POWER QUALITY IMPROVEMENT IN A 0.3 MW GRID-CONNECTED SOLAR PV SYSTEM USING INCREMENTAL CONDUCTANCE MPPT UNDER LOW INSOLATION AND TEMPERATURE CONDITIONS

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ARTICLE INFO

Article history:
Received: 3. 9. 2025.
Received in revised form: 29. 9. 2025.
Accepted: 30. 9. 2025.

Keywords:
Maximum Power Point Tracking (MPPT)
Grid-connected photovoltaic solar systems
Power quality
Incremental Conductance MPPT
PSCAD
Variable irradiance
Temperature variation
Total Harmonic Distortion (THD)
LCL filter
Power quality mitigation

DOI: 10.30765/er3040

Abstract:

The integration of grid-connected photovoltaic (PV) systems presents critical challenges to power quality due to their weather-dependent and transient nature. Under low solar insolation and temperature fluctuations, these systems often encounter voltage instability, harmonic distortion, and reactive power imbalance, which can lead to non-compliance with standards such as IEEE 519 and CEA guidelines. This paper presents a detailed power quality analysis of a 0.3 MW grid-connected PV system simulated in PSCAD. The system employs an Incremental Conductance (IC) Maximum Power Point Tracking (MPPT) algorithm to ensure optimal power extraction under varying irradiance and temperature conditions. To replicate realistic operating environments, the PV system is subjected to dynamic resistive–inductive–capacitive (R-L-C) loads, which represent practical grid demands. Key performance indicators including voltage stability, current total harmonic distortion (THD), and reactive power fluctuations are evaluated. To mitigate these issues, LCL filters and reactive power compensation techniques are incorporated into the system model. Simulation results confirm that the IC MPPT algorithm effectively tracks the maximum power point, even at low irradiance levels, thereby improving overall energy capture. Furthermore, the integration of LCL filtering and reactive power compensation significantly reduces current THD, enhances waveform quality, and stabilizes both voltage and current profiles. The study demonstrates that with appropriate control strategies and compensation measures, grid-connected PV systems can achieve high reliability and compliance with regulatory standards, even under adverse environmental conditions. These findings reinforce the potential of PV technology for sustainable and stable grid integration.

1 Introduction

The growing global concern over climate change, fossil fuel exhaustion, and increasing energy demand has accelerated the application of renewable energy technologies [1]. Solar photovoltaic (PV) systems, in this context, have become a tangible choice due to their sustainability, minimal operating cost, and scalability [2].

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In India, conducive policies, government incentives, and increasing public awareness have significantly promoted the adoption of grid-connected solar PV systems, primarily in the domestic and industrial sectors [3]. However, photovoltaic (PV) system integration to the grid is not without problems, mainly the uncertainty of solar irradiance and temperature fluctuations, which have adverse impacts on grid reliability and power quality (PQ) [4]. Such problems are typically expressed as voltage instabilities, harmonic distortions, flicker effects, and frequency deviations, especially under low irradiance or changing environmental conditions [5]. Studies have shown that inverter control strategies can influence the performance of grid-connected PV systems as well as load characteristics [6]. With higher penetration of PV, the grid is increasingly prone to power quality problems, especially when large PV systems are paralleled to feed industrial loads with high PQ demands [7]. As the interface connection between the PV system and the grid, voltage source inverters (VSIs) play a major role in contributing to PQ disturbances if not designed efficiently [8]. Maximum Power Point Tracking (MPPT) algorithms are significant to maximize the efficiency of photovoltaic (PV) systems because they continuously change the operating point in order to maximize power generation. Among many techniques, Incremental Conductance (IC) is the most used algorithm because of its accuracy at different irradiance levels [9]. Studies also highlight the better performance of IC compared to simple algorithms like Perturb and Observe (P&O) [10].

Aside from efficient Maximum Power Point Tracking (MPPT), suitable power quality (PQ) standards through high-level filtering and voltage distortion as well as harmonic mitigation control methods are required. Various power electronic topologies and custom power devices have been developed to address these requirements [11]. Grid support functions such as reactive power control and harmonic suppression need to be integrated to satisfy IEEE 519 and Central Electricity Authority (CEA) standards [12]. Simulation software like PSCAD/EMTDC and MATLAB/Simulink are widely employed to analyze the steady-state and dynamic performance of grid-connected PV systems under various environmental and loading conditions [13]. These enable the examination of voltage sag, THD, frequency response, and inverter switching behaviour [14]. Adaptive filtering and signal processing techniques, like passive LCL filters and FACTS devices, have proven highly promising in THD minimization and voltage profile enhancement of PV systems connected to weak grids [15]. In rural and urban installations, harmonic distortion and flicker mitigation remains highly important issues in real implementations [16]. Different studies have been carried out to evaluate the performance as well as the quality of power in PV installations across the globe. From small residential rooftop installations to large utility-scale solar farms, the findings always point to grid code compliance and optimal inverter control [17]. Hybrid integration with energy storage systems is also being increasingly considered for ensuring more reliable power supply and greater grid stability [18]. In addition, sophisticated MPPT methods and inverter-level controllers are being used more and more to provide dynamic voltage regulation and mitigate network resonance issues [19]. The use of custom power equipment like DVRs, UPQCs, and STATCOMs in grid-connected PVs is being studied to provide reactive power requirements and transient response [20].

Experiments in developing nations such as India have contrasted the economic and technical feasibility of grid-connected PV systems and established the fact that they are both environmentally friendly and economical in nature if maintained in a wise manner [21]. Real-time monitoring and forecasting tools are also being incorporated to enable smart control and grid communication [22]. Recent studies also point to newer solutions for PQ enhancement, such as machine-learning-based MPPT controllers, hybrid algorithms, and grid-forming inverters [23]. Digital control and high-speed signal processing are making it easy to enhance inverter response to environmental change and load change [24]. Policy initiatives by MNRE and regulatory compliance as per CEA norms have made it a point that new installations adopt good control measures and monitoring schemes [25], [26]. FACTS devices such as IPFCs are widely employed to increase power flow and control PQ issues in multi-feeder schemes [27]. Small PV system integration is studied extensively for potential rural electrification and microgrid stability with focus on PQ measurements during low-load and high-solar-irradiance situations [28]. Experiences from field tests confirm that well-designed filters and controllers are able to maintain THD within IEEE 519 limits even under worst-case scenarios [29]. Most importantly, national and international standards compliance is still a major concern for large-scale PV deployment, with technical reports informing best practice in PQ management and system design [30].

In this research, a 0.3 MW grid-connected solar PV system is modeled in PSCAD to analyze power quality challenges under low solar irradiance (200 W/m²) and moderate temperature (20.5 °C) conditions. The study applies the Incremental Conductance (IC) MPPT algorithm, which not only ensures maximum power extraction but also improves voltage and current stability during fluctuating weather conditions. To represent practical grid behavior, the PV system is tested with dynamic R-L-C loads, allowing for a more realistic assessment of voltage stability, harmonic distortion, and reactive power variations. For mitigation, a customized LCL filter with damping resistance and reactive power compensation is implemented, which successfully reduces current THD to 4.93% and voltage THD to 2.18%, both within the permissible limits set by IEEE 519 and CEA guidelines. The findings confirm that with effective control strategies and filtering, medium-scale PV systems can achieve stable operation and comply with national and international power quality standards, even under adverse environmental conditions.

