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Power Factor Corrector System Optimization of a Grid-Tied Photovoltaic (PV) System

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Abstract

Indonesia has considerable potential for solar energy, but it is currently constrained by restrictions that make it impossible to connect photovoltaic (PV) systems to the grid. This is usually due to problems with the quality of the power, such as a low power factor caused by loads in homes and businesses. Capacitor banks and other old-fashioned alternatives don't work very rapidly, and it costs a lot of money to buy a STATCOM. This paper proposes an optimization utilizing a Grid-Tied PV inverter as a dynamic Power Factor Corrector (PFC). The system employs a Vector Control method that utilizes transformation to differentiate the control of active and reactive power. A Boost Converter with Maximum Power Point Tracking (MPPT) maximizes active power. The inverter, on the other hand, changes the amount of reactive power it adds or takes away dependent on the load's needs at the time. Simulation results show that the system can preserve a unity power factor at the Point of Common Coupling (PCC) even when there are inductive and capacitive loads. The controller was quite precise and didn't make many steady-state mistakes. It could accurately track reference signals when it was in four-quadrant mode. This study indicates that PV inverters can perform well as distributed STATCOMs. This makes the grid more reliable without needing to add any new hardware.

Keywords: Power Factor Correction; PV Inverter; DQ Transformation; Reactive Power Compensation; Grid-Tied PV

1. Introduction

A big part of the global energy revolution is using photovoltaic (PV) systems to collect solar energy. Indonesia has a lot of Using photovoltaic (PV) systems to collect solar energy is a big part of the global energy revolution. Indonesia has a lot of room to grow in this area. Indonesia is a tropical country that is close to the equator and gets sun all year. It gets about 4.8 kWh/m^2 of sunlight every day. The sun, wind, water, geothermal energy, and bioenergy could give Indonesia 419 GW of renewable energy. Of these, solar energy has the most potential, with a possible technological capacity of 207.8 GW to 3,294.36 GW[1], [2]. By 2025, the government wants 23% of its energy to come from renewable sources, and by 2050, it wants 31%[3]. But there are still big rules that make it hard to use, especially for solar power plants on roofs, even though it has a lot of potential. One major issue is that laws make it illegal or very difficult for rooftop solar PV systems to send electricity to the PLN grid. This method is necessary because inductive and capacitive electrical loads are common in homes and businesses and need reactive power (Q). Regular PV systems are only designed to supply active power (P)[4]. This situation lowers the power factor (cos φ), which puts stress on the network infrastructure. This is one reason for the restriction.

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This paper describes a PV system that makes active power while also controlling reactive power at the connection point. A three-phase inverter that uses a vector control method based on DQ transformation is the basis of this system. The main advantage of this system is that it can separate the control of active and reactive power. The d-q reference frame turns three-phase AC values into DC values. The d-axis current component (Id) controls active power flow, and the q-axis current component (Iq) controls reactive power flow. The system will use this feature by measuring the load's reactive power demand (Qload) and using it as a reference (Qref) for the controller to add reactive current to the system[5].

A comprehensive examination of the literature indicates a significant disparity between the power quality challenges of the grid and the existing solutions, facilitating the development of a more cohesive and economical strategy. Industrial customers often add demand patterns to power networks that are very different and hard to guess. This makes the power quality bad, with power factors as low as 84%[6]. A techno-economic study shows that a 130 kVAr installation could raise the power factor from 84% to 98.29% in 16 months. But the best choice is still to use old methods like fixed capacitor banks, which are less expensive[7]. Dixit, Kundu, and Jariwala discovered that 45% of capacitor banks in overhead networks and 36% of capacitor banks in key substations are malfunctioning[8]. This makes people worry about how reliable it is and how easy it is to keep up with. Additionally, it was explained that choosing the incorrect size or position can result in additional issues, including increased voltage levels and power loss. However, modern Flexible AC Transmission System (FACTS) devices, such as STATCOM, provide improved dynamic solutions[9]. This device has been able to fix problems with power quality that capacitors can't handle[10]. It has cut down on voltage flicker in factories from 17.8% to only 4.5%. It is important to keep in mind that STATCOM is marketed as an expensive standalone device. Installing just one unit at the distribution level could cost as much as $176,000[11]. A recent study on network optimization has shown that this investment is not worth the high cost. Rincón-Miranda et al. (2023) did a study on the IEEE 33 and 69 bus distribution networks and found that the only way to get the best operational efficiency is to use both PV sources and D-STATCOM at the same time. You could save as much as 35.53% on your yearly operating costs with this. This number showed that it was better than cases that only used PV (35.36%) or D-STATCOM (0.69%). The optimization models in the literature still treat PV and D-STATCOM as two different investments. This means that network operators have to pay for both devices at the same time[12]. Tarigan (2023) says that rooftop solar systems in Indonesia are now financially possible because the Unit Cost of Energy (UCE) is between Rp1,410 and Rp1,860 per kWh, which is about the same as the PLN utility energy price of Rp1,500 per kWh. The only reason to buy PV inverters is to get the power they make. This means that they are a "sunk cost" asset in the future grid[13].

