A Scalable Power Factor Controller for Low-Voltage Distribution System

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Abstract: - This paper proposes a single phase scalable power factor controller (PFC) to support reactive power in distribution power system. The controller calculates power factor (PF) of a system directly by taking data from the distribution line. Considering the power factor deficit, capacitors of different values are connected to the line to improve the power factor. The line data is sensed and processed with the help of instrument transformers and zero crossing detectors. Further, the processed data are fed to a microcontroller which calculates the load power factor of the system. Capacitors of appropriate size are then connected to the line to support the reactive power. The performance of the PFC model is verified by simulation results, and its effectiveness is investigated on residential loads in distribution power system. The results show that the system is capable of maintaining power factor at an optimum level. Moreover, it reduces the power losses, and compensate reactive power in the distribution power system.

Key-Words: - Distribution power system; Energy savings; Microcontroller; Power factor controller; Reactive power compensation.

1 Introduction

With the advancement of modern civilisation, energy consumption increases day by day. Notably, the penetration of inductive loads in power system concerns power quality issue. Inductive loads cause excessive current flow through the power line and make the distribution system weak – a small system capacitance and poor power factor. As a result, electrical energy consumption efficiency reduces and resistive power losses increases. Thereby, it is necessary to monitor the customer's load profile to observe this power quality index. Power factor improvement in the distribution network is a control strategy for effective power delivery with maximum efficiency [1], [2]. Lack of reactive power injection not only leads to poor performance but also affects the power system economy. The electric power generation, transmission and distribution cost become higher due to power losses. Thereby, power factor improvement is essential which ensures economical energy usages. As the energy losses and control system voltage level can be minimized; hence electricity consumption costs for a given load level can be reduced [1]–[3].

A significant amount of researches are done on power factor controlling for industrial loads. Power factor improvement is a big challenge for most of the industries, as the loads used are inductive in nature. Some of the utility operators impose levies on the industrial customer due to the poor power factor.

The inductive loads cause current delays as well as inject higher order current harmonics [4]–[8]. Usually, in industries, the general practice is to balance the reactive power by capacitive loads. The inductive loads include induction motors, transformers, alternators, and relay coils. Utilization of power factor controller (PFC) saves both the energy and cost. In contrast to industry, the power factor correction scheme adopted by the residential customer is still inadequate. In some countries, the residential customers use the controller embedded with home appliances which are limited to a specific power rating. It is not mandatory for the customer with installed power less than that of the range. Furthermore, the cost of the reactive power usage is not taken seriously by the utility. Therefore, the reactive power consumption cost is not taken into consideration when preparing invoice [9], [10].

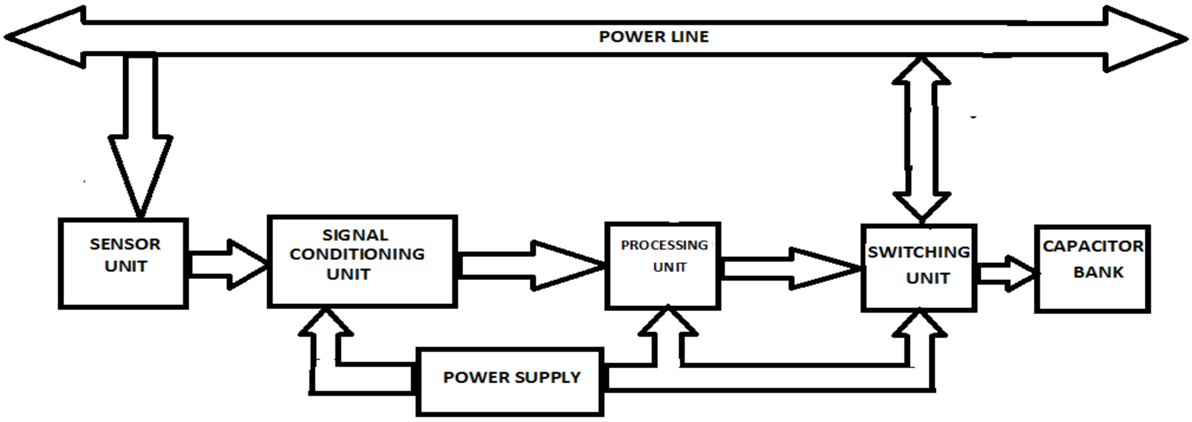

Fig.1. Block diagram of the designed power factor controller system

Although, supporting reactive power by activating supply side spinning reserve is practised [11], [12]; however, this strategy needs additional generators in-line. Nonetheless, the strategy is costly and harmful to the environment. In the majority of the previous studies, using demand-side resources to balance supply-demand disregarded reactive power control [13], [14]. In the past, capacitor based reactive power compensation mainly focused on optimal capacitor placement in the system [15]. In recent years, some reactive power compensation systems are designed for saving energy and increasing efficiency for small-scale customers [15]–[17]. Several cases also include compensation system for particular types of consumers like agricultural sector, welding machines, unbalanced loads and so on. [18]–[21].

