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Original Article

Control of Active and Reactive Power in Grid-Connected Photovoltaic Systems Using QBC and Dual Three-Phase Inverter

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Abstract - *This research investigates the processes for controlling active and reactive power with dual inverter based grid-connected Photovoltaic (PV) systems. Integrating PV systems into the grid poses substantial issues for preserving power quality and stability, particularly in regulating active and reactive power flows. A Dual Three-phase Inverter(DTI) with QBC configurations offers a promising solution by distributing voltage stress and enhancing overall system efficiency and reliability using the D-Q Synchronous (DQS) approach. Advanced control algorithms for active and reactive power management and mathematical models customized for dual inverter systems are developed. Simulation results demonstrate the superior performance of dual inverters in maintaining grid synchronization and power delivery. The findings demonstrate the capabilities of dual inverter-based PV systems to improve the stability and efficiency of grid-connected renewable energy systems.*

Keywords - *Photovoltaic systems, Dual Three-phase Inverter (DTI), Active power control, Reactive power control, Grid stability, Renewable energy sources, DQS and QBC.*

1. Introduction

The global energy environment is undergoing significant disruption because of the growing utilization of renewable energy sources. Photovoltaic (PV) systems have become more well-known because of their ability to capture solar energy, which is a plentiful and clean resource. Advanced control mechanisms are essential to regulate the interaction between PV installations and the grid. PV system penetration in the power grid increases.

It is frequently difficult for conventional single-inverter photovoltaic systems to efficiently regulate active and reactive power, which is essential for preserving grid power quality and voltage stability. Regarding power quality, particularly harmonic distortion, Total Harmonic Distortion (THD), and voltage fluctuations, dual inverters are comparable to three-phase inverters. These difficulties include being susceptible to grid disruptions, restricted control bandwidth, and worse efficiency under different load scenarios. The application of dual three-phase inverter technology offers a potential remedy for these problems.

Dual three-phase inverters, which are made up of two independent inverter units working together, provide better control capabilities because they can regulate active and reactive power. This architecture provides various advantages, including higher fault tolerance, improved dynamic response, and increased flexibility in power management. Dual inverters can improve PV system performance in a variety of grid scenarios by separating the

control scenario of active and reactive powers, which helps to improve voltage regulation and lower harmonic distortions. This paper explores the theoretical foundations, design considerations, and simulation of dual inverter systems in grid-connected PV applications [1].

Explore the control strategies and algorithms that accurately regulate reactive and active power, guaranteeing a smooth and seamless integration with the current power grid. Furthermore, here are simulated outcomes to illustrate the effectiveness of the suggested methodology.

The following sections provide a comprehensive overview of the system architecture, control methodologies, and performance evaluation. By highlighting the benefits and potential challenges of dual inverter technology, This essay seeks to support the advancement of grid-connected PV systems, fostering a more resilient and sustainable power grid.

2. Description of the Proposed Grid-Connected PV System Using Dual Inverter Technology

2.1. Mathematical Modeling of Photovoltaic (PV) Cell and PV Panel

In order to evaluate PV cells and panels' performance and incorporate them into power systems, mathematical modeling is necessary. The components of a photovoltaic cell's corresponding electrical circuit are a diode, a current source, series resistance, and shunt resistance. This section describes and applies the basic formulas that control photovoltaic cells to PV panels.

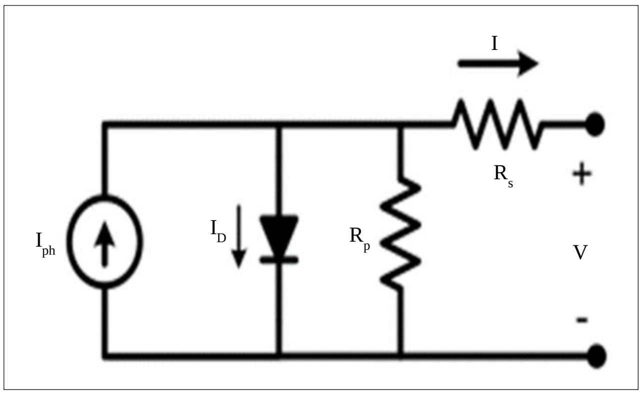

Fig. 1 Model of PV cell circuit

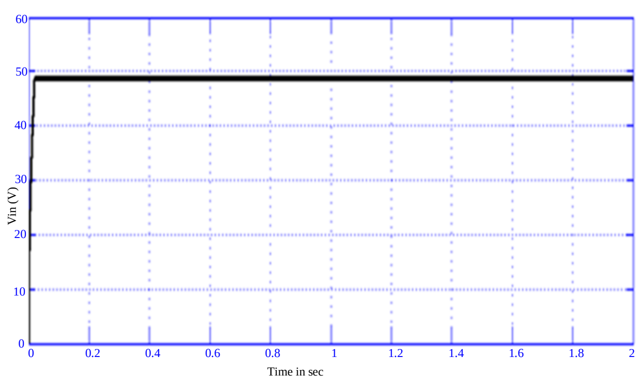

Fig. 2 Voltage of the PV array's output (Vpv)

$$I = I_{ph} - I_D - \frac{V+IR_S}{R_P} \quad (1)$$

$$\text{Where } I_D = I_{01}\left\{\exp\left(\frac{q(V+IR_S)}{\alpha KT}\right) - 1\right\} \quad (2)$$

Where,
I_{ph} = Current generated by a solar
I_D = The ideal factor of diode
α = Diode's Ideal factor.
K = The Boltzmann's constant.
T = The PV cell temperature.
q = An electron's charge.
I_{01} = Current from diode saturation.