2 Literature gap and contribution of the study

2.1 Literature gap

Although extensive studies have been conducted on the integration of photovoltaic (PV) systems into the grid, several gaps remain:

- Limited focus on low irradiance and temperature conditions – Most research emphasizes PV performance under standard or high irradiance, while fewer studies investigate power quality behavior under low insolation and moderate temperature, which frequently occur in real-world conditions (e.g., cloudy weather, early mornings).
- Insufficient coupling with dynamic R-L-C loads – Prior works often consider simplified or steady-state loads. The impact of dynamic resistive–inductive–capacitive loads, which closely represent real grid behavior, is less explored in simulation-based studies.
- Inadequate PQ mitigation strategies in small-to-medium PV systems – While large-scale systems often employ advanced custom power devices (STATCOM, DVR, UPQC), medium-scale PV systems (≈0.3W) with optimized passive solutions (e.g., LCL filtering with reactive power compensation) are underreported.
- Comparative MPPT analysis bias – Previous studies validate the superiority of Incremental Conductance (IC) MPPT over Perturb & Observe (P&O) at varying irradiance, but its explicit performance in mitigating PQ disturbances under adverse conditions remains underexplored.
- Compliance validation gap – Few studies validate compliance of PV systems with IEEE 519 and CEA standards under low irradiance and fluctuating temperatures in the Indian grid context.

2.2 Contribution of the study

This study addresses the above gaps with the following contributions:

- Comprehensive PQ analysis under adverse conditions – A 0.3 MW grid-connected PV system is modeled in PSCAD to evaluate voltage stability, THD, and reactive power fluctuations specifically under low irradiance (200 W/m²) and moderate temperatures (20.5 °C).
- Integration of Incremental Conductance MPPT for PQ enhancement – The study demonstrates that IC MPPT not only maximizes power extraction but also contributes to voltage/current stability during transient and low-insolation conditions.
- Dynamic R-L-C load modeling – Unlike many prior works, the system is exposed to dynamic R-L-C loads to replicate realistic grid interaction and assess PQ disturbances more accurately.
- Mitigation via LCL filter and compensation – A carefully designed LCL filter with damping resistance and reactive power compensation scheme is proposed, achieving current THD of 4.93% and voltage THD of 2.18%, both within IEEE 519/CEA limits.
- Validation of regulatory compliance in Indian context – The study confirms that with optimized control and filtering, medium-scale PV systems can ensure reliable grid operation and compliance with national and international PQ standards, even in challenging environmental scenarios.

3 System under study

The simulation circuit was developed by authors of the paper in PSCAD software tool whose block diagram representation is illustered in Figure 1.

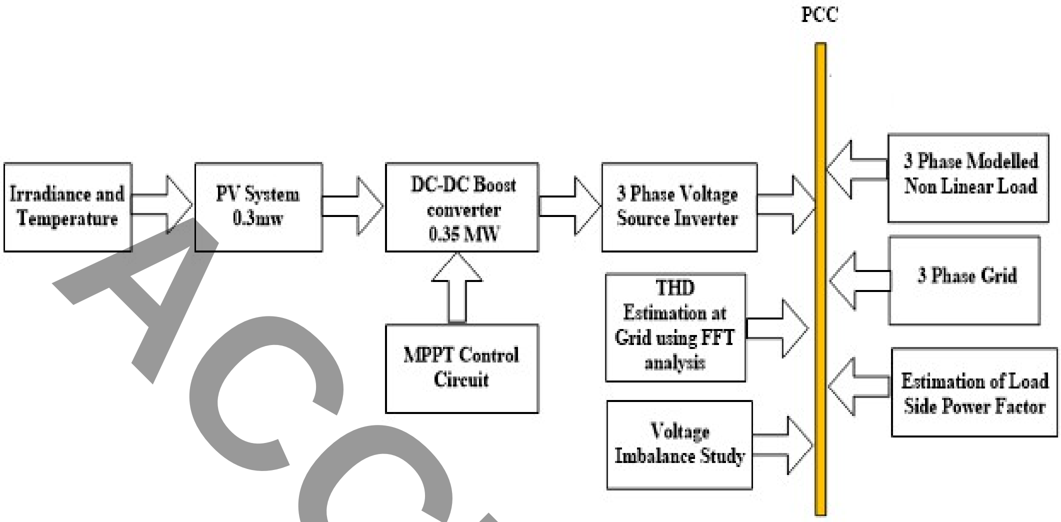

Figure 1. Block diagram representation of grid connected Solar PV System under study.

Figure 1 shows a self-developed block diagrammatic representation for the evaluation and control of problems in power quality in grid-integrated photovoltaic (PV) system. The system starts with irradiance and temperature parameters, which are environmental parameters that influence solar PV generation. The photovoltaic system is designed to provide 0.3 MW of direct current (D.C.) power, which is supplied to a boost converter. The power supplied from the converter, which is controlled by MPPT control circuit, is maximized for system performance and is then boosted to 0.35 MW. The boosted DC power is then converted to alternating current (A.C.) by three phase VSI, rendering it suitable for grid connection. At Point of Common Coupling (PCC), the system communicates with various elements and measurement tools intended for power quality problem-solving. The system uses advanced analysis techniques to identify and solve power quality issues. Total Harmonic Distortion (THD) is monitored using Fast Fourier Transform (FFT) analysis in order to identify and quantify harmonic distortions. Voltage imbalance analysis is conducted in order to study phase voltage symmetry, which is important for grid reliability. The system offers good performance, energy efficiency, and reduced THD, thus making it a good option to incorporate renewable power sources into the grid.

4 Incremental conductance algorithm

The Incremental Conductance (Inc Cond) algorithm is a method used in solar power systems to continuously find and operate at the Maximum Power Point (MPP) of a photovoltaic (PV) panel. It works by comparing the incremental conductance (ΔI/ΔV) with the instantaneous conductance (-I/V).
At MPP,

Algorithm Steps:

Measure current I and voltage V from the solar panel.
Calculate changes:

$$\Delta I = I(n) - I(n-1) \tag{1}$$

$$\Delta V = V(n) - V(n-1) \tag{2}$$

Check for voltage change:

$$If\ \Delta V = 0\ at\ MPP\ \rightarrow\ no\ change \tag{3}$$

$$If\ \Delta I > 0\ left\ of\ MPP\ \rightarrow\ decrease\ voltage \tag{4}$$

$$If\ \Delta I < 0\ right\ of\ MPP\ \rightarrow\ increase\ voltage \tag{5}$$

If $\Delta V \neq 0$:

Compute: $\Delta I/\Delta V$

Compare with $-I/V$

$$If\ \frac{\Delta I}{\Delta V} = -\frac{I}{V}\ at\ MPP:\ \ no\ change \tag{6}$$

$$If\ \frac{\Delta I}{\Delta V}: left\ of\ MPP\ \rightarrow\ increase\ voltage \tag{7}$$

$$If\ \frac{\Delta I}{\Delta V} < -\frac{I}{V}: right\ of\ MPP\ \rightarrow\ decrease\ voltage \tag{8}$$

Adjust the duty cycle of the DC – DC converter to move toward the new operating point.
Repeat the steps continuously.

