
CLOSED LOOP POWER FACTOR CORRECTION FOR STANDALONE POWER APPLICATIONS

¹Shilpa Acharya²Sandeep Acharya¹ Asst. Professor, Department of
Electrical and Electronics
Engineering,
AMC Engineering College,
Bangalore, India.² Alumni, Department of Electrical
Engineering,
Indian Institute of Technology, Delhi,
IndiaCorresponding author:
shilpaach16@gmail.com**ABSTRACT**

Nowadays, due to the rapid rise of fossil fuel emissions and fall in air quality there is an increased focus on renewable energy sources for power generation over conventional fossil fuel-based power generation. There have been numerous advances in renewable power generation which have made it extremely attractive to the common man. However, there needs to be a lot of focus to make the most of the installed capacity. Solar power and Wind Power use the battery as the source which is charged through standalone connected systems. This charging happens via an AC-DC Controlled converter which regulates the output DC voltage and current. AC-DC converters serve as nonlinear loads making peak current from the supply and producing an extremely low input power factor. Furthermore, due to the high current requirement in fast chargers, domestic loads and voltage stability issues shall be seen under low power factors. This paper evaluates a method to improve the efficiency of AC-DC converters at the AC input side. The emphasis is on power factor correction converters based on boost converters, which offer good power factor, and outstanding efficiency, at reasonable prices. The proposed topology is simulated using MATLAB/Simulink.

Received: October 06, 2024
Revised: December 08, 2024
Published: December 31, 2024**Keywords-** Power factor improvement, Power quality, AC-DC Converters, Phase Locked Loop

INTRODUCTION

The market for standalone renewable power generation is growing rapidly. Based on the available market data 25 percent rise is seen YoY. The ecology surrounding solar power is currently favoured by factors such as the increased global carbon footprint, the rate at which fossil fuel prices are rising, advancements in battery technology, and effective maximum power transfer and charge controller methods. For a growing nation like India, the market for low to medium-sized standalone power generation is sizable in both volume and size [1]. Therefore, there is a strong push from the government and regulatory bodies as all the power demands of the cities cannot be met with conventional power generation [2]. The problem is multi-faceted with the rise in renewable applications which are used in standalone mode. In such applications, the size of the equipment, and the area needed are all controlled by the net power consumption. With a lower power factor to supply the same load, a higher current is needed [3]. Thereby it becomes imperative to always operate at close to the unity power factor. Power System networks with high switching and/or inductive loads suffer from low input power factor. Under transient conditions there is a high surge in input current drawn from the supply grid which can seriously affect the power stability. Typical filter circuits, like those that combine capacitors and inductors, are used in passive power factor adjustment.

Power Factor Concepts

The Power factor is the cosine of the angle between the phase current and phase voltage which is computed by using methods such as Zero crossing Detection, Zero Voltage/Current switching etc. When the angle is positive its said to be a lagging power factor, when the angle is negative it is said to be leading power factor. A lagging power factor is caused due to inductive loads, however leading power factor is caused due to capacitive loads. The nett goal of a system is to have a unity power factor where there will be no phase difference between the voltage and the current. This implies the Zero Crossing of the voltage and the current shall be overlapping. As noted, practically most of the loads are inductive in nature. A lagging power factor can be compensated by using Switched Capacitor Banks, similarly leading power factor can be compensated by using Switched Inductors. Power consumed by any load can be divided into Active and Reactive Power. The vector sum of these two is called the Nett power. Active power is the useful power however the reactive power is largely unutilized. Although it provides the function of regulating voltage levels across the system ensuring the smooth supply of active power. Thus, the reactive power helps maintain efficiency, reduces the risk of sudden change in voltage, prevents overheating of conductors and thus prevents damage to electrical systems. Higher the reactive power lower the power factor. Thus, it is important to have reactive power and compensate it at the load side which can be achieved by power factor compensation techniques.