The approach, which being applied in several earlier research [5, 6, 9, 19], offers a sensible compromise between model complexity and precision. The outcome of integrating calculations (1) and (2) is,

$$I = I_{ph} - I_{01}\left\{\exp\left(\frac{q(V+IR_S)}{\alpha KT}\right) - 1\right\} - \frac{V+IR_S}{R_P} \quad (3)$$

The PV system provides the MPPT algorithm using Ipv (PV current) and Vpv (PV voltage). The algorithm then generates the MPP and generates Vdcref.

2.2. Three-Phase Dual Inverter Description

An advanced power conversion system called a three-phase dual inverter [7, 8] is intended to increase the control, flexibility, and effectiveness of Photovoltaic (PV) systems connected to the grid. The two inverters in this system cooperate to control reactive and active power, improving the stability and performance of the photovoltaic mechanism. The three-phase dual inverter system is described in detail here. Two inverters, known as Inverter A and Inverter B, linked to a different PV system, are integrated into a three-phase dual inverter system. This design enhances grid support capabilities and power quality by allowing the control of both active and reactive powers. PV arrays are commonly used as the dual inverter system's DC supply. The two inverters are fed via QBC, which is connected to the PV array.

An MPPT ensures the PV array runs at its peak power. The PV array's DC power with a QB converter must be converted into AC power mainly via Inverter A. Its key objectives are to maximize active power output and keep the system in sync with the grid. Reactive power management is the main function of Inverter B, which works in tandem with Inverter A to enhance power quality and assist grid voltage regulation. When required, it also shares the active power load with Inverter A. The architecture of the two-step grid-tied solar power system based on DTI is shown in Figure 3. It consists of two standard inverters that feed voltage in three independent phases to the open winding of a three-phase transformer. Solar modules were connected via DTI's DC-links. The voltages across windings a, b, and c of DTI are represented by the formulas in volts [10, 11].

$$V_a = \frac{2}{3}(V_{a1} - V_{a2}) - \frac{1}{3}(V_{b1} - V_{b2}) - \frac{1}{3}(V_{c1} - V_{c2}) \quad (4)$$

$$V_b = -\frac{1}{3}(V_{a1} - V_{a2}) + \frac{2}{3}(V_{b1} - V_{b2}) - \frac{1}{3}(V_{c1} - V_{c2}) \quad (5)$$

$$V_c = -\frac{1}{3}(V_{a1} - V_{a2}) - \frac{1}{3}(V_{b1} - V_{b2}) + \frac{2}{3}(V_{c1} - V_{c2}) \quad (6)$$

Va1, Vb1, and Vc1 are the voltages of the pole of inverter-1, and Va2, Vb2, and Vc2 are the voltages of the pole of inverter-2.

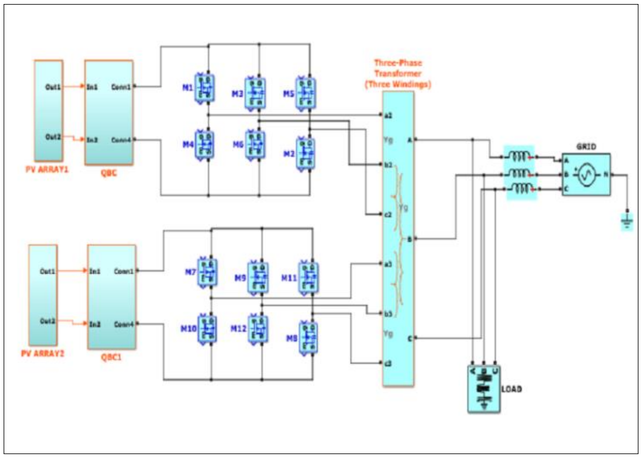

Fig. 3 The grid-connected PV system's dual three-phase inverter structure

2.3. QB Converter (QBC)

The DC voltage from a Photovoltaic (PV) array can be efficiently increased using a Quadratic Boost Converter (QBC) [2, 4 , 16], guaranteeing a steady and elevated voltage level for further power conversion stages of direct use in DC applications. Applications needing strong step-up voltage gains from a low-voltage PV array can benefit significantly from this approach.