Most of the cases, these systems are based on sophisticated technologies like real-time data acquisition, advanced signal processing and control theory [22]–[24]. Some of the systems also incorporate Field Programmable Gate Array (FPGA), Verilog Hardware Description Logic (VHDL), Digital Signal Processor; however, a major challenge is their implementation in reality. Additionally, operating these systems successfully and effectively demand higher technology support. Furthermore, running cost is also a considerable issue for these systems. In recent years, PFC based on Arduino – some sorts of embedded systems, customised for reactive power support are investigated in [1], [2], [25]–[27] leaving cost-benefit analysis.

In the distribution system, most of the cases, power factor improvement is investigated by using capacitors focusing on its optimal placement. A microcontroller based power factor controlling system is the simplest and cost-effective solution for the problem related to power factor for residential loads investigated in [1], [3], [4], [9], [17].

In this paper, we proposed a microcontroller based power factor controller. Fig. 1 shows a block diagram of the proposed PFC system. The system consists of six units. The power supply unit gives regulated power to rest of the units. The interconnections of these systems are shown in the figure. In the controller, the phase difference between the line voltage and current is measured using instrument transformers. The line currents have been acquired with the current transformer (CT). Similarly, the line voltage data have been sensed from the output of the potential transformer (PT) connected to the power line. Power factor angle is synthesized from the zero crossing detectors and microcontroller. Based on the requirement of the reactive power of the system for a given load level, the switching of the capacitor is actuated.

The rest of the paper is structured as follows. In section 2 the concepts of real and reactive power components are revisited. Section 3 presents the basic block diagram describing the interconnections among the components of the systems followed by the individual unit details of the system. Section 4 covers the operating algorithm in details. Section 5 provides results and discussion followed by concluding remarks in Section 6.

2 Reactive Power Support

The power factor can be defined as the ratio of the real power to the apparent power flowing in a circuit. It is a dimensionless number varying from 0 to 1. It arises due to a phase difference between the alternating current and voltage. The current (I) has two components, one is the real component, and the other is the reactive component. The real current drawn by the load is related to the consumption of the active power. On the other hand, the reactive current is related to the reactive power. The electric machines such as motors, transformers and generators operate on electromagnetic induction principle. The magnetic flux is essential for normal operation of those electric machineries. To produce magnetic flux, these machineries require magnetizing current which is reactive in nature. The mathematical relationship among the real (I_p), reactive (I_q) and alternating current are represented by the following equations [10].

$$I_p = I\cos\theta \quad (1)$$

$$I_q = I\sin\theta \quad (2)$$

Similarly, the relationship among the real, reactive, and apparent power is given by

$$P = S\cos\theta \quad (3)$$

$$Q = S\sin\theta \quad (4)$$

Where, S is the apparent power and θ is the angle between the supply voltage and total current [28], [29]. If a massive amount of reactive power is drawn, under voltage problem arises at distribution system which is harmful to the sensitive load. That is why reactive power compensation schemes are needed in the distribution power system.

Fig. 2 shows a power triangle for a non-compensated and a reactive power compensated scheme. A distribution system with an active power P is to compensate a power factor, $\cos\theta_1$ to a power factor, $\cos\theta_2$. The required reactive power, Q_c for the compensation can be determined by using (5)

$$Q_c = P(\tan\theta_1 - \tan\theta_2) \quad (5)$$

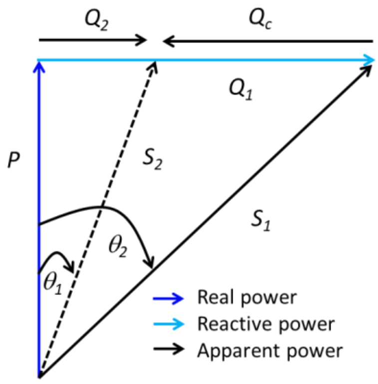

Fig.2. A phasor power triangle for a non-compensated and a compensated scheme.