5 Case Study: Performance evaluation of grid-interconnected photovoltaic (PV) system with Incremental Conductance (IC) MPPT technique under reduced solar insolation conditions

This case study examines performance of grid-interconnected photovoltaic (PV) system with Incremental Conductance (IC) MPPT technique under reduced solar insolation conditions. The study is particularly concerned with an irradiation of 200 W/m² and 20.5°C to be used to signify low insolation conditions. The study purposes to assess the performance of the IC technique in maintaining maximum power output and addressing power quality problems, including voltage fluctuation, harmonic distortion, and system stability. The analysis is carried out at varied insolation and temperature conditions like 200W/m^2, 500W/m^2 and 1000W/ and temperature conditions of 20.5℃,25℃ and 35.5℃ respectively.

5.1 System specifications

The following system specifications have been determined based on in-depth analysis, mathematical modeling, and a technical understanding of the Maximum Power Point Tracking (MPPT) system. Additionally, the filter circuit was designed by iteratively configuring a series inductance. The process was repeated with adjustments to the inductance value until the Total Harmonic Distortion (THD) was brought within the permissible range, ensuring compliance with power quality standards.

Table 1. System specifications.

Parameter	Value	Illustration
Irradiance	200 W/m²	This is the solar energy incident per square meter of PV panel surface. 200 W/m² is a low irradiance condition, leading to reduced power generation from the PV array. It is critical for testing the responsiveness of the MPPT algorithm under sub-optimal sunlight.
Temperature	20.5 °C	This is the ambient temperature affecting the PV module performance. A temperature of 20.5 °C is moderate, typically resulting in higher efficiency of PV modules compared to hotter conditions.
Solar PV rating	0.3 MW	This is the maximum power output capacity of the solar PV array under standard test conditions (STC: 1000 W/m², 25 °C). All control and MPPT logic aim to extract power close to this level when irradiance permits.
DC-DC Converter Power Limit (P_{limit})	0.35 MW	The maximum permissible power transfer through the DC-DC converter. It provides a safe margin above the rated PV capacity to handle transient conditions or MPPT overshoots.
Reference Converter Power (P_{ref})	0.3 MW	This is the target power that the MPPT controller aims to achieve from the PV system. It is equal to the PV rating, ensuring optimal operation when environmental conditions allow.
Input Inductor (L)	100 µH	This inductor is part of the boost converter circuit. It stores energy when the switch is ON and releases it when OFF.
Input Capacitor (C_{in})	1000 µF	It stabilizes the input voltage to the DC-DC converter, filtering voltage ripples caused by switching. Ensures a steady voltage source for MPPT tracking.
Output Capacitor (C_{out})	3000 µF	It maintains a constant output voltage and filters out switching ripples before the power is passed to the grid or load. It helps achieve DC voltage regulation.
Base MVA of Grid	50 MVA	This is the power base used for per-unit (p.u.) system calculations in simulation. It helps normalize power levels for analysis and design in software like PSCAD.
Base Voltage of Grid (L-L RMS)	0.5 kV	This is the RMS voltage (L-L) of the grid at the point of interconnection. It sets the voltage base for the per-unit system and helps define transformer and inverter ratings.
Load Power	0.3 MW	This is the constant or controlled load connected to the system. It matches the rated PV output, ideal for controlled MPPT evaluation. Any mismatch between generation and load is handled by the grid.
LCL Filter Configuration	-	The LCL filter is coupled between the grid and inverter to filter high-frequency switching harmonics. This helps in maintaining power quality and ensures grid code compliance.
MPPT Algorithm	Incremental Conductance	The chosen MPPT method compares the incremental and instantaneous conductance to locate the MPP. It adapts quickly to irradiance and temperature changes and avoids oscillations around MPP, unlike basic methods like P&O.

5.2 Simulation results

The study considers an irradiance of 200 W/m² and a temperature of 20.5°C to represent low insolation conditions in Nagpur, Maharashtra, India. These values are chosen based on typical climatic patterns observed in the region, particularly during early morning hours in winter or during overcast conditions in the monsoon season. Nagpur generally experiences peak solar irradiance levels between 600–1000 W/m² on clear days; however, during cloudy weather or in the early and late hours of the day, irradiance can drop significantly, often reaching around 200 W/m². Similarly, while Nagpur is known for high summer temperatures, average temperatures during winter months, especially in December and January, range between 15°C and 25°C, with 20.5°C being a representative daytime average. Therefore, the selected values of 200 W/m² and 20.5°C realistically reflect the low insolation conditions under which photovoltaic system performance may be adversely affected in this region.

5.3 Variation of solar PV output power, voltage and current

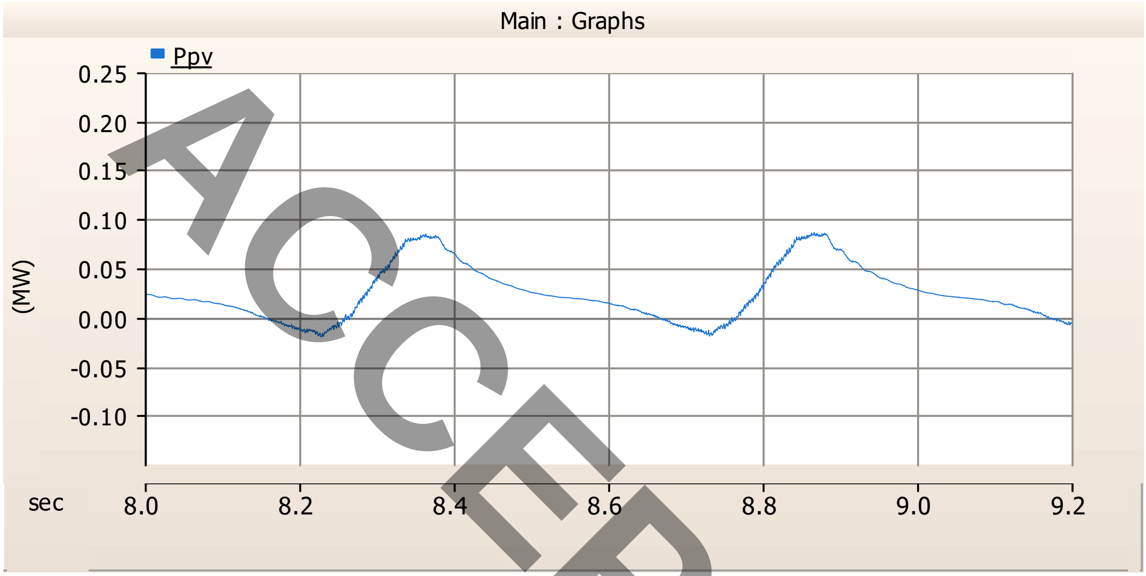

Figure 2. Variation of Solar PV power output.