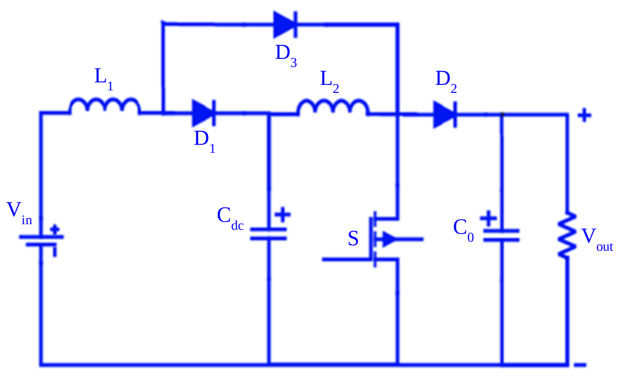

Fig. 4 An illustration of a Quadratic Boost Converter circuit (QBC)

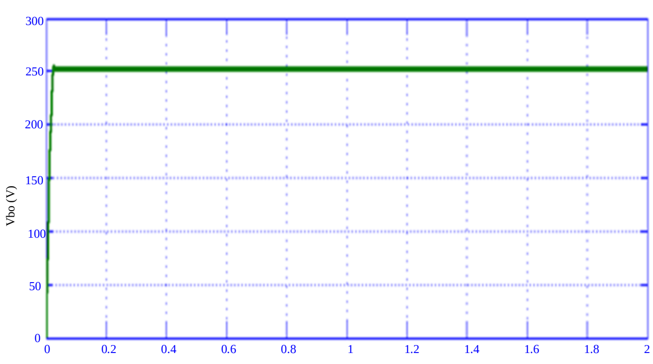

Fig. 5 Voltage (Vo) through QBC

The voltage of the quadratic boost converter is increased to 250V, as Figure 5 illustrates. The subsequent action involves integrating this voltage source into the cascaded dual three-phase inverters.

3. Control Method for Active Power and Reactive Power

MPPT, a quadratic boost converter, and coordinate control of two inverters illustrate power control approaches. A coordinated strategy is used in the Active power control technique for a two-inverter grid-connected photovoltaic system and a quadratic boost converter to optimize power extraction and delivery while preserving grid stability. By integrating predictive control and MPPT algorithm monitoring, the system can dynamically adapt to changing conditions, guaranteeing dependable and efficient power delivery. This technique contributes to a more stable and sustainable power system by utilizing the flexibility of twin inverters and the improved voltage boosting capabilities of the converter with quadratic boost. These tactics used for control include: DC-link voltage is modulated via the outside control loop. The inner current control loop follows reference currents from the outside voltage loop to modify the outgoing currents of the inverter. The desired reference value for the voltage connected to the DC is maintained via the outside voltage control loop. Keeping the PV array and the grid's power balance control is a primary priority. The Proportional Integral (PI) current control approach can modify the inverter's current produced to govern active and reactive power, as shown in Figure 7. Compiling reactive active powers requires a dq synchronously rotating frame (DQS) method.

DC-link Voltage Error can be calculated as follows,

$$Vdc_{errr} = Vdc_{ref} - Vd(t) \tag{7}$$

Where,
Vdc_{ref} = The proposed voltage standard for DC.
$Vdc(t)$ = Measurement on DC voltage.

A PI regulator [3] processes the voltage error by applying the Voltage Control Law.

$$Id_{ref}(t) = Kpv \,.\, Vdc_{err}(t) \; + \; Kiv \,.\, \int_0^t Vdc_{err}(T)dT \tag{8}$$

Where,
$Id_{ref}(t)$ = The internal current regulation loop's referencecurrent.
Kpv = Proportional voltage controllers gain.
Kiv =Inherent gain of the voltage regulator.

The inner current control loop sets a reference current provided by the external voltage cycle, which governs the inverter output currents.

The current errors with components d and q in amperes are calculated as

$$\mathrm{Id_{err}(t) = Id_{re}(t) - Idm(t)} \quad (9)$$

$$\mathrm{Iq_{err}(t) = Iq_{re}(t) - Iqm(t)} \quad (10)$$

Where,
$\mathrm{Id_{re}(t)}$ = current of d-axis referenced from the external voltage controller loop
$\mathrm{Iq_{re}(t)}$ = Reference q-axis current for reactive power control.
$\mathrm{Idm(t)}$ = Measured d-axis current.
$\mathrm{Iqm(t)}$ = Measured q-axis current.