As seen in the figure, the reactive power compensation reduces the transmitted apparent power. Thereby, the resistive transmission losses reduce by the square of the line currents.

3 The Proposed PFC System

The schematic diagram in Fig. 3 better describes the functions of the PFC subsystems. The subsystems are described as follows:

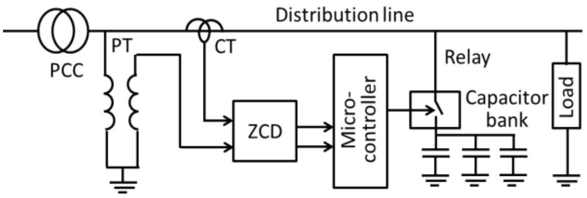

Fig. 3. Schematic diagram of the designed power factor controller

A power supply unit consists of a 220/9 volt transformer, a bridge rectifier and a generic integrated circuit. The unit provides regulated power for a different subsystem of the PFC.

The sensor unit consists of two instrument transformers, a current transformer (CT) to actuate current signal and a potential transformer to actuate the voltage signal. To acquire the voltage signal a 220/5 volt potential transformer (PT) has been used and similarly, a current transformer has been used to sense the current. The current transformer converted the current signal to half of its original values. A resistor is used here as current to voltage converter, which converts the acquired current signal to a voltage signal so that it can be fed to the input of the signal conditioning unit.

Fig. 4 presents the circuit diagram of the signal conditioning unit. The signal processing unit consists of two zero-crossing detectors. A generic integrated circuit has been used for this purpose. The unit can sense the zero crossing of the signals and has made the signals suitable to feed to the microcontroller.

The data processing unit consists of a microcontroller of PIC 18F family. The microcontroller is used to calculate power factor coefficient as well as the reactive power to select appropriate capacitor. To operate the microcontroller appropriately, a 20 MHz crystal oscillator has been used.

A sensing unit consists of relays, which act as static switches and connect each capacitor to the line

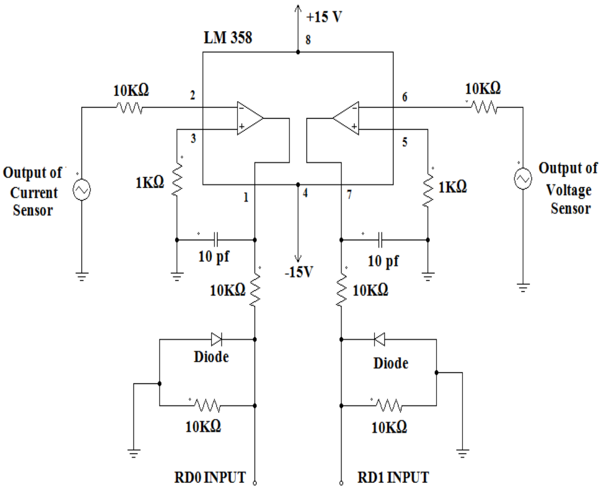

Fig. 4. Circuit diagram of zero crossing detector

for power factor correction whenever needed. The capacitor bank consists of capacitors of different values.

4 Operating Algorithm of The System

In the proposed controller circuit, the voltage and current signals have been acquired from the PT and CT respectively. These are connected to the power line, for which we want to determine the power factor coefficient. The zero-crossing detector is used for capturing the zero crossing times of voltage and current samples. The microcontroller is used to process the data. In the proposed system, the voltage and current data acquired from the PT and CT are given to the zero-crossing detectors. The outputs obtained from the zero-crossing detectors are given to the microcontroller as input. The time delay between the voltage and current are calculated. The time delay is used to measure the power factor as well as the reactive power requirement. Both the detectors give high (logic 1) signal when the respective signals cross a zero. The delay angle between the two signals determined from the zero crossing detectors represents the phase difference between the voltage and the current. This phase difference is utilized to calculate the power factor.

The processed samples obtained from the zero-crossing detectors are given to the microcontroller. When the voltage signal passes through the zero crossing, the timer inside the microcontroller has been started, and when the current signal passes through the zero crossing, it has been stopped. The time difference between the starting and stopping of the timer has been stored in a variable. The time difference between the voltage and current has been transformed into an angle. The cosine of the recorded angle signifies the power factor. Similarly, the reactive power is calculated using the equation (4). To make an exact and effective compensation, the values of the power factor and reactive power needs to be known. Considering these values, the relays connected with capacitors could be turned on or not. In this way, the compensation is done to control the power factor and to provide reactive power to the system.