There exists a significant research gap between these findings. The financial sustainability of photovoltaic (PV) assets is evidenced (Tarigan, 2023), and the imperative for dynamic control is evident (Rincón-Miranda et al., 2023); however, the existing literature is deficient in a comprehensive technical validation of a hybrid solution that integrates both components. This research addresses this deficiency by demonstrating the technical capability of contemporary photovoltaic inverters to function effectively as distributed STATCOMs. The objective of the study is to verify the system's ability to dynamically inject or absorb reactive power to equilibrate both inductive and capacitive loads, thereby maintaining a unity power factor at the grid side and ensuring grid stability without the need for supplementary external STATCOM hardware.

2. System Design and Methodology

2.1. Principle of Active and Reactive Power Control

The most important part of the proposed system is that the inverter can automatically control the flow of P and Q power. This is made possible by using dq control-based vector control techniques[14]. This technique facilitates the regulation of sinusoidal three-phase AC-current and its conversion into constant DC values (Id and Iq) inside the dq rotating frame. In this configuration, the d-axis current component (Id) regulates active power, while the q-axis current component (Iq) governs reactive power. This maintains their separation and prevents interference between them. Three-phase coordinates (abc) are converted to stationary coordinates (αβ) and subsequently to rotational coordinates (dq) using typical Clarke and Park transformation matrices. These matrices are also used to make the opposite transformation[15]. A Proportional-Integral (PI) controller generates the modulation signal by processing the error signal, which is derived from the comparison of actual and reference values in the dq frame. Ultimately, the signal was reverted to the time domain to generate gate inverter pulses via Pulse Width Modulation (PWM) techniques[16].

2.2. Proposed Control Strategy

The core of the proposed system lies in the current control mechanism that uses the *dq* control scheme to achieve independent power regulation. In the *dq* rotating frame, three-phase sinusoidal currents are transformed into constant

DC quantities through coordinate transformation. In this architecture, the d-axis current component (I_d) is dedicated to maintaining the stability of the DC bus voltage, while the q-axis current component (I_q) is changing to inject or absorb reactive power according to the load requirements. Figure 1 shows the control block diagram implementing this dq logic in a systematic manner.