The present error is processed using a PI controller in accordance with the current control law.

$$Vd_{ref}(t) = Kpi\,.Id(t) + \mathrm{Kii}\,.\int_0^t \mathrm{Id_{err}(T)dT + Vd_{fforward}} \quad (11)$$

$$Vq_{ref}(t) = Kpi\,.Iq(t) + \mathrm{Kii}.\int_0^t \mathrm{Iq_{err}(T)dT + Vq_{fforward}} \quad (12)$$

Where,
$Vd_{ref}(t)$= d-axis voltage for ref.
$\mathrm{Vq_{ref}(t)}$= q-axis voltage for ref.
Kpi = Current controller's proportional gain.
Kii = Current controller's intrinsic gain.
$\mathrm{Vd_{fforward}}$ = d-axis feed forward voltage.

$$\mathrm{Vd_{fforward} = Vdgrid - \omega LIq} \quad (13)$$

$\mathrm{Vq_{fforward}}$ = Feed forward voltage term for the q-axis.

$$\mathrm{Vq_{fforward} = Vqgrid + \omega LId} \quad (14)$$

Where,
ω = Grid angular frequency.
L = Filter inductance.
Vdgrid = component of d-axis at grid side voltage.
Vqgrid = component of q-axis at grid side voltage

Gating signals for inverters are produced via SV Pulse Width Modulation (SVPWM) [15, 19, 21] using the reference voltages from the inherent control loop of current. This inner current loop controls the inverter currents to adhere to reference values obtained from the outer loop, while the outer voltage loop maintains a steady DC-link voltage. Expressing the grid's active power supply Pgrid [22] is feasible regarding the current's d-axis component. The relationship can be given if The d-axis and the grid voltage are aligned.

$$Pgrid = \frac{3}{2} VdId \ Watts \quad (15)$$

Where,
Pgrid = Active power delivered to the grid.
Vd = Grid voltage's Daxis component.
Id = Current's Daxis component

Reference for Power of Reactive: Reference for reactive power Qref can be set in accordance with power factor correction requirements or grid requirements. This reactive power reference is the source of the reference q-axis current.

$$Iq_{ref}(t) = \frac{Qref}{Vgrid} \ Amps \quad (16)$$

Where,
Qref = Desired reactive power.
Vgrid = Grid voltage magnitude

The following formula can be used to get the reactive power:

$$Qgrid = \frac{3}{2}\big(Vd(t) * Iq(t) - Vd(t) * Id(t)\big)\ Var \quad (17)$$

Where,
$Qgrid$ = Reactive power delivered to the grid

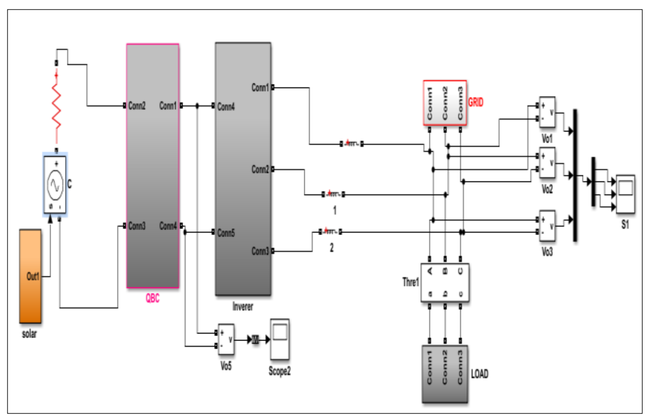

Fig. 6 Block diagram of single three-phase inverter interfacing PV system

The entire DC power from the array is converted to AC by a single inverter, which centrally controls the active power output. The single inverter's capacity and the overall DC input from the PV array set limits on active power output. Each of the two inverters in a dual inverter system regulates a different array section. Independently, each inverter maximizes the active power for the array's corresponding segment. Better reactive power management and voltage regulation are made possible by dual inverters in complicated PV systems, as shown in Figure 7.