Figure 2 illustrates the temporal variation in the power output (Ppv) of a photovoltaic (PV) system. The *x*-axis represents the time in seconds, while the *y*-axis indicates the power output in megawatts (MW). The waveform exhibits periodic fluctuations characterized by alternating maxima and minima, which reflect dynamic variations in power generation. These fluctuations can be primarily attributed to intermittent solar irradiance, shading effects, or variations in load demand. Notably, the power output oscillates around zero, suggesting the presence of transient or alternating operational modes within the system, potentially induced by rapid environmental changes or control dynamics.

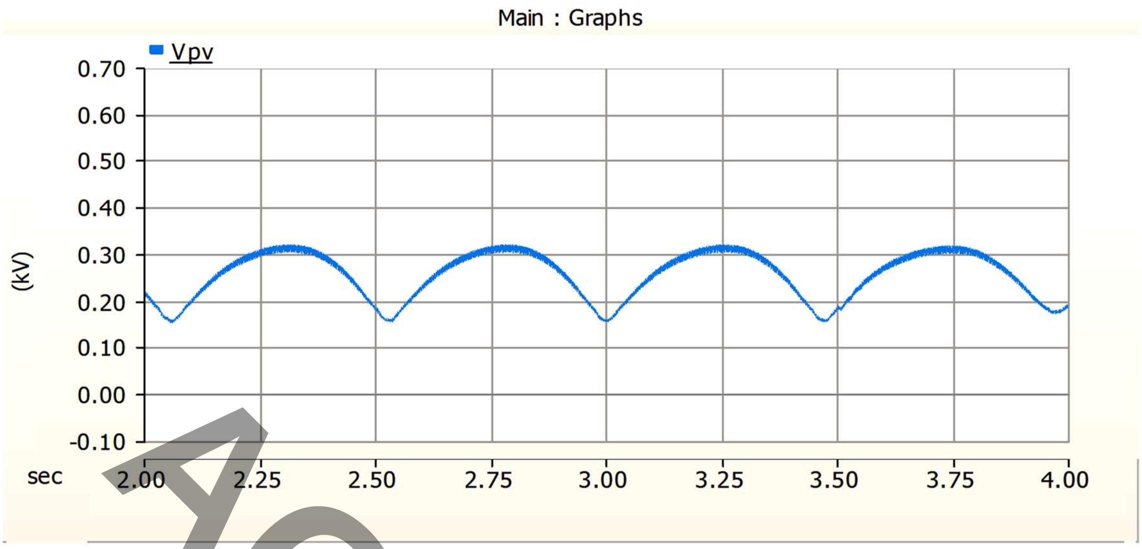

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Figure 3. Variation of Solar PV output voltage.

As indicated in Figure 3, the graph shows the voltage (Vpv) produced by a photovoltaic (PV) system for a period of time. Time in seconds is plotted along the *x*-axis, and voltage in kilovolts (kV) along the *y*-axis. The waveform demonstrates a cyclical trend with rising and falling peaks, showing fluctuations in PV voltage. Fluctuations could be a result of varying solar irradiance, load variation, or control system dynamics. The voltage is kept constant at a specific value, which reflects a cyclical but steady trend in the PV system.

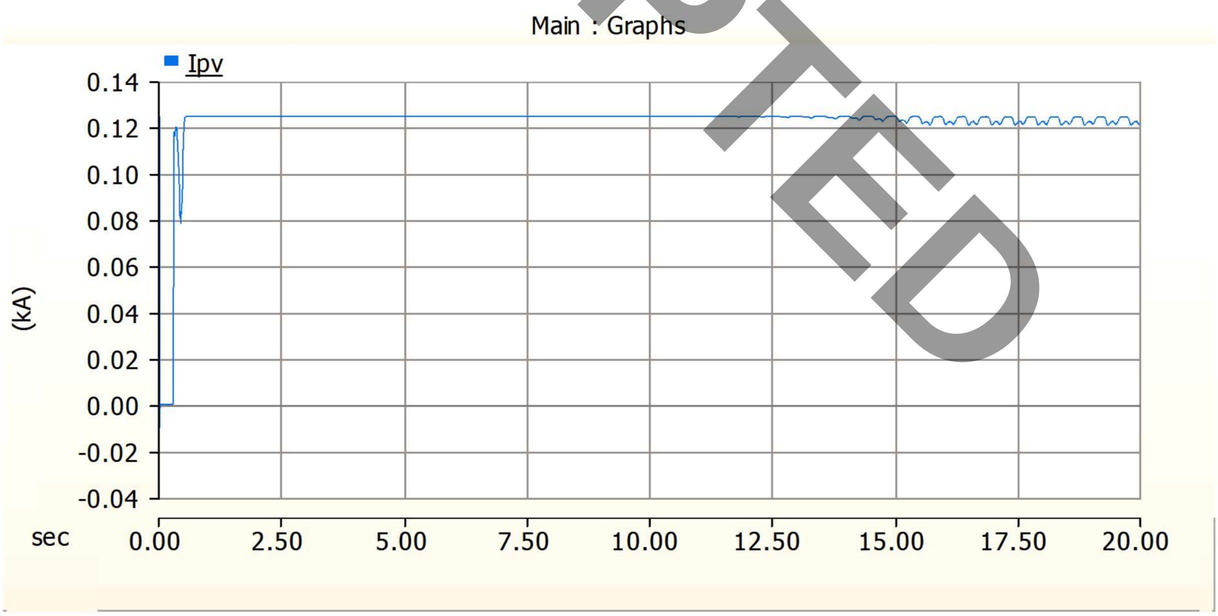

Figure 4. Variation of Solar PV output current.

As represented in Figure 4, the current (Ipv) starts from zero and quickly rises to a stable value with initial oscillations without significant oscillations. It signifies that the system is effectively tracking the maximum power point and delivering consistent current to the load or grid. The lack of fluctuation under steady-state condition highlights the reliability of the control mechanism under the given operating conditions. The stable Ipv indicates that there are no major disruptions, such as shading effects or system instability, affecting the PV array's performance.