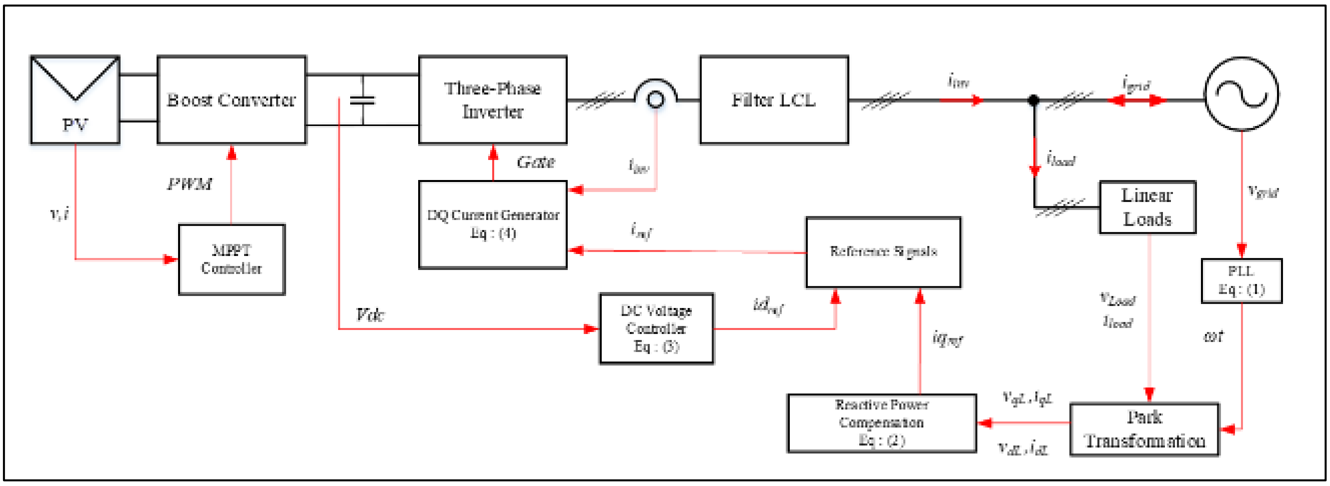

Figure 1 Single diagram of power factor corrector PV-GRID

Figure 1 shows how the suggested control method works. This system combines DC voltage regulation and reactive power compensation for loads into a single control framework based on an synchronous reference frame (SRF). The main way to control things is to use a Phase Locked Loop (PLL) to sync the grid. The PLL keeps the grid phase angle stable by setting the q-axis voltage component (V_q) to zero. The phase angle (θ or ωt) is calculated by integrating the nominal grid frequency ($\omega 0$) that the PI controller has changed[17].

$$\theta = \int(\omega_0 + K_{p,pll}V_q + K_{i,pll} \int V_q \, dt)dt \qquad (1)$$

The angle θ is used to change the load current and voltage (IL, VL) from the abc frame to the dq frame. The Load Power Calculation block figures out the load's reactive power (Qload) in order to set the compensation goal. The inverter must send reactive current that opposes the load in order to get a power factor of one on the source side. So, the q-axis current reference (Iq_ref)) is defined as[18]:

$$I_{q\_ref} = -\frac{2}{3}\frac{Q_{load}}{V_d} \qquad (2)$$

At the same time, the DC Voltage Controller keeps the DC Bus voltage (V_{dc}) stable. This controller checks the real DC voltage V_{dc} against the 800V reference value. A PI controller takes care of the error difference so that it can give the active current reference (I_{d_ref})[19]:

$$I_{d\_ref} = K_{p,v}(V_{dc}^* - V_{dc}) + K_{i,v} \int (V_{dc}^* - V_{dc})dt \qquad (3)$$

The Reference Signals block combines the two reference signals, I_{q_ref} and I_{d_ref}, and then sends them to the DQ Current Generator. To make the modulation voltage (V_{dq}^*), the reference current is compared to the actual inverter current (I_{inv}). The PI current regulator then fixes the mistake that this comparison makes[20].

$$V_{dq}^* = K_{p,i}\left(I_{dq\_ref} - I_{dq\_inv}\right) + K_{i,i} \int \left(I_{dq\_ref} - I_{dq\_inv}\right) dt \qquad (4)$$

After that, the output signal V_{dq}^* is transformed back to the abc domain and turned into a Gate PWM signal. This controls the Three-Phase Inverter's switching so that the inverter's output current matches the required compensation objective.

Figure 2 explains how to utilize the Perturb & Observe (P&O) method to gain the greatest electricity from the PV array. This algorithm changes the Boost Converter's duty cycle all the time to make sure that the DC-Link capacitor gets as much power (PMPP) as possible. The voltage on the DC-Link (V_{dc}) will vary due to this power transfer. This is where inverter control strategies are crucial. To convey this active power to the electrical grid, the DC-Link voltage must be maintained at a constant reference level of 800V. Consequently, the active current reference (I_{d_ref}) is produced by the DC Voltage Controller in accordance with Equation (3). This technique guarantees that regardless of the power supplied by the MPPT (Figure 2.2) to the DC-Link, it will be promptly sent by the inverter to the grid as active current Id[21].