Power Factor Compensation Techniques

Practically, the transients in the reactive power are largely seen on load changes.[4] In cases of motor load, a sudden change of torque always leads to a sudden inrush of reactive power as well. In this paper, more emphasis is only on correcting the steady state behaviour and shall not focus on the transient behaviour for now. Steady-state correction can be achieved through precisely estimating the load angle under all conditions. One of the accurate ways to estimate the load angle is by using a Phase Locked Loop (PLL). A PLL locks onto the load angle, this instantaneous load angle is passed through a PI controller to low-pass filter the variations. The PI controller is a form of feedback control. The voltage feedback from the output voltage, the PI control parameters were chosen based on heuristics of the variations, however for different models of batteries this may lead to changes in the PI parameters. The values as chosen for the PI also affect the reaction time for any switching changes for the compensatory circuit. For simulation purposes, an universal motor with varying mechanical load is chosen.

Literature Study

In recent years, there has been rapid growth in adoption of standalone power generation, thereby also increasing the need steadily for better power quality across the globe. Power Quality of input AC power is measured in terms of parameters such as Total Harmonic Distortion (THD), Power factor (PF). As most of the practical loads are inductive in nature being connected to the grid, the reactive power demand is also thereby quite high which can seriously affect the power quality and balance of the grid. As a solution to this, a Static Var Generator (SVG) with cascaded H-bridge is proposed as the reactive power compensation device of the charging pile, which can effectively improve the power quality of the power grid [1]. In the development of the DC supply system for any charging station for example, the Active Power Factor Correction circuit is incorporated to upgrade the power factor of the input AC power supply unit and to deteriorate the total harmonic distortion (THD) of the input current [2]. When for example any DC appliance is connected to the utility grid conventional AC-DC converter acts as a nonlinear load drawing peak current from a supply and results in a very poor input power factor. The converter present at the input AC side which converts alternating current (AC) into direct current (DC) must have high efficiency. Normally, the inverter output voltage has a Pulse Width Modulation (PWM) waveform structure. The quantity of this power can be deemed as the active power and reactive power that will be sent to the load by the electrical grid. The power transfer from the grid to the load will carry a positive sign for all the power variables. The single-phase conversion of AC power into DC power will result in a significant ripple power component,

which is a swinging component of power between the grid and the load. For a given active power demand, the reactive power needs to be controlled to reduce the net system losses. Thus, the reactive power compensation is needed to increase the efficiency by means of local compensation or hierarchical compensation [3]. Passive power factor correction uses conventional filter circuits like inductors and capacitors [4] that constitute an open loop system and is not recommended for power factor improvements as it does not consider the dynamics of load and internal resistance. So, a closed-loop power correction system is better than an open-loop. [5] It becomes imperative that with the increasing number of domestic loads comprising of loads such as battery chargers for various appliances, to have a power factor correction. Power factor correction is essential for circuits having high inductive loads. This correction makes use of conventional filter circuits such as a combination of capacitors and inductors and constitutes an open-loop system and hence not typically recommended for improving the power factor. A closed-loop system is proposed in this work to alleviate this effect. This type of power factor correction technique incorporates an electronic circuit, which acts both as a filter and closed-loop controller and is known as Active power factor correction (APFC) technique [6]. Poor Power Quality at AC Mains and harmonic disturbances due to nonlinear loads have adverse effects on power system components.[7]. The integration of nonlinear loads in the grid leads to non-sinusoidal currents introducing harmonics that distort the voltage and current waveform. To improve the power quality the fundamental component of the load current and the distorted harmonic voltage of the grid is compared using PLL [8]. An innovative control method for the boost Power factor correction controller by an advanced phase locked loop is developed that eliminates DC offset and provides harmonic robust estimation of the grid voltage fundamental component. The dual loop control architecture is explored in this technique. Compared to other techniques, this technique results in the reduction of THD by approx. 40 percent for a grid-connected system. However, this paper cannot be directly used in the case of a standalone power system due to the various assumptions made regarding the voltage being constant on change of load etc. [9] This paper proposes a small signal transfer function integrated model showing the interaction of grid impedance, phase-locked loop, and current control loop. The loop consisting of impedance and PLL can lead to oscillation that needs to be suppressed. In this system proposed since it deals with standalone applications, there is no mechanism to inherently suppress the oscillations. To reduce these harmonics and to improve power quality Shunt Active Power Filters give the grid the ability to inject active power[10].