5.4 Inverter voltage and current variations

As seen in Figure 5, the voltage response of a Voltage Source Converter (VSC) system is illustrated by the graphs. The three-phase voltage waveforms (V_VSC) are illustrated by the first graph by their smooth nature, sinusoidal shape, and balanced arrangement, showing a consistent 120-degree phase shift between the phases. The voltage amplitude peaks at approximately ±0.35 kV, indicating the converter's output voltage level. The periodicity of the waveforms suggests operation at a standard AC frequency, likely 50 Hz. The smoothness of the waveforms highlights the efficiency of the converter's modulation technique and control system. As represented in Figure.6, the graph shows the three-phase current waveforms (I_VSC), which exhibit some distortion compared to the voltage. The current amplitudes peak at around ±0.15 kA, reflecting the load demand on the converter. Despite the minor distortion, the current waveforms maintain the characteristic 120-degree phase shift of a balanced three-phase system. The observed distortion in the current may stem from harmonics introduced by the VSC's switching operations, non-linear loads, or minor inaccuracies in the control system. Overall, while the voltage signals demonstrate high quality and balance, the current waveforms suggest areas for further analysis to improve system performance, particularly in minimizing harmonic distortion.

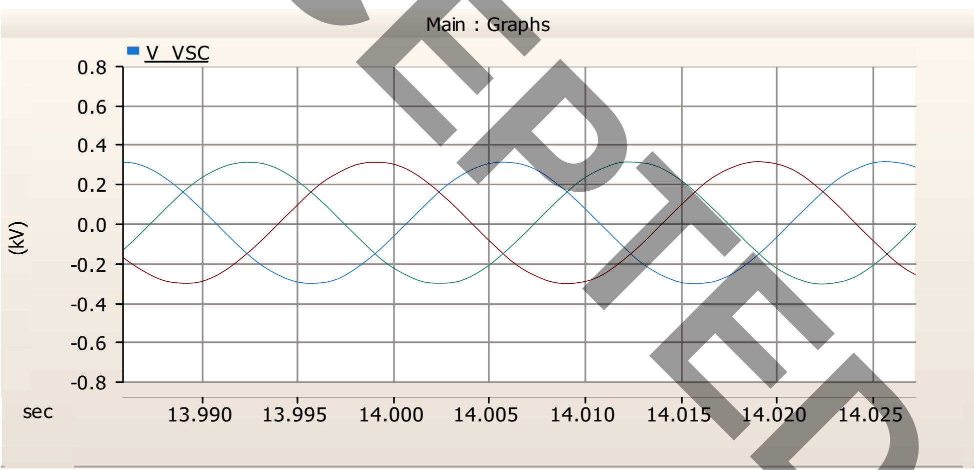

Figure 5. Variation of Solar PV Inverter voltage.

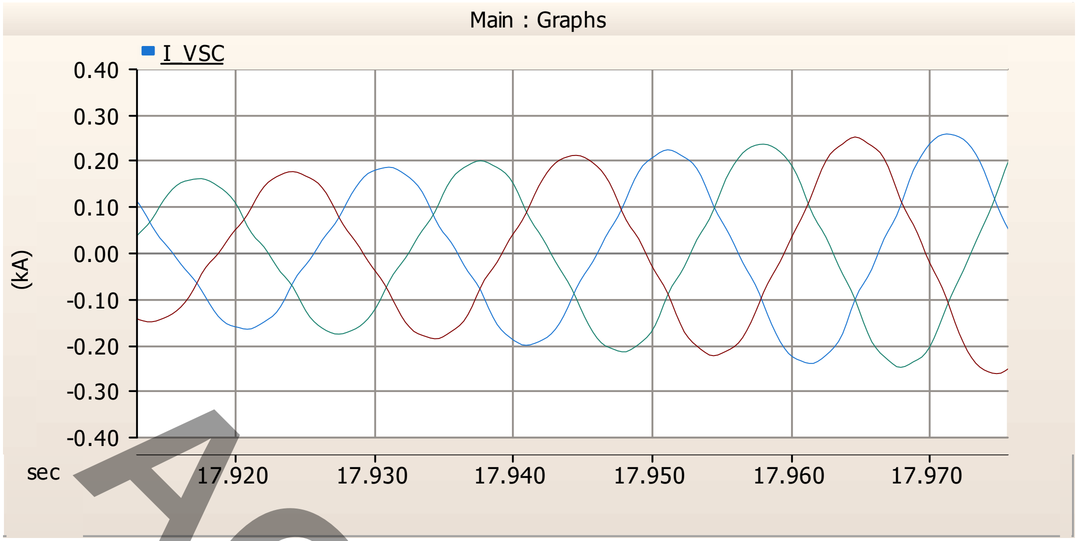

Figure 6. Variation of Solar PV Inverter current.

5.5 Solar PV converter DC output voltage

As represented in Figure.7, the graph represents the DC voltage (VDC2) output of a system, likely from a Voltage Source Converter (VSC). The waveform shows pulsating DC variation around 1.2 kV. These fluctuations, or ripple components, are characteristic of switching operations in power electronic converters or variations caused by load dynamics.

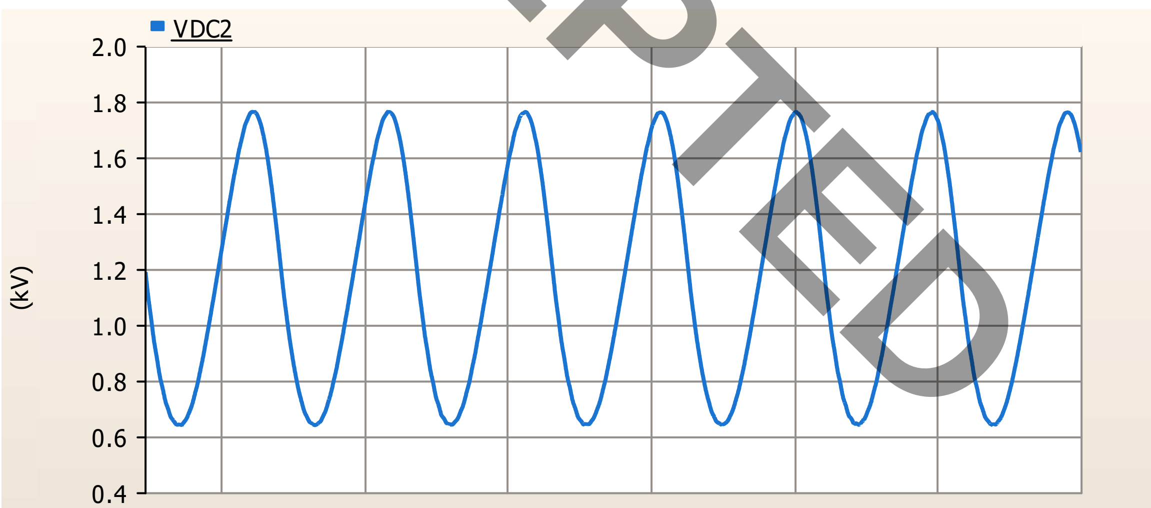

Figure 7. Variation of Solar PV Converter dc output voltage.

5.6 Apparent power variations at load, grid and inverter output

As represented in Figure 8, the real power (Pgrid, Pload, and P_VSC) is plotted against time in megawatts (MW). The Pgrid (grid power) and Pload (load power) curves are closely aligned, maintaining a consistent value of approximately 0.3 MW. This indicates a balance between the grid's power supply and the load's demand. On the other hand, the P_VSC (active power contribution from the Voltage Source Converter) remains near 0-0.10MW throughout the observation period. This suggests that the VSC is not actively contributing to or absorbing significant amounts of real power, likely because its role is primarily focused on other functions, such as maintaining voltage stability or providing reactive power support.