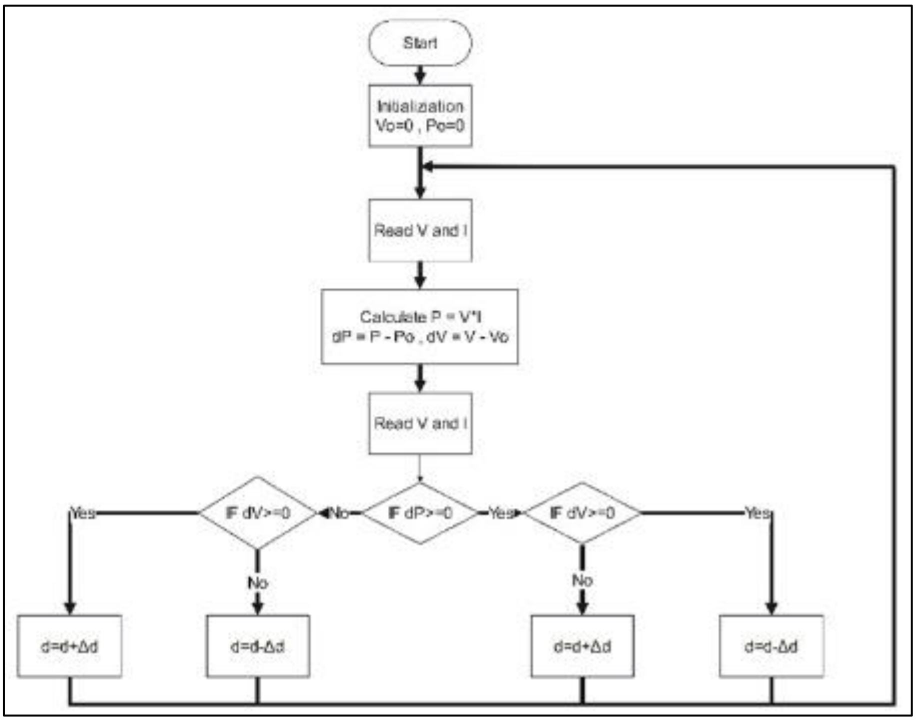

Figure 2 Flow diagram of the MPPT Control[22]

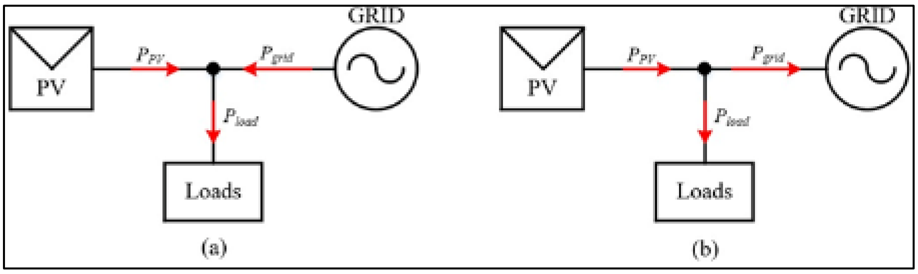

Figure 3 Power flow interaction at the PCC: Power Deficit scenario (PPV < Pload)(a), and Power Surplus scenario (PPV > Pload) (b)

The power balance at the Point of Common Coupling (PCC) is modeled to confirm the active power interaction among the PV inverter, local load, and power grid. The direction of power flow is significantly influenced by the ratio of the power generated by the photovoltaic system (PPV) to the load demand (Pload), as depicted in Figure 2.3. The mathematical expression for the active power balance at the PCC is represented as:

$$P_{grid} = P_{load} - P_{PV} \quad (5)$$

The direction of power flow (P_{grid}) is dictated by the resultant sign of Equation (5). Figure 3(a) shows that when the calculated value of P_{grid} is positive ($P_{load} > P_{PV}$), it means that the PV system hasn't been able to fully meet the load demand. The grid has to make up for the power shortfall. If P_{grid} is negative ($P_{load} < P_{PV}$), the system has too much power. In this case, photovoltaic systems provide all of the load's needs, and any extra power is sent to the grid (Figure 3(b)). This is the method used in Chapter 3's simulation testing to see if the inverter can handle power flow in both directions.

3. Results and Discussion

To validate the analysis, simulations were conducted based on Figure 1 For the MPPT, a controller based on perturb and observe was employed, while the DQ Control was utilized for the three-phase inverter. The parameters utilized for simulations are presented in Table 1.

Table 1 Parameters for Simulation Works

Components	Parameter
PV Modules	4 series, 15 parallel of 200 W Vmpp = 28.5 Volt, Impp = 7.02
Grid Voltages	380 Volt (RMS)
Vref	800 Volt (DC)
Load (for PPV is greater than Pload)	RL = 1 x 10^5 Ohm and 0.01 H, RC = 1 x 10^5 Ohm and 1 x 10^{-6} F
Load (for PPV is less than Pload)	RL = 1 Ohm and 0.05 H, RC = 1 Ohm and 0.001 F
System	Three-Phase Three Wire
Inverter	Three-Phase Three-Legs VSI

3.1. System Performance Under Inductive Load

The initial test sought to assess the system's capability to mitigate reactive power in inductive loads, prevalent in both residential and industrial applications. Figure 4 illustrates that the load current (b) lags the source current (a). Figure 5 illustrates that the voltage and current at the source are in phase, as the power factor correction system effectively mitigates the phase shift induced by the inductive linear load. Figure 6 illustrates the scenario in which PPV exceeds Pload, resulting in the excess electricity from the photovoltaic system being fed into the grid.