Core Design

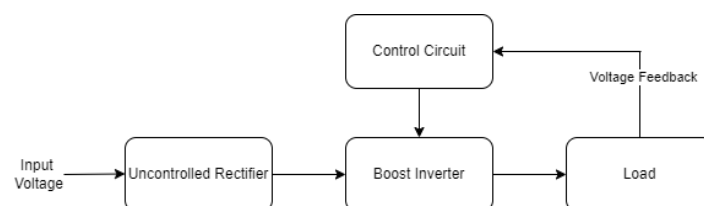


Fig. 1 System Block Diagram

As is seen from the diagram above, the system is comprising of an uncontrolled rectifier, Buck-Boost inverter stage, which is converting the DC to a controlled AC output voltage. This controlled AC voltage is further converted back to DC voltage by means of an uncontrolled rectifier.

Operation of Power Factor Controller

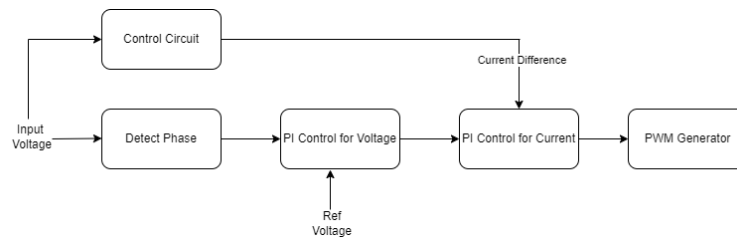


Fig. 2. Power Factor Controller Block Diagram

The system consists of an AC-DC Uncontrolled Rectifier, Boost Inverter Stage, and a feedback loop. The PWM for the Boost Inverter stage is generated by using feedback from Inductor Current, Output Voltage and Source Voltage. The PWM is generated by using PLL. The PLL locks onto the load angle which is then used to compute the current. On comparison with the measured current, the difference is fed through a tuned PI controller which thus controls the duty cycle. The control stage generates PWM pulses, gate drivers to handle the base driving circuit and handle the switching losses, and the filter circuit.

PWM signal generated by the control circuit needs to be isolated between the power stage and the control stage by use of opto-couplers for protection and safety. The outputs of the control circuit are fed to electrically isolated MOSFET drivers. The output of the inverter has a varied square waveform due to the switching pattern. To get a sine-wave signal and reduce the harmonics a parallel LC filter is used. Using an SPWM Inverter, the topology also maintains the load voltage constant along with operating the Power Factor at an ideal level.

This topology can be used in various use-cases such as domestic systems and standalone systems as well. The input Inductor is meant to damp oscillations coming from a rapidly changing load system, thus causing a slow change of current irrespective of the output system. This together with the input side MOSFET acts as a boost converter.

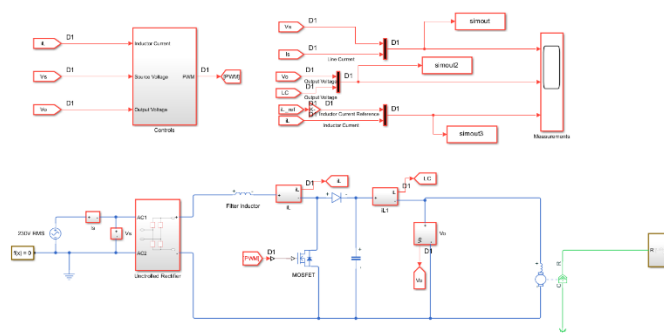


Fig. 3 Closed Loop Simulation MATLAB Model

Control System

Power Factor Control

The MOSFET switch (S5) as in Fig.3 governs whether the energy is being stored in the Inductor (during on state) or being dissipated through the Inductor (during off state). This change of voltage across the Inductor is gradual in nature and increases to a value that is higher than the combined voltage across the diode (D1) and the capacitor

(C1). The moment this happens, the diode starts conducting and the voltage that appears across the output capacitor, is higher than the input voltage.