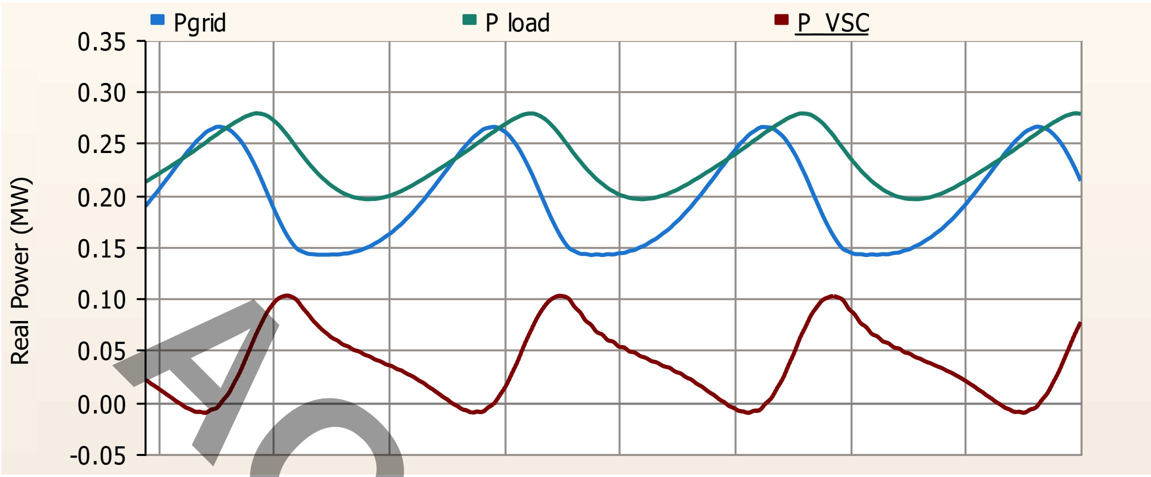

Figure 8. Active power variations at load, grid and inverter output.

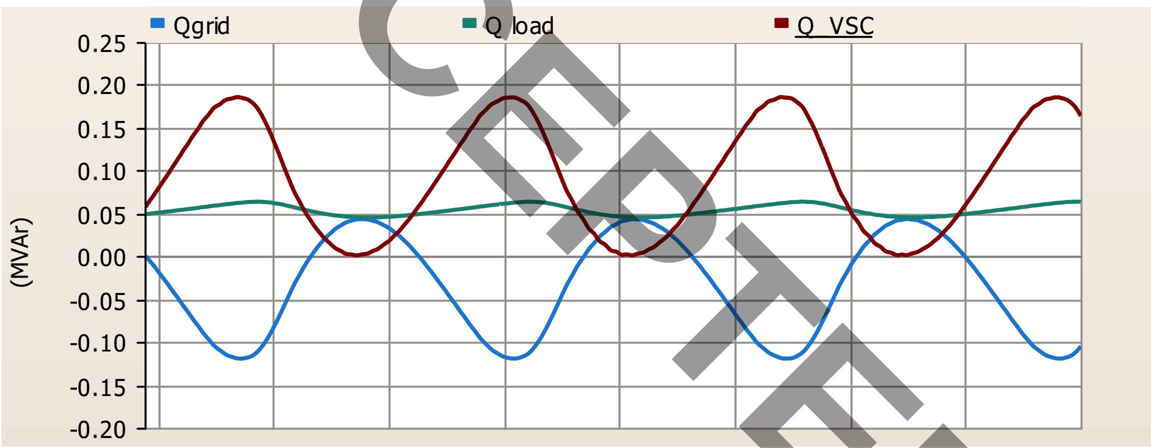

Figure 9. Reactive power variations at load, grid and inverter output.

As represented in Figure 9, the graph represents reactive power (Qgrid, Qload, and Q_VSC) in megavolt-amperes reactive (MVAr). The slight downward trend in these curves is negligible, suggesting stable system behaviour. Similar to the real power graph, Q_VSC (reactive power from the VSC) stays close to zero VSC is in a standby or non-operational mode for reactive power support during this timeframe.

5.7 Grid voltage and current variations at load, grid and inverter output

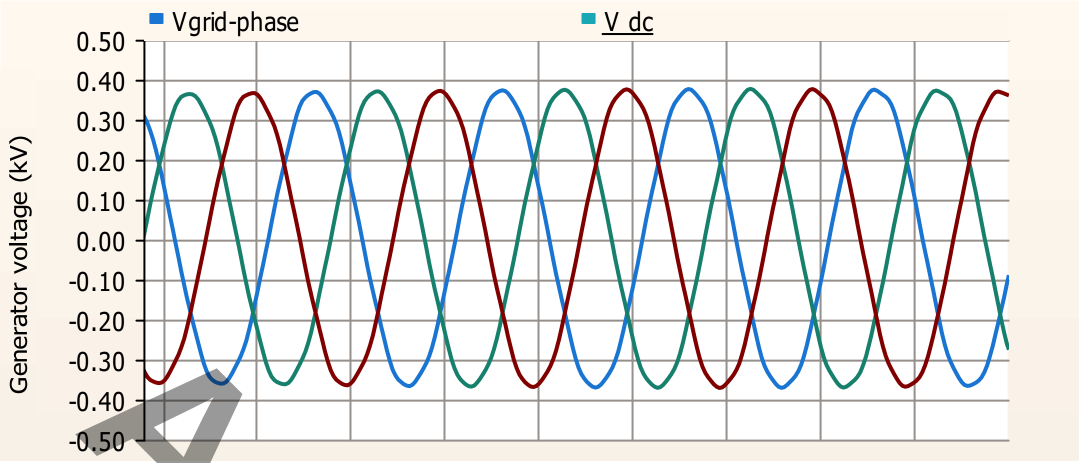

Figure 10. Grid Voltage variation at PCC.

As represented in Figure 10, the graph showcases the three-phase grid voltage waveforms (Vgrid-phase) in kilovolts (kV). The sinusoidal nature of the waveforms, with a consistent amplitude of approximately ±0.35 kV, indicates a well-balanced and stable voltage profile across all three phases. The absence of distortion or amplitude variations suggests that the system is operating under normal conditions with no significant disturbances or imbalances in the grid voltage. As represented in Figure 11, the graph displays the three-phase grid current waveforms (Igrid) measured in kilo amperes (kA). The sinusoidal patterns indicate a balanced and stable current flow across all three phases. Each phase waveform is evenly spaced and maintains consistent amplitude, approximately ±0.5 kA, suggesting proper synchronization between the phases. The absence of distortions, harmonics, or phase shifts demonstrates that the system is operating under ideal conditions with minimal disturbances.