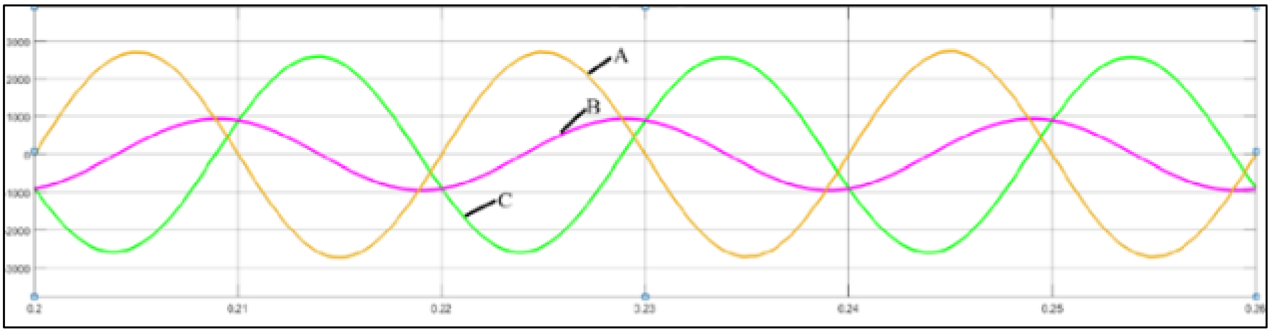

Figure 4 Comparison that shows the Current for an Inductive load (A) source side, (B) Load side, (C) Compensation side

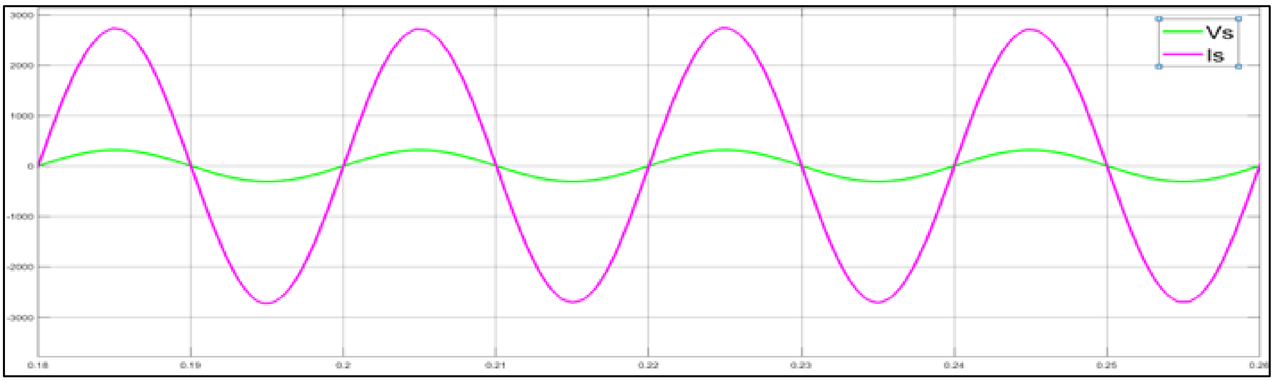

Figure 5 Voltage and Current on Source Side to Compensate Phase Shift Lagging from Inductive Linear Load from Reactive Power Inject. Vs (Voltage Source-Green) and Is (Current Source-Purple)

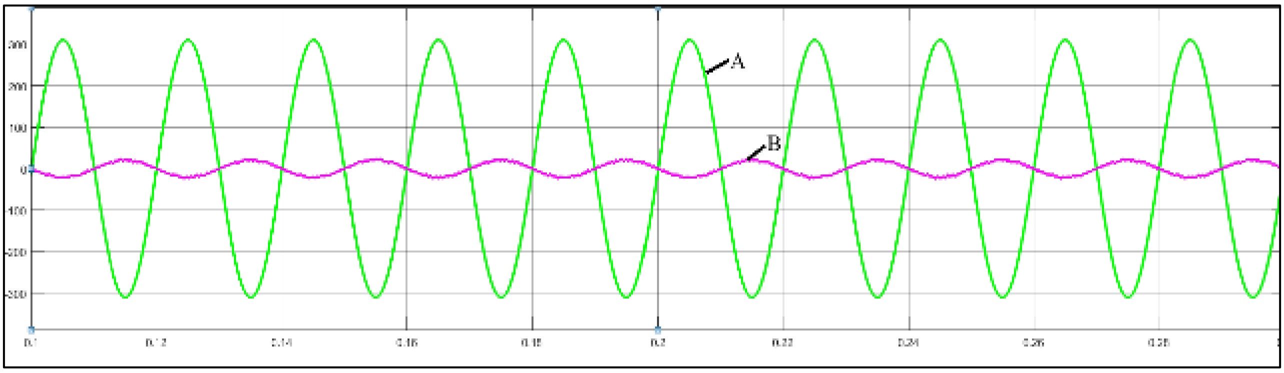

Figure 6 Voltage and Current on Source Side to inject the surplus from PV towards the grid (A) Voltage Source (B) Current Source

3.2. System Performance Under Capacitive Load

The second test was performed on a solely capacitive load to evaluate the system's capacity to manage leading power factor circumstances. Figure 7 illustrates that the load current (b) precedes the source current (a). Figure 8 illustrates that the voltage and current at the source are in phase, as the power factor correction system effectively compensates for the phase shift induced by the linear capacitive load. Figure 9 illustrates the scenario in which PPV exceeds Pload, resulting in the excess electricity from the photovoltaic system being fed into the grid.