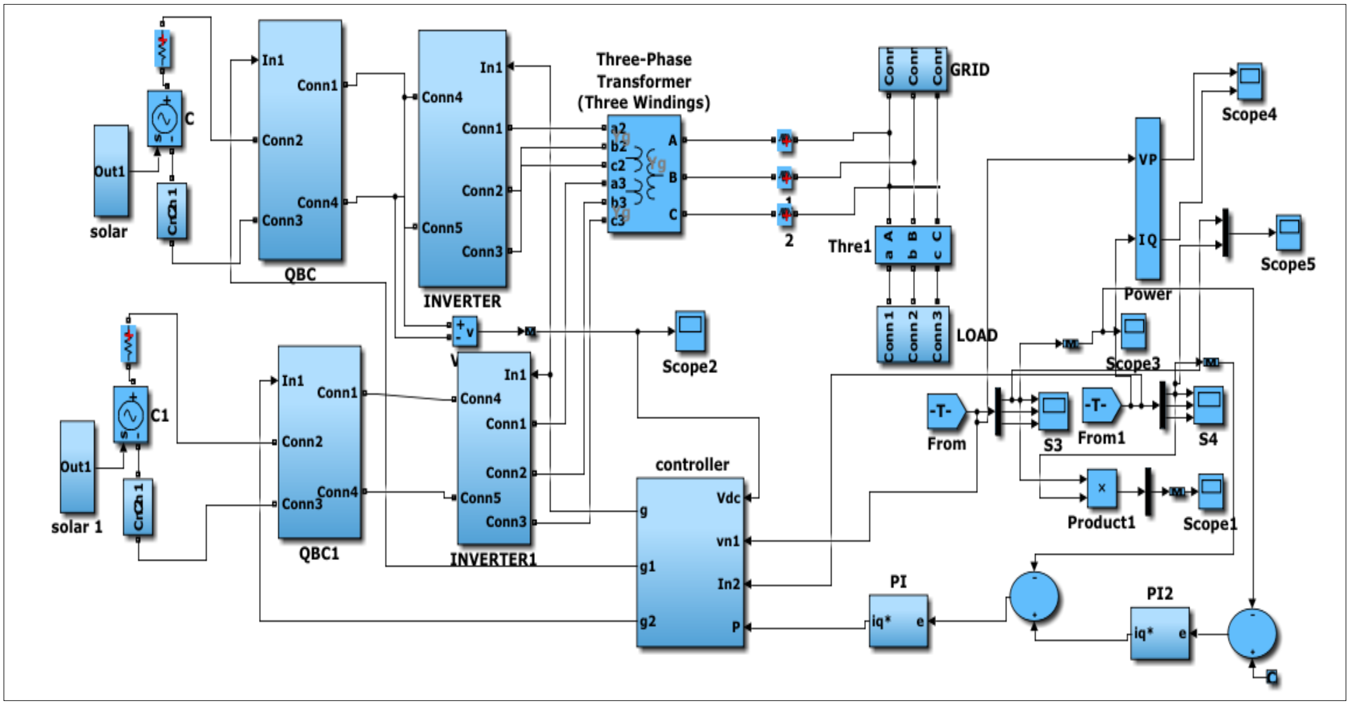

Fig. 7 Block diagram of DTI interfacing PV system

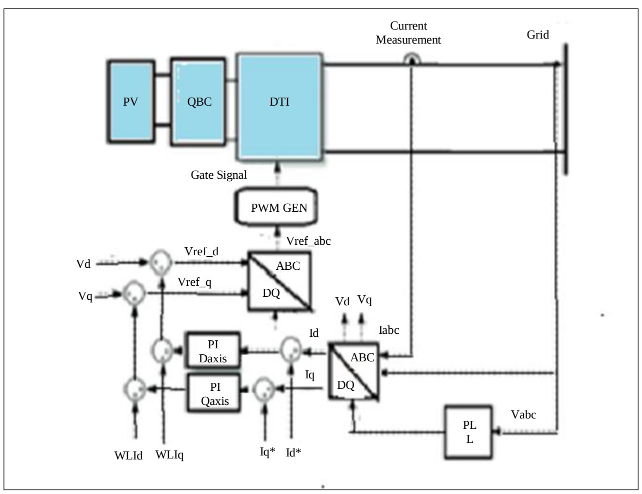

Fig. 8 PI controller module for power control

Using Id and Iq currents, outer loop voltage controllers Vd and Vq are established with D-axis PI and Q-axis PI controllers. Next, these controllers are transformed into three-phase Va, Vb, and Vc for a PWM generator to supply gate signals to dual three-phase inverters. Figure 8 provides a clear demonstration of PI control with the DQS method.

4. Results and Discussions from Simulations

Grid-connected single three-phase inverter and DTI, which provide a closed-loop interface between PV systems and PI controllers, are simulated using MATLAB and the respective voltage and current waveforms of both techniques are shown below.