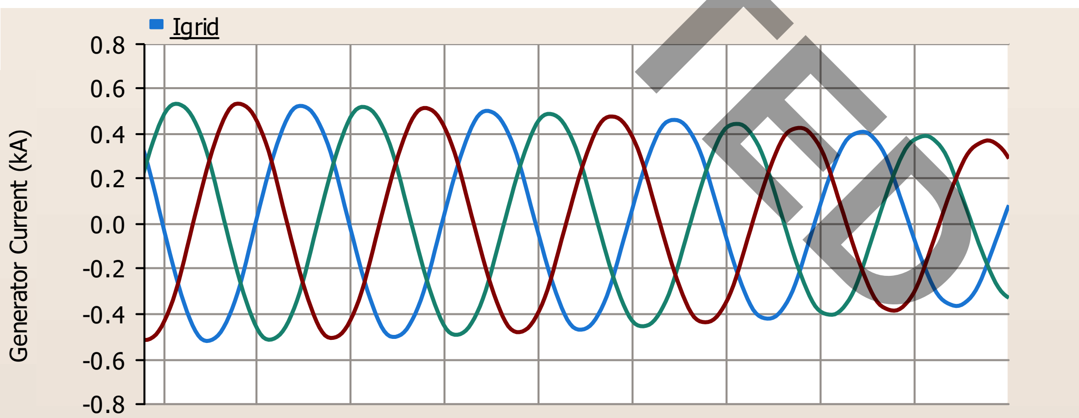

Figure 11. Grid current variation at point of common coupling.

The uniform nature of the waveforms also implies that the load connected to the grid is balanced, with equal current distribution among the three phases. This level of stability is crucial for maintaining the efficiency and reliability of power system operations. Overall, the graph confirms that the grid current is in a steady state, free from imbalances or fluctuations, and supports the overall stability of the power network.

6 LCL Filter configuration to mitigate THD

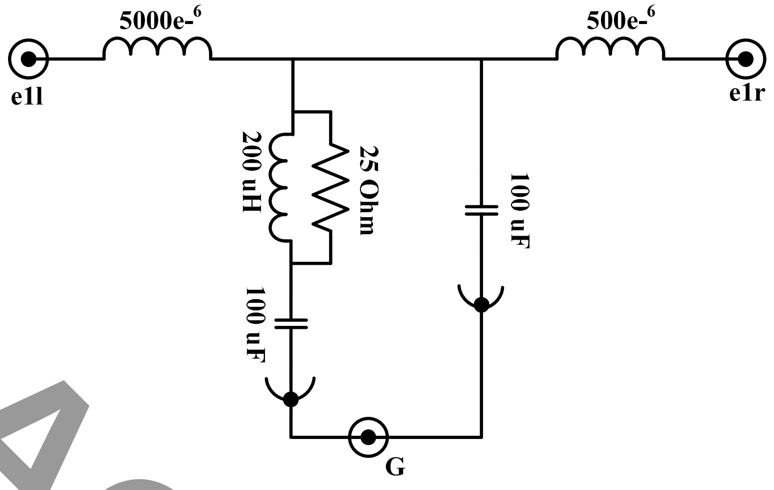

Figure 12. LCL filter configuration for improved THD limits.

The circuit represented in Figure 12 is a detailed representation of a single-phase LCL filter with passive damping, typically used at the output of inverter to minimize harmonic distortion. The filter consists of two outer series inductors of 500 µH each one on the inverter side (input) and the other on the grid side (output)—which primarily block high-frequency switching harmonics generated by the inverter. Between these inductors lies a damped RLC branch, composed of a 200 µH inductor, a 100 µF capacitor, and a 25 Ω resistor connected in parallel. This branch forms a resonant circuit that targets specific harmonic frequencies, and the resistor serves to dampen the resonance, thereby preventing amplification of harmonics near the filter's resonant frequency. Additionally, a 100 µF capacitor is connected to ground, providing a low-impedance path for high-frequency components to be safely diverted, further aiding in voltage ripple suppression. This LCL configuration is highly effective in attenuating switching noise and harmonic currents before they reach the grid. In the context of the earlier THD results—4.93% current THD and 2.18% voltage THD—this filter plays a crucial role. The inductors help limit the rate of current change, while the capacitors shunt high-frequency harmonics away from the grid, and the resistor ensures stability by preventing oscillations. The result is a significant reduction in both current and voltage harmonics, keeping them well within the limits set by IEEE 519 and CEA regulations, which generally allow up to 5% THD. Therefore, the presence of this damped LCL filter in the system design directly supports compliance with grid interconnection standards.

$$L1 = L2 = 500\ \mu H, C = 100\ \mu F, f_g = 50\ Hz \tag{9}$$

$$f_r = \frac{1}{2\pi}\sqrt{\frac{L1 + L2}{L1 + L2.C2}} = 1.006\ Hz \tag{10}$$

Also,

$$Vph = \frac{VLL}{\sqrt{3}} = 288.7\ V \tag{11}$$

$$Q_C = V_{ph}^2 \cdot \omega_g \cdot C \approx 288.7^2 \cdot 2\pi \cdot 50 \cdot 100 \cdot 10^{-6} \approx 2.618\ var\ (per\ phase) \tag{12}$$

So a 100 μF capacitor at 0.5 kV L-L provides ~7.8 kvar reactive support acceptable for many medium-scale systems but you must check whether this reactive injection is acceptable for your site and grid code. A relatively large resistor (25 Ω) across the RLC branch in your document is primarily to damp the LCL resonance so that the resonance peak is small and the system stays stable. With C=100 μF, the resistor will dissipate switching-frequency harmonic energy and reduce resonance amplification.

- Too small R → insufficient damping → resonance peak → high THD.
- Too large R → heavy damping but high steady-state losses and heating in the resistor and degraded harmonic attenuation.

25 Ω is a practical, conservative choice for a passive damping branch in simulation: it gives strong damping at the ~1 kHz resonance without imposing excessive losses at fundamental frequency (note capacitor is the primary 50 Hz reactance; R mostly shunts high-frequency currents).

7 Modelled non-linear load

The block diagram illustrating the controlled load modeling of 0.3MW connected at PCC is presented in Figure 13. The load resistance, inductance, and capacitance are determined by evaluating the active and reactive power supplied to the load. In this context, accurately estimating these parameters is closely tied to the effective management of both active power (real power) and reactive power delivered to the load.