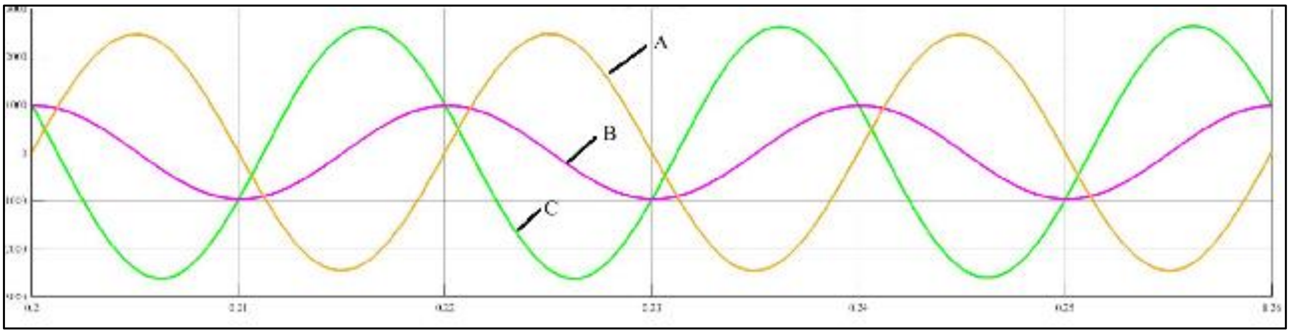

Figure 7 Comparison that shows the Current for a Capacitive load (A) source side, (B) Load side, (C) Compensation side

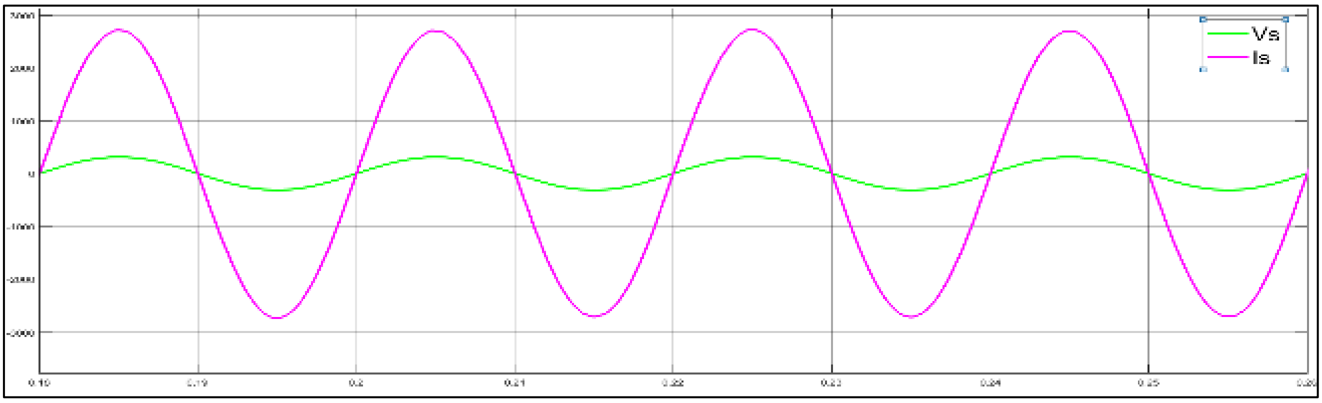

Figure 8 Voltage and Current on Source Side to Compensate Phase Shift Leading from Capacitive Linear Load from Reactive Power Inject. Vs (Voltage Source-Green) and Is (Current Source-Purple)