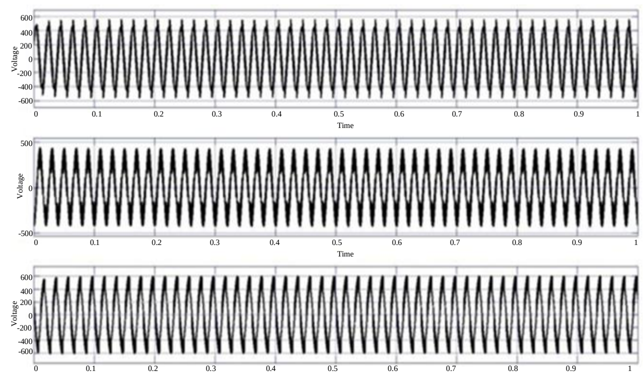

Fig. 9(a) Grid side phase voltages using a single three-phase inverter

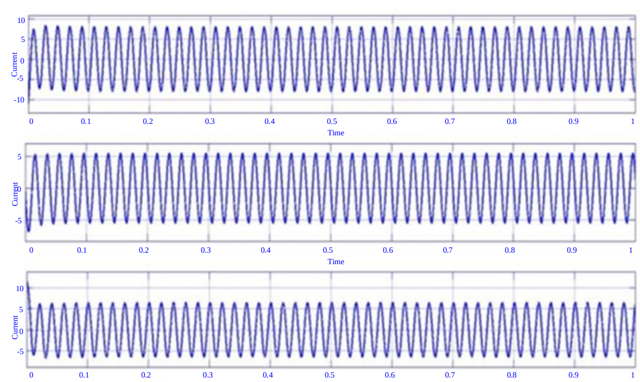

Fig. 9(b) Grid side active currents using a single three-phase inverter

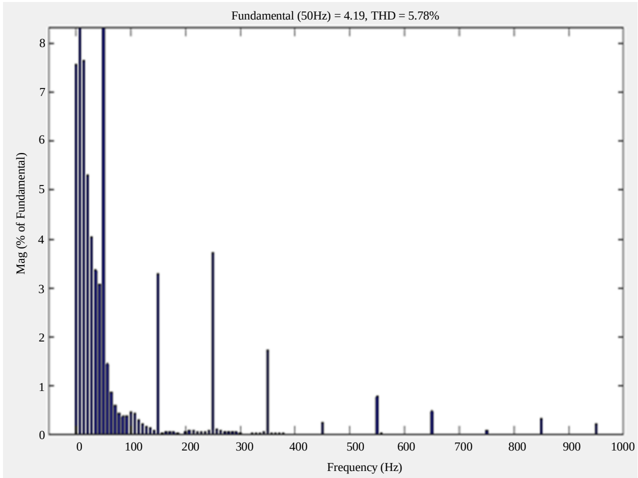

Fig. 10 THD across grid side current using a single three-phase inverter

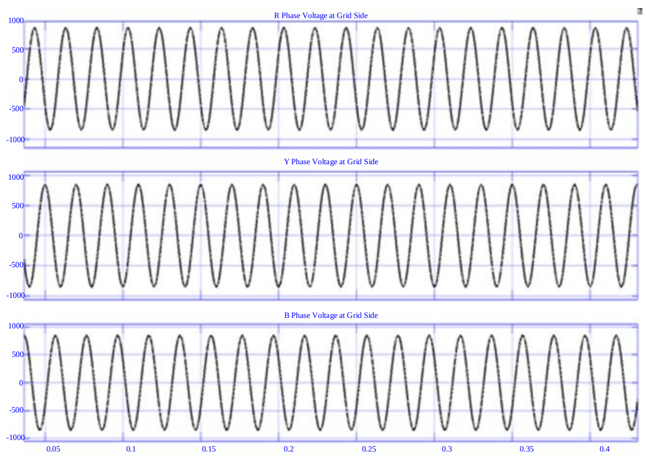

Fig. 11(a) Grid side phase voltages using DTI

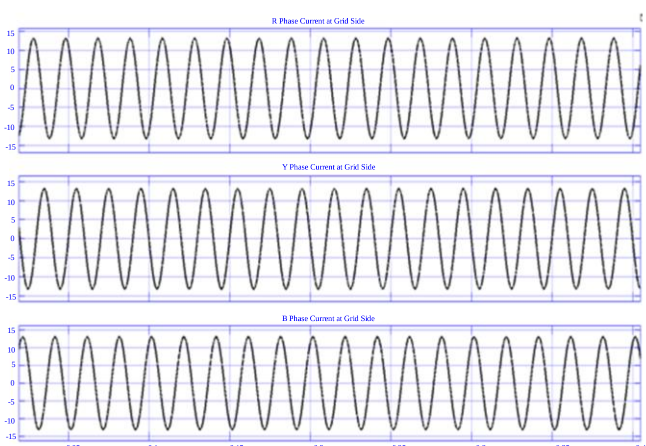

Fig. 11(b) Grid side active currents using DTI

Figures 9(a) and 9(b) show grid side phase voltages, and phase active belongs to active and reactive powers using a single three-phase inverter, producing more current harmonic distortion, as shown in Figure 10.

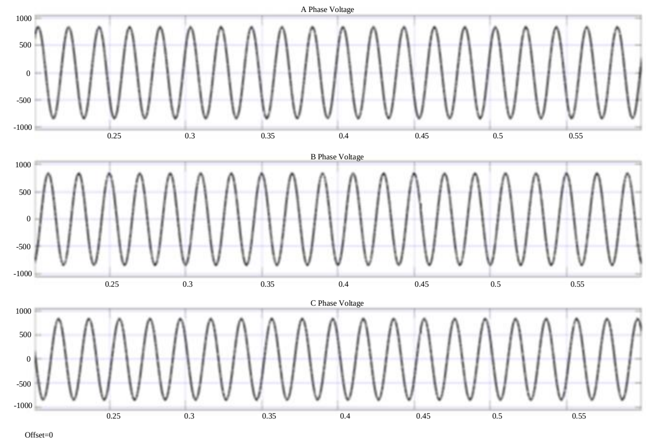

Fig. 11(c) Grid side reactive Currents using DTI

Figures 11(a),11(b) and 11(c) belong to dual inverter grid side voltages, and currents show less harmonic current at the grid side, as shown in Figure 13. This shows that phase voltage and phase currents are in phase while pushing active power into the grid and out of phase when driving reactive power.