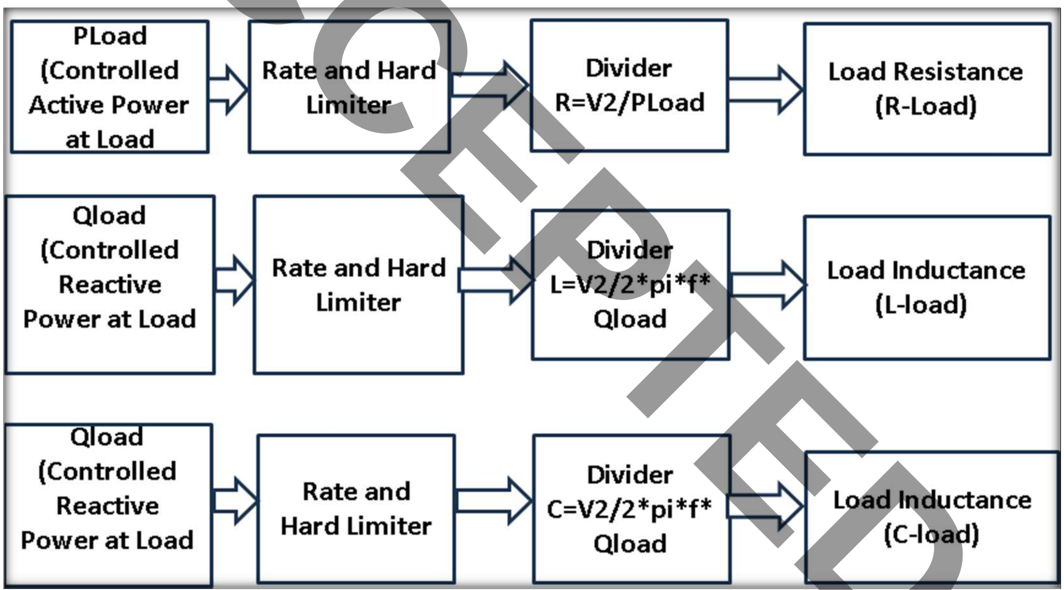

Figure 13. Modelled Non-Linear RLC load.

8 Total harmonic distortion analysis

Table 2. Power quality analysis in terms of Total harmonic distortion.

S.N	MPPT Technique	Irradiance in W/m^2	Temperature in °C	% THD in Inverter Current	%THD in Inverter Voltage	Compliance as per IEEE519/CEA regulations
1	Incremental Conductance	200	20.5	4.93	2.18	Complied

The provided data in Table 2 represents the performance of a grid-connected solar PV system using IC MPPT technique under specific environmental conditions. At a low irradiance level of 200 W/m² and a moderate ambient temperature of 20.5°C, the system operates with a Total Harmonic Distortion (THD) of 4.93% in inverter current and 2.18% in inverter voltage. These THD values are well within the permissible limits specified by IEEE 519 and Central Electricity Authority (CEA) regulations, which generally allow voltage THD up to 5% and current THD typically around 5% depending on the system configuration. The Incremental Conductance method proves effective in accurately tracking the maximum power point even under low irradiance conditions, without introducing significant harmonic distortion. As a result, the system is marked as "Complied," indicating that it maintains acceptable power quality standards and does not negatively impact the grid's performance.

Table 3. Comparative analysis of various THD mitigation strategies.

Parameter	LCL Filter Mitigation	Active Power Filters (APF)	Custom Power Devices (STATCOM/DVR/UPQC)	Hybrid Solutions (Filter + Controller)
Type	Passive filter placed between inverter and grid	Active filter injecting compensating current/voltage	Power-electronic device providing reactive power and voltage support	Combines passive LCL filters with active control algorithms
Primary Purpose	Attenuates high-frequency switching harmonics from inverter	Cancels load or inverter-generated harmonics dynamically	Mitigates voltage sags, swells, flicker and reactive power imbalance	Simultaneously attenuates harmonics and controls voltage/reactive power
Harmonic Mitigation Effectiveness	High for high-frequency harmonics; less effective for low-order harmonics	Effective for both high- and low-order harmonics	Primarily for voltage issues; limited harmonic mitigation	High combined effectiveness across harmonic orders
Reactive Power Compensation	Not inherent (requires separate compensation)	Limited (depends on control strategy)	Strong capability for dynamic VAR support	Moderate to strong depending on controller
Dynamic Response	Passive – fixed characteristics; no adaptation to load/irradiance changes	Fast dynamic response due to real-time control	Very fast, supports grid codes and transient conditions	Fast response with optimized filter performance
Complexity	Simple passive components; easy to design and implement	High complexity (requires sensors, controllers, fast switching)	Very high complexity and cost	Moderate complexity; requires both filter design and controller tuning
Cost	Low to medium (inductors, capacitors, damping resistor)	Medium to high due to power electronics	High (utility-scale FACTS devices are expensive)	Medium

9 Conclusion

This paper provides an in-depth power quality analysis of a 0.3 MW grid-connected solar photovoltaic (PV) system at low irradiance and moderate temperature conditions using the Incremental Conductance (IC) MPPT algorithm, simulated in PSCAD. The environmental conditions used 200 W/m² irradiance and 20.5°C temperature reflect actual low-insolation conditions of early mornings or cloudy weather in Nagpur, Maharashtra, India. Simulation results confirm that the Incremental Conductance (IC) algorithm can follow the maximum power point even under suboptimal conditions, thus ensuring a constant current output and reducing voltage oscillations. The inverter voltage showed a stable sinusoidal waveform of about ±0.35 kV, and the inverter current achieved ±0.15 kA with slight distortions due to switching harmonics. The grid voltage and current at the point of common coupling (PCC) were also found to be sinusoidal and balanced, establishing the stable operation of the system. The most significant finding was the measured Total Harmonic Distortion (THD) in the system. THD current was measured at 4.93%, and THD voltage was measured at 2.18%, both well within the limits of IEEE 519 and CEA guidelines (usually <5%). This was realized using an optimized LCL filter with series inductors of 500 μH, shunt capacitors of 100 μF, and damping resistance of 25 Ω. The filter components successfully suppressed high-frequency switching harmonics and met the regulatory requirements.

10 Limitations and Future Scope

Although this study demonstrates that the Incremental Conductance (IC) MPPT algorithm combined with LCL filtering can effectively improve power quality in a 0.3 MW grid-connected solar PV system under low irradiance and moderate temperature conditions, some limitations remain. First, the analysis is based on simulation in PSCAD, and real-world field validation is not performed. Second, the study considers a single medium-scale PV system; larger-scale or hybrid systems with storage integration may exhibit different behaviours. Third, only one MPPT technique (IC) is evaluated in detail, without comparative benchmarking against advanced hybrid or AI-based controllers. Future research should focus on experimental validation of these findings in real installations under varying climatic and load conditions. Comparative analysis of emerging MPPT techniques, including machine-learning-based controllers, can provide deeper insights into dynamic performance. Additionally, integrating energy storage systems and testing advanced custom power devices such as STATCOMs or UPQCs may further enhance grid stability. Investigations into cost–benefit trade-offs and compliance with evolving IEEE/CEA standards will also help strengthen the applicability of the proposed approach for large-scale deployment.

Acknowledgements

We express our gratitude for the contributions made by the Manitoba HVDC Research Centre concerning grid-connected photovoltaic systems. We are profoundly grateful to the Manitoba HVDC Research Centre for their unwavering support.

Conflicts of Interest

The authors have no relevant financial or nonfinancial interest to disclose.

Funding source

This research received no external funding.

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