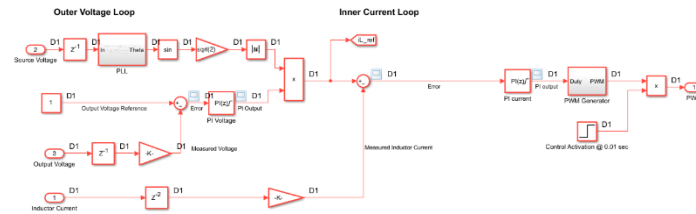


Fig. 4 Power Factor Control Simulation

Boost Converter Equations

The boost converter output voltage is a square wave and can be written as follows. When the switch is on, the voltage across the Inductor is

$$V_L = L \frac{di}{dt} = L \frac{I_{LPK}}{T_{ON}} \text{ AND } I_{LON} = \frac{V_{IN} - V_{SAT}}{L} t_{ON}$$

When the switch is off, the voltage across the Inductor is given by and the current is given by

$$V_L = L \frac{di}{dt} = L \frac{I_{LMIN} - I_{LPK}}{T_{OFF}}$$

PLL Operation

In general, it is seen that in power factor control circuits, PLL is rarely used. In the proposed topology it is proposed to use a PLL to track the phase and this computed output phase is used in the PWM generation circuit. The PLL comprises of a feedback system that includes a voltage-controlled oscillator (VCO), phase detector and low pass filter in its loop. Its purpose is to force the VCO to replicate and track the frequency and phase when in lock. Thereby PLL acts as a control system allowing one oscillator to track with another. PLLs are used in a variety of applications such as the generation of clocks, frequency synthesis, clock recovery etc. which are varied applications in the communications field. However, in this paper we have attempted to use a PLL for Phase detection. Although in all of the below applications the design constraints and criteria are different, the basic topology of the loop always remains the same.

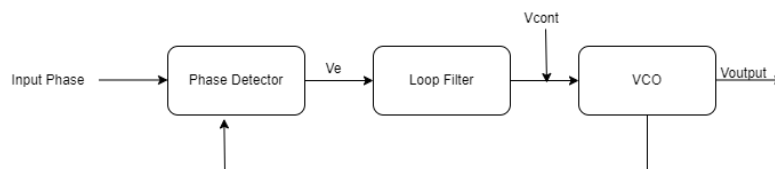


Fig. 5 Power Factor Control Block Diagram

The Phase Detector compares the phase at the input and generates an error signal as denoted by V_e . This error signal is proportional to the difference in the phase of the 2 inputs. As one familiar circuit example, an analogue multiplier or mixer can be used as a phase detector. The mixer takes the product of two inputs.

$V_e(t) = A(t)B(t)$. Taking, $A(t) = A\cos(w_0t + \varphi_A)$, $B(t) = B\cos(w_0t + \varphi_B)$

$$A(t)B(t) = \left(\frac{AB}{2}\right) [\cos(2w_0t + \varphi_A + \varphi_B) + \cos(\varphi_A - \varphi_B)]$$

$$V_e = K_d * (\text{Output Phase} - \text{Input Phase})$$

Since the two inputs to the phase detector are at the same frequency when the loop is locked, we have one output at twice the input frequency and an output proportional to the cosine of the phase difference. The doubled frequency component must be removed by the low pass loop filter. Any phase difference then shows up as the control voltage to the VCO, a DC or slowly varying AC signal after filtering. K_d is the gain of the phase detector. This PLL can be implemented in software in a microcontroller with a zero-crossing detector.