Figure 12 shows the active, reactive powers injected into the grid, which has a fast dynamic response in settling time and with less steady-state error. Figure 13 shows the harmonic distortion, which is lowered across the grid side current while injecting power into the grid using DTI with PI control techniques, thus increasing the grid-connected renewable energy systems' stability and efficiency.

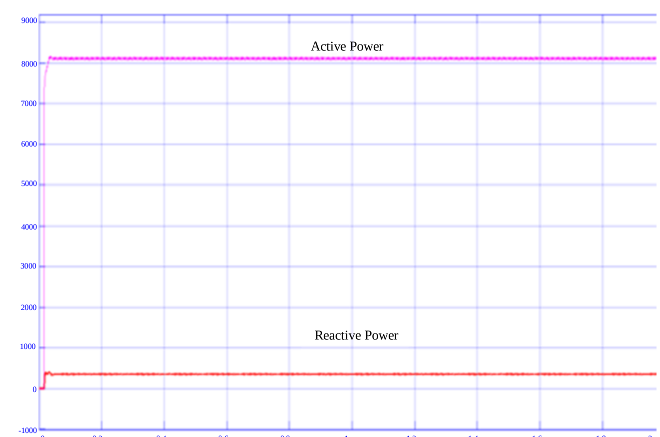

Fig. 12 Active power and reactive power

Table 1. Comparison of THD

Type of Inverter	THD at Grid Side Current
Single Three-Phase Inverter	5.78%
Dual Inverter	4.65%

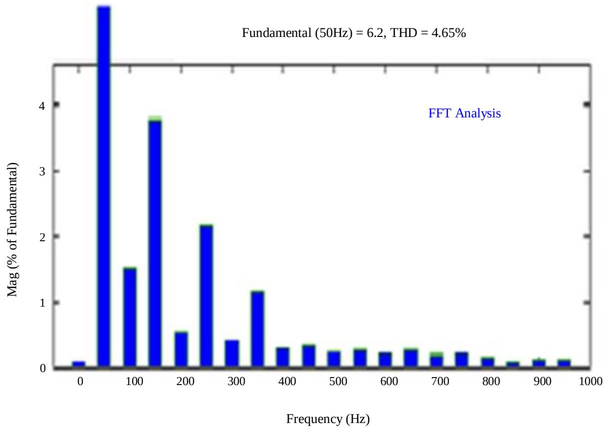

Fig. 13 THD across grid side current

5. Conclusion

The synchronization of active, reactive power regulation in a dual-inverter grid-interfaced PV system is critical for efficient operation and grid compatibility. Effective synchronization improves the system's ability to control power flow, minimize harmonics, and increase reliability. By carefully coordinating the inverters using the DQS method with the PI controller, the system can balance the active power provided by the PV arrays with the grid's reactive power requirements, enabling voltage management and lowering grid disturbances. Advanced control strategies enable seamless integration and performance, creating a more stable and robust power system.

5.1. Future Scope

Dual inverters have been increasingly used in grid-connected Photovoltaic (PV) systems, and this technology has a bright future. Dual inverter configurations are growing in popularity as the need for increased grid stability, scalability, efficiency, and energy optimization grows, particularly for larger and more intricate PV systems. A dual inverter with improved phased locked loops can reduce additional harmonics at the grid side. A dual inverter with improved phased locked loops can reduce additional harmonics at the grid side.

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References

[1] Eyyup Demirkutlu, and Ires Iskender, "Grid Connected Three-Phase Boost-Inverter for Solar PV Systems" *International Journal of Renewable Energy Research (IJRER*), vol. 11, no. 2, pp. 776-784, 2021. [Google Scholar] [Publisher link]

[2] Oswaldo Lopez-Santos et al., "Quadratic Boost Converter with Low-Output- Voltage Ripple," *IET Power Electronics*, vol. 13, no. 8, pp. 1605-1612, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[3] Abdelkrim Thameur et al., "Particle Swarm Optimization of PI Controllers in Grid-Connected PV Conversion Cascade Based Three Levels NPC Inverter," *2020 IEEE International Conference on Environment and Electrical Engineering and 2020 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe)*, Madrid, Spain, pp. 1-5, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[4] Selva Kumar. R et al., "Design and Comparison of Quadratic Boost Converter with Boost Converter," *International Journal of Engineering Research & Technology*, vol. 5, no. 1, pp. 877 -881, 2016. [Google Scholar] [Publisher Link]