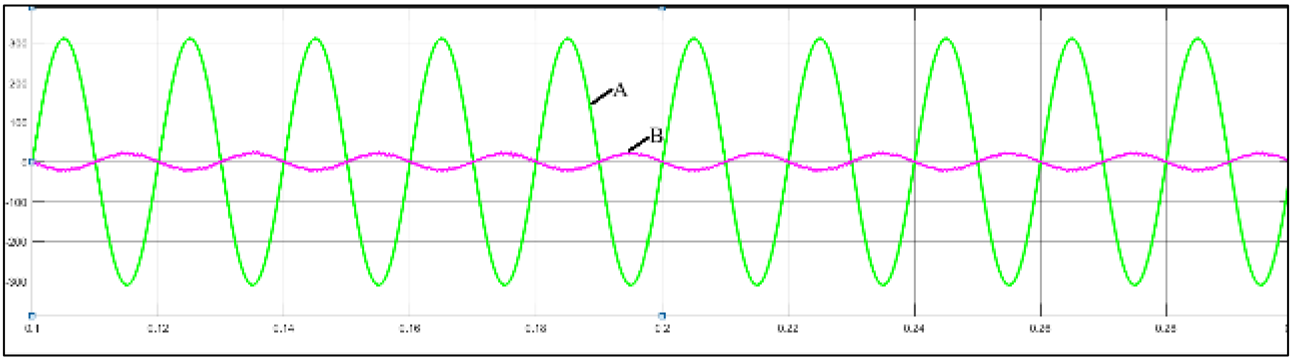

Figure 9 Voltage and Current on Source Side to inject the surplus from PV towards the grid (A) Voltage Source (B) Current Source

Similar to the inductive situation, the system effectively synchronized the source current (Is) with the voltage (Vs). The power factor was effectively enhanced to nearly one.

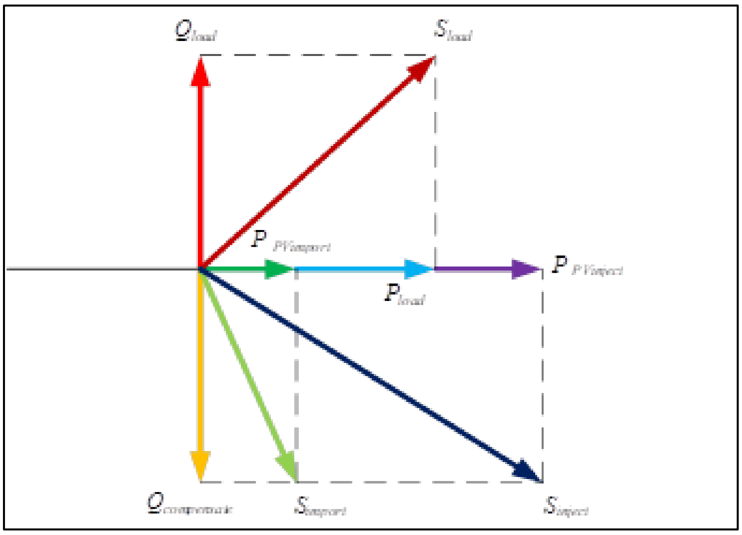

Figure 10 Phasor Diagram Representation of Load, PV Generation, and Compensation Power

Figure 10 illustrates the power equilibrium that transpires during the compensatory phase. The load has many parts, such as active load power (P_{load}) and reactive load power (Q_{load}). To keep phasor displacement from happening on the grid side, the system needs to fix reactive load power. As a result, the controller generates compensatory reactive power ($Q_{Compensate}$). The position of $Q_{Compensate}$ in the phasor diagram above is 180 degrees from Ql_{oad}. To make sure the Power Factor gets close to unity, $Q_{Compensate}$ must be equal to the power generated by Q_{load}. S_{load} is the same as P_{load} plus Q_{load}. The PV-Grid can also be divided into two groups based on the conditions that exist there. The first group is when the load power (P_{load}) is greater than the PV power ($P_{\_PVimport}$), which means that the system has to import from the Grid to meet the load needs (S_{Import}). The second situation happens when the photovoltaic power ($P_{\_PVinject}$) is greater than the load power (P_{load}). In this case, the system sends power to the grid (S_{Inject}).

3.3. Controller Performance Analysis Discussion

The quantitative data shown above definitively demonstrates that the engineered PFC system is exceptionally effective in enhancing the power factor under both inductive (lagging) and capacitive (leading) load circumstances. This means that the inverter can work adaptively, giving reactive power (positive value) when there are inductive loads and taking reactive power (negative value) when there are capacitive loads. An investigation of the tracking of the q-axis current signal (Iq) proved that the controller was working properly. When inductive conditions were present, the mean value of Iq_Inject (887.3) was very good at keeping an eye on the reference Iq_ref (887.0). In capacitive conditions, the system also showed similar consistency. It was able to keep an eye on the negative axis with an average Iq_Inject value of -984.3, which was close to a reference value of -984.5. The small average steady-state error between the two scenarios shows that the controller works well at handling the dynamics of different types of loads.