PLL Implementation

A PLL can be realized in multiple ways [10] such as

- Analog PLL** - This type of PLL implementation is a pure hardware implementation of a hardware block that has key inputs such as current and voltage in a negative feedback loop. Largely available off the shelf and ready to use.
- Hybrid PLL** - This type of topology uses a mixture of hardware and software components. Digital Phase detectors and digital filters are used along with analogue-controlled oscillators. Such type of PLLs is smaller in size as compared to analogue PLLs.
- Digital PLL** - In this topology all the elements are digital. The phase detector loop filter and VCO in all digital PLL is completely customized however the design is a lot more complex due to full software implementation and realization of the filter. The VCO tuning is the most complex as it must efficiently react to the phase of the transient change during turn-on or load switching. The advantage of such an operation is non-dependence on any hardware component, thus lower cost. The topology hereby proposes to use a hybrid PLL, the hybrid nature of the PLL operation comes from the usage of a timer for generation of the clock for the VCO.

PI Controller Design

A PI controller is one of the most used techniques for smoothing out the transients.

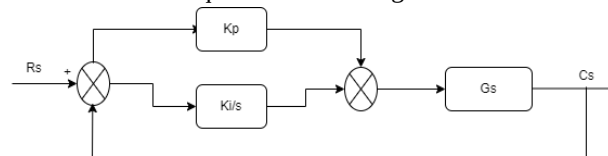


Fig. 6 PLL Block Diagram

The usage of PI here is to correct both the voltage and current transients for the inputs for the phase detection. A rapidly changing phase detection can be detrimental to the performance of the system. The proportional factor is to control the gain and the Integral factor is used to control the amount of damping used in the system. The parameters of the PI controller are chosen by use of the optimization method for fractional order systems. The PI controller parameters are first chosen based on the boundary locus method which is the standard method to solve the PI controller equation.

Type	K_p	K_i
Voltage PI Controller	1	35
Current PI Controller	0.8	0.06

Further, once the stability is ensured with those parameters, further fine-tuning is done keeping in mind stability constraints and system performance. Simulation studies in MATLAB has been done with use of the fractional order transfer function with time delay. The system uses 2 PI controllers, one for the voltage control and the next one for current control. The parameters chosen are depicted in table.

Power Factor Control in Closed Loop System

The Power Factor control in a closed loop system is achieved using voltage and current feedback. This, voltage feedback is highly transient in nature and with the help of a PLL the actual phase of the voltage is determined [11]. The block diagram of the PI controller is explained below. This estimation is used to compute the PWM reference voltage level which will be dynamically changing. The switching circuit comprises a switched capacitor which is used to negate the lagging power factor of the load [12]. With the change in the duty cycle of the PWM, the reactive power is actively controlled to close to 0. There would be transients at the time of sudden change in load and there would be a finite time in reacting to the change in load, however, this was a system decision to not react to transients as quickly as transient switching leads to an increase in reactive power transients which is hard to compensate. This part to react faster in case of transients of the load is not considered as a major stress on the standalone system and thereby shall be considered as a future scope of improvement currently.

Circuit Design

The circuit was designed using the MATLAB model as shown in Fig (3) and Fig (4). The important design constraints is to choose a voltage/current feedback sensing circuit with an extremely fast response. If the response of the voltage/current sensing circuit is slow, the performance of the PID controller and thereby the entire feedback mechanism is severely impacted.

RESULTS

Closed Loop System

By means of using a closed loop system, it's been able to always achieve close to unity power factor. Using this topology, there has been a reduction in load power drawn from the battery thereby leading to increased longevity of the battery as well.

