results

| | Current (A) | Reactive Power (KVAR) | Apparent Power (KVA) | Capacitor ON | PF |
|------|-------------|-----------------------|----------------------|--------------|------|
| 215V | 2.28A | 46.32VAR | 62.41KVA | 00 | 0.67 |
| 215V | 2.46A | 16.50VAR | 44.96KVA | 40 | 0.93 |

4.2.3. Hardware results low power factor

In Phase A $V_{rms}=219V$, Peak Voltage is $V_p = 309V$ and Peak Current is $I_p=3.25A$ and Rms value of current is $I_{rms} = 2.30A$. In Phase B $V_{rms}=219V$, Peak Voltage is $V_p = 311V$ and Peak Current is $I_p=1.69A$ and Rms value of current is $I_{rms} = 1.20A$. In Phase C $V_{rms}=219V$, Peak Voltage is $V_p = 311V$ and Peak Current is $I_p=1.64A$ and Rms value of current is $I_{rms} = 1.16A$. Figure 14 show low PF waveform.

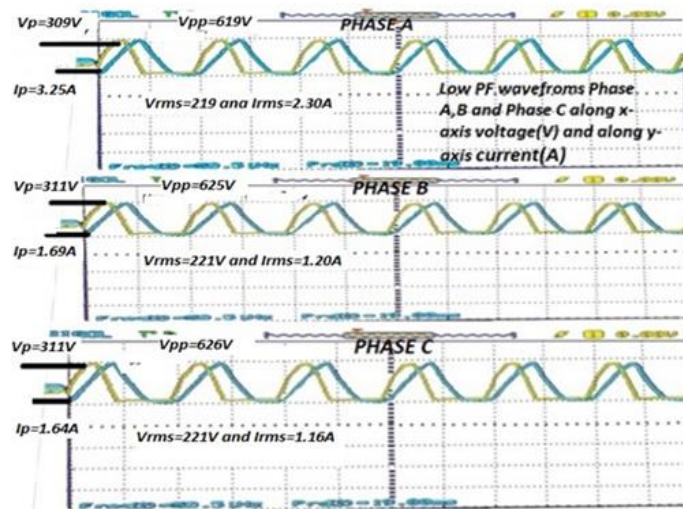


Figure 14. Hardware simulation results (at low pf) when Phase A, B and C inductive loads are ON

4.2.4. Hardware results improve power factor

Figure 15 shows the waveform of improve power factor (Phase A, Phase B and Phase C). In Phase A $V_{rms}=221V$, Peak Voltage is $V_p = 312V$ and Peak Current is $I_p=1.65A$ and Rms value of current is $I_{rms} = 1.17A$. In Phase B $V_{rms}=221V$, Peak Voltage is $V_p = 312V$ and Peak Current is $I_p=1.28A$ and Rms value of current is $I_{rms} = 0.91A$. In Phase C $V_{rms}=221V$, Peak Voltage is $V_p = 312V$ and Peak Current is $I_p=1.01A$ and Rms value of current is $I_{rms} = 0.72A$

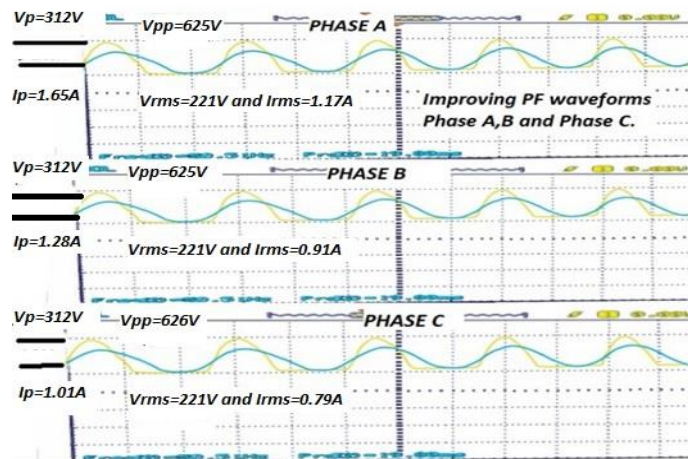


Figure 15. Hardware simulation results (at improve pf) when Phase A, B and C inductive loads are ON

5. CONCLUSION

Power factor correction scheme is designed primarily depend upon microcontroller and capacitors banks which are utilized for the estimation and checking of modeled electrical stack. In this paper the power factor has been improved by using the capacitors banks and by using microcontroller for Three phase systems. Before the system automatic power factor correction utilizing reactive power compensation for three phase systems the conclusion was per year payment before corrected is 12.59\$ and per year payment after power factor corrected is 9.27\$ and annual savings is 3\$. After the design of systems, the conclusion was per year payment before corrected is 13.12\$ and per year payment after power factor corrected is 9.12\$ and annual savings is 4\$. The annual savings is to increase in the design, so Automatic Power Factor Correction utilizing Reactive Power Compensation is better than the previous design.

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