Table 2 Tracking Performance of I_{q_Inject} to I_{q_ref} on Inductive and Capacitive Loads

Load Condition	Parameter	I_{q_ref}	I_{q_Inject}
Inductive	Reactive Current	887.0	887.3
Capacitive	Reactive Current	−984.5	−984.3

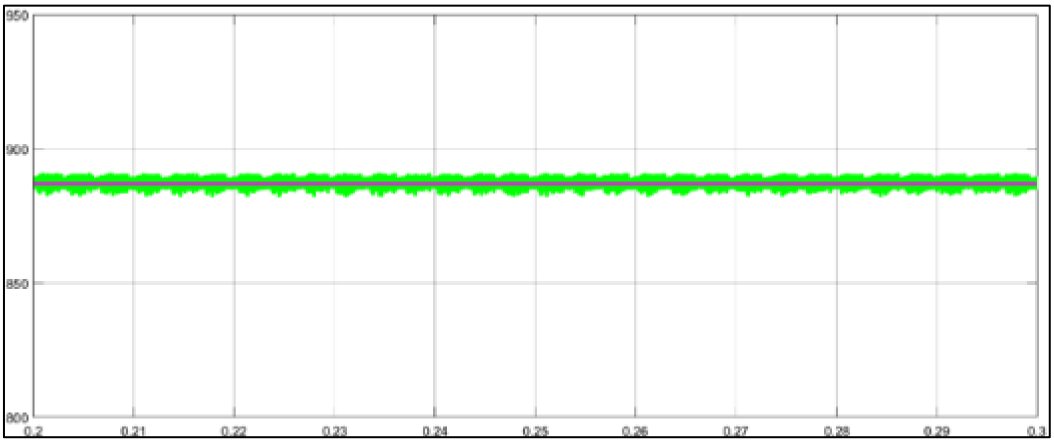

Figure 11 Steady State Condition of I_{q_Inject} and I_{q_ref} that Inject to the Grid for Compensating Inductive Linear Load. I_{q_Inject} (q-side Injection Current-Green) and I_{q_ref} (q-side Reference Current-Magenta)

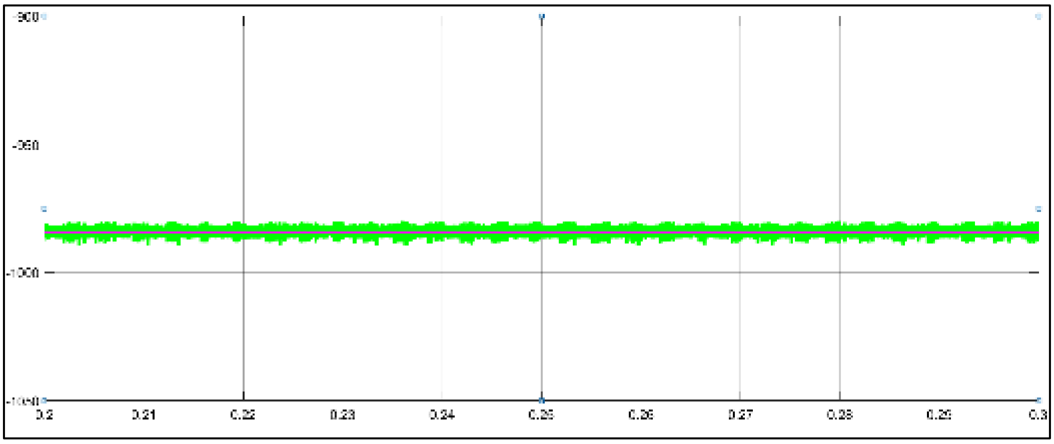

Figure 12 Steady State Condition of Iq_Inject and Iq_ref that Inject to the Grid for Compensating Capacitive Linear Load. Iq_Inject (q-side Injection Current-Green) and Iq_ref (q-side Reference Current-Magenta)

4. Conclusion

This study has effectively developed and verified a PFC system utilizing a PV inverter regulated by the DQ transformation technique. The simulation results and analysis indicate that the suggested system is highly effective in mitigating power quality difficulties stemming from a low power factor at the source. During the testing of inductive and capacitive loads, the system effectively adjusted, markedly enhancing the power factor to nearly one (unity power factor). The success in both instances definitively demonstrates that PV inverters governed by this way may function in four quadrants, allowing them to inject reactive power into lagging loads and absorb reactive power from leading loads. The controller's performance was validated using precise signal tracking analysis, which exhibited a reliable system response with negligible steady-state error.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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