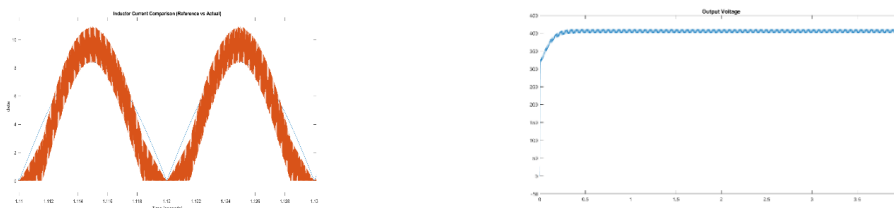


Fig 8 Current and Voltage Comparison with reference

CONCLUSION

The single-phase high-efficiency Active Power Factor Controller is designed and tested in a closed loop which can lead to significant improvement in range and battery consumption. It was found that as expected the power quality is also achieved with a closed loop system with load current and voltage feedback. The fundamental advantage of this topology is to obtain a high power factor and lower the burden on the power system to supply reactive power. Further scope of work includes trying to limit the initial current in such use cases as well as with the use of current limit devices such as inductors. With the use of inductors though there would be further challenges of harmonics created during current switching. For simulation, a universal motor load was used to simulate the practical use case of fans, mixers etc. As seen even in such a scenario close to unity power factor is achieved. This generic topology of PLL-based load angle sensing and correction can be employed to improve the efficiency and correction of a wide variety of systems employing non-linear loads.

REFERENCES

1. Patil, R., & Ugale, R. T. (2022, December). Comparative Study of Single-phase Power Factor Correction Topologies for Electric Vehicle Battery Charger Based on Boost Converter. In *2022 IEEE Conference on Interdisciplinary Approaches in Technology and Management for Social Innovation (IATMSI)* (pp. 1-5). IEEE.
2. Sinjari, K., Alzahrani, S., Lawson, R., & Mitra, J. (2021, November). Reactive Power Compensation in a Microgrid Coupled to Electrical Vehicles. In *2021 North American Power Symposium (NAPS)* (pp. 1-6). IEEE.
3. Sinjari, K., Kim, J., & Mitra, J. (2021, April). Single-phase and Three-phase Reactive Power Support for Microgrids by Grid connected Electric Vehicle. In *2020 52nd North American Power Symposium (NAPS)* (pp. 1-6). IEEE..
4. Pandya, D. J., Kumar, Y., Singh, D. P., Vairavel, D. K., Deepak, A., Rao, A. K., & Rana, A. (2023, September). Automatic Power Factor Compensation for Industrial Use to Minimize Penalty. In *2023 6th International Conference on Contemporary Computing and Informatics (IC3I)* (Vol. 6, pp. 2499-2504). IEEE.
5. Cai, A., Yu, Y., Xu, L., Niu, Y., & Yan, J. (2019, August). Review on reactive power compensation of electric vehicle charging piles. In *2019 22nd International Conference on Electrical Machines and Systems (ICEMS)* (pp. 1-4). IEEE..
6. Sarker, L., Nazir, M., & Razzak, M. A. (2021, November). Harmonics reduction and power factor correction for electric vehicle charging system. In *2021 Innovations in Power and Advanced Computing Technologies (i-PACT)* (pp. 1-6). IEEE.
7. Chakravarthy, R. S. S. P. S., & Gudey, S. K. (2020, July). Active Power Factor Correction for Automation of Electrical Vehicle Charging Station Using myRIO. In *2020 IEEE Students Conference on Engineering & Systems (SCES)* (pp. 1-6). IEEE.
8. Chaudhuri, S. P., & Singh, S. (2016, November). Power quality improvement in a vector controlled PMSM drive using non-isolated PFC zeta converter. In *2016 7th India International Conference on Power Electronics (IICPE)* (pp. 1-6). IEEE.
9. Bansal, P., Dixit, S., Gupta, S., Alotaibi, M. A., Malik, H., & Márquez, F. P. G. (2024). A robust modified notch filter based SOGI-PLL approach to control multilevel inverter under distorted grid. *Ain Shams Engineering Journal*, 15(5), 102675.
10. Pay, M. L., Christensen, J., He, F., Roden, L., Ahmed, H., & Foo, M. (2023). PLL-Based enhanced control of boost PFC converter for smart farming lighting application. *Renewable Energy Focus*, 47, 100502.
11. Xie, Z., Chen, Y., Wu, W., Xu, Y., Wang, H., Guo, J., & Luo, A. (2019). Modeling and control parameters design for grid-connected inverter system considering the effect of PLL and grid impedance. *IEEE Access*, 8, 40474-40484.
12. Kumaresan, S., & Habeebullah Sait, H. (2020). Design and control of shunt active power filter for power quality improvement of utility powered brushless DC motor drives. *Automatika*, 61(3), 507-521.