[5] Weidong Xiao et al., "Review of Grid Tied Converter Topologies used in Photovoltaic Systems," *IET Renewable Power Generation*, vol. 10, no. 10, pp. 1543-1551, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[6] Andrew Hintz, Udupi R. Prasanna, and Kaushik Rajashekara , "Comparative Study of the Three-Phase Grid-Connected Inverter Sharing Unbal- Anced Three-Phase and/or Single-Phase Systems," *IEEE Transactions on Industry Applications*, vol. 52, no. 6, pp. 5156-5164, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[7] Nayan Kumar, Tapas Kumar Saha, and Jayati Dey, "Sliding-Mode Control of PWM Dual Inverter-Based Grid-Connected PV System: Modeling and Performance Analysis," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 4, no. 2, pp. 435-444, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[8] Sachin Jain et al., "A Single-Stage Photovoltaic System for a Dual-Inverter-Fed Open-End Winding Induction Motor Drive for Pumping Applications," *IEEE Transactions on Power Electronics*, vol. 30, no. 9, pp. 4809-4818, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[9] Francesco Alonge et al., "Identification and Robust Control of a Quadratic DC/DC Boost Converter by Hammerstein Mode," *IEEE Transactions on Industry Applications*, vol. 51, no. 5, pp, 3975-3985, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[10] Nayan Kumar, Tapas Kumar Saha, and Jayati Dey, "Cascaded Twolevel Inverter Based Grid Connected Photovoltaic System: Modelling and Control," *2014 IEEE International Conference on Industrial Technology (ICIT)*, Busan, Korea (South), pp. 468-473, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[11] N.N.V. Surendra Babu, and B.G. Fernandes, "Cascaded Two-Level Inverter-Based Multilevel STATCOM for High-Power Applications," *IEEE Transactions on Power Delivery*, vol. 29, no. 3, pp. 993-1001, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[12] Tan Kheng Suan Freddy et al., “Comparison and Analysis of Single-Phase Transformer less Grid-Connected PV Inverters,” *IEEE Transactions on Power Electronics*, vol. 29, no. 10, pp. 5358-5369, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[13] Giuseppe Marsala et al., “Analysis and Design of a DC–DC Converter with High Boosting and Reduced Current Ripple for PEM FC,” *2011 IEEE Vehicle Power and Propulsion Conference*, Chicago, IL, USA , pp. 1-8, 2011.[CrossRef] [Google Scholar] [Publisher Link]

[14] Shuitao Yang et al., “A Robust Control for Grid- Connected Voltage-Source Inverters,” *IEEE Transactions on Industrial Electronics*, vol. 58, no. 1, pp. 202–212, 2011.[CrossRef] [Google Scholar] [Publisher Link]

[15] Behrooz Mirafzal, Mahdi Saghaleini, and Ali Kashefi Kaviani, “An Svpwm-Based Switching Pattern for Stand-Alone and Grid Connected Three-Phase Single-Stage Boost-Inverters,” *IEEE Transactions on Power Electronics*, vol. 26, no. 4, pp. 1102-1111, 2010. [CrossRef] [Google Scholar] [Publisher Link]

[16] Jean-Paul Gaubert, and Gwladys Chanedeau, “Evaluation of DC-to-DC Converters Topologies with Quadratic Conversion Ratios for Photovoltaic Power Systems,” *2009 13th European Conference on Power Electronics and Applications*, Barcelona, Spain, pp. 1-10, 2009. [Google Scholar] [Publisher link]

[17] Ahmet M. Hava, and Emre Ün, “Performance Analysis of Reduced Common Mode Voltage PWM Methods and Comparison with Standard PWM Methods for Three-Phase Voltage Source Inverters,” *IEEE Transactions on Power Electronics*, vol. 24, no. 1, pp. 241-252, 2009. [CrossRef] [Google Scholar] [Publisher link]

[18] Antonio Cataliotti et al., “Generalized PWM–VSI Control Algorithm Based on a Universal Duty-Cycle Expression: Theoretical Analysis, Simulation Results, and Experimental Validations,” *IEEE Transactions on Industrial Electronics*, vol. 54, no. 3, pp. 1569-1580, 2007. [CrossRef] [Google Scholar] [Publisher link]

[19] Zeliang Shu et al., “An Efficient SVPWM Algorithm with Low Computational Overhead for Three-Phase Inverters,” *IEEE Transactions on Power Electronics*, vol. 22, no. 5, pp. 1797, 2007. [CrossRef] [Google Scholar] [Publisher link]

[20] S.B. Kjaer, J.K. Pedersen, and F. Blaabjerg, “A Review of Single-Phase Grid-Connected Inverters for Photovoltaic Modules,” *IEEE Transactions on Industry Applications*, vol. 41, no. 5, pp. 1292-1306, 2005. [CrossRef] [Google Scholar] [Publisher link]

[21] Arkan A. Kadum, “PWM Control Techniques for Three Phase Three Level Inverter Drives,” *TELKOMNIKA Telecommunication, Computing, Electronics and Control*, vol. 18, no. 1, pp. 519-529, 2020. [CrossRef] [Google Scholar] [Publisher link]

[22] Harun Özbay, Selim Öncü, and Metin Kesler, “Active and Reactive Power Control of Grid-Tied Three Phase Inverter for PV Systems”, *ECRES – 4th European Conference on Renewable Energy Systems*, Istanbul, Turkey, pp. 1-5, 2016.