5 Results and Discussion

5.1 Simulation Results

Fig. 5 shows the flowchart of the proposed PFC system. According to this algorithm, at first the voltage and current samples are acquired and given to the controller. Then the controller compares the zero crossing time. If the time is less than 1 ms, it indicates that the power factor of the load is within the desired range. So the system waits for the next sample for 1 second. If the time delay is within 1-2 ms, the controller gives the signal to close the relay corresponding to the first capacitor C_1 and the indicator. Similarly, for time delay 2-3 ms and 3-4 ms activate relays corresponding to the capacitors C_2 and C_3 respectively. In the system, the capacitors C_1 and C_3 have the minimum and maximum values respectively. After connecting the relays, it waits for next samples for 1second.

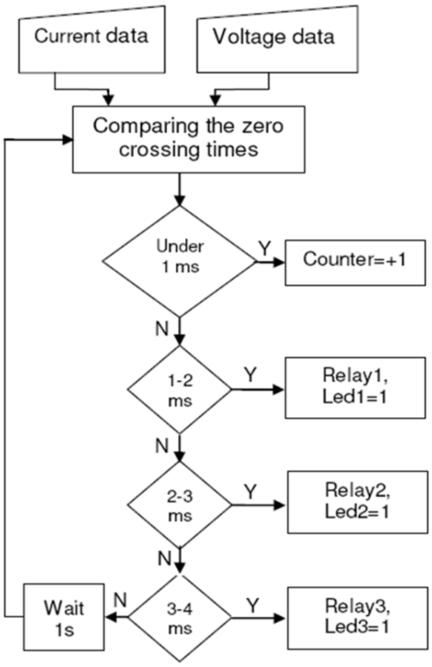

Fig. 5. Flowchart for the operation of the proposed system

A few zip loads are used as constant real and reactive power injections. Two loads namely Load#1 and Load#2 commonly used by the residential customers are used in the simulation. The load consumes a considerable amount of reactive power. Uncompensated loads have their power factor of 0.50. The Load#1 and Load#2 have rated the power of 20W and 36W respectively. Both the loads have been represented by a single inductor connected with a resistor in series with it. The values of resistor and inductor are determined from their power rating as presented in Table 1.

Table 1: Input parameters of the loads used in simulation

Load	Power	Voltage	PF	Value of resistor	Value of inductor
Load #1	20W	220V	0.50	605Ω	3.3 H
Load #2	36W	220V	0.50	336 Ω	1.834 H

Table 2: Power factor of the loads before and after connecting capacitors

Load	Power	Voltage	Power factor	
			Without PFC	With PFC
Load #1	20W	220V	0.5	0.926
Load #2	36W	220V	0.5	0.925

The results of both compensated and uncompensated system are presented in Table II. Figure 6 and 7 shows the waveforms of voltage and current for both the loads before and after connecting the capacitors respectively. The values of current are multiplied by a scale factor 200 for clear visualization compared to the voltage. Comparing the figures, it is clear that the power factor improves due to connecting the capacitors.

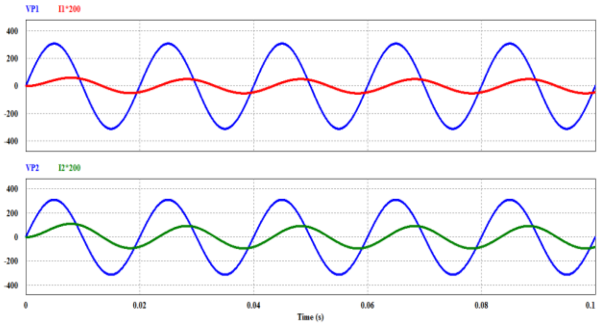

Fig. 6. Voltage and Current for both the loads before connecting the capacitors

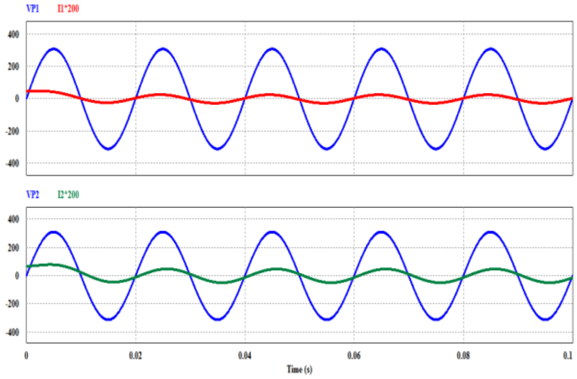

Fig. 7. Voltage and Current for both the loads after connecting the capacitors

Following benefits are obtained due to the proposed PFC scheme. The power factor improvement minimises the electricity consumption. As the power factor improves, the current drawn by the load reduces; the utility operator can serve more residential customers with the same rating cables. The power factor improvement for a given load level reduces ohmic losses of the transmission lines, transformers and distribution equipment. The proposed PFC results in a lower current being consumed for a given load. Also, the voltage drop in the transmission line reduces. Improved power factor reduces cable size to be used for the distribution system. Overall, the power delivery becomes robust in terms of efficiency and reliability.

5.2 Experimental Results

The proposed controller and the developed PFC algorithm has implemented in a test rig as shown in Fig. 8. The major subsystems include power supply unit, microcontroller, capacitor bank, relay unit, and the instrument transformers are indicated. For the test rig a load of 220V, 36 W having power factor 0.5 is considered. Three capacitors having capacitance 1.5µF, 2.5µF and 3.5µF are used. The power supply unit for the controller system includes a 220/9 volt transformer and a regulator integrated circuit.

A microcontroller in the PFC includes a central processing unit, memory and input/output peripherals. It receives the signal from the zero crossing detectors and then passes the control signal to the relay. The relay is electrically operated switches which control the connection of the capacitor bank. To make sure proper switching an additional LCD and an ammeter is interfaced with the prototype test rig. The LCD helps to observe the power factor at different stages.

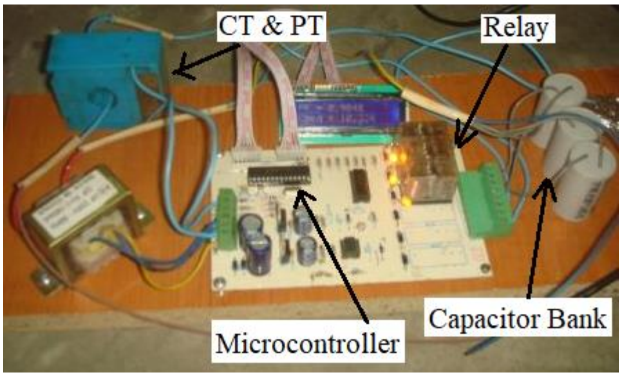

Fig. 8. The test rig for the proposed PFC system

Table 3: The test results of the implemented PFC

	Load #1			**Load #2**		
	PF	***I*** (Amp)	***I*** **reduced in %**	**PF**	***I*** (Amp)	***I*** **reduced in %**
With-out PFC	0.534	0.187	0.00	0.523	0.336	0.00
With PFC	0.93	0.108	42.25	0.925	0.194	42.27

The voltage and current data from the distribution power line are sensed, and the phase angle difference between these two has been determined. Using the phase difference, the power factor coefficient is calculated by a program loaded inside the microcontroller. Under the usual operating condition, the controller devices are connected to the load and the distribution line. The results are captured for three hours of the test period and presented in Table III. Analyzing the obtained results, it is observed that the power factor, $\cos\theta$ has reached the expected level. According to the test results, power factor coefficient has been reached above 90% with an average current savings of 42%.

In summary, the improved PF reduce stress on the physical transmission and distribution infrastructure. It improves the power quality, voltage stability and eliminates operational complications.

6 Conclusions

The main focus of this work is to develop a cost-effective and scalable PFC to support reactive power in the distribution network. The results from the simulation and experimental test rig validate its applicability for residential and small-scale commercial purpose. The PFC comprises a microcontroller embedded with the control algorithm. The algorithm measure the power factor value for the load switches proper capacitors to compensate for excessive reactive power, thus bringing power factor within the desired range.

Using the designed controller, the effects of unnecessary capacitive loading of the system can be avoided. Unnecessary capacitive loading occurs at the time of having no current in the supply line, or no reactive power is consumed, i.e. the connected load is totally resistive. The designed controller manages the reactive power flow smartly at a cheaper cost. The controller is cost-effective as a microcontroller is used as a processor, instead of using any other costly programmable hardware like Arduino.

With the designed controller, when power factor of the system changes, different capacitors are connected effectively to compensate the reactive power, thereby the power factor improves. Thus the inductive power flow through the line reduces. The power delivery becomes effective with maximum efficiency and minimum ohmic loss. As results, the energy consumption cost reduces and saving is made.

The numerical values used for the programming can be changed considering the requirements of the lines, loads and the system. This flexibility makes the system scalable and effective to achieve maximum saving.

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