ANALYSIS AND MITIGATION OF POWER QUALITY (PQ) ISSUES IN 0.3MW SOLAR PHOTOVOLTAIC SYSTEM (SPV) CONNECTED TO GRID WITH MPPT TRACKER AND CONTROLLED LOAD USING PSCAD SOFTWARE

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Abstract:

The escalating global demand for distributed generation systems has driven the widespread integration of Solar Photovoltaic (PV) system into the distribution grid. This paradigm shift, while promising in meeting energy demands, introduces intricate power quality challenges within distribution systems. This research deals with the comprehensive analysis and strategic mitigation of PQ issues of 0.3MW solar PV system, featuring advanced components like an MPPT tracker and a controlled load. Utilizing PSCAD software for simulation, the study incorporates vital input parameters like irradiance and temperature to generate 0.3MW power. The generated power undergoes a meticulous transformation process through boost converter, ensuring both voltage regulation and Power Point Tracking. The regulated DC power is then seamlessly supplied to the voltage source inverter, facilitating its supply to the Point of Common Contact (PCC), where both the conventional grid and the controlled load are intricately connected. The study employs advanced techniques, including FFT analysis to measure THD at the inverter output. Additionally, an in-depth examination of voltage imbalances adds further granularity to the power quality assessment. The THD values for inverter current and voltage are systematically evaluated through FFT analysis, offering insights into the harmonic characteristics of the system. As a strategic measure to mitigate THD and enhance overall power quality, a Static Var compensator is introduced at the inverter output. This intervention proves effective, showcasing a substantial reduction in THD levels. The research contributes significantly to the understanding and management of PQ challenges associated with the integration of solar PV systems in distributed generation scenarios. Through its comprehensive analysis and targeted mitigation strategies, the study provides valuable guidance for ensuring integration of renewable energy sources into the evolving landscape of modern power systems.

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1 Introduction

The surging global demand for electricity is propelling the integration of Solar PV systems, casting a spotlight on power quality concerns. This research delves into the intricate realm of THD in voltage and current within grid-connected solar PV systems [1, 2]. The complex challenges posed by overvoltage and power factor fluctuations in grid-connected PV systems necessitate dynamic solutions, incorporating reactive power-based compensation and thyristor-driven LC compensators [3, 4]. Researchers are employing a diverse array of control strategies, encompassing AI-based and conventional algorithms, to effectively mitigate power quality issues in distributed generation systems [5]. The nuanced management of voltage sag and low voltage ride-through is achieved through strategic adjustments in inverter operation and the injection of reactive power [6]. Adherence to IEEE 519-1992 standards is paramount in guiding the seamless integration of solar PV systems [8]. The granular analysis of load characteristics proves indispensable for addressing power quality issues across both on-grid and off-grid systems [9].

The strategic development of risk mitigation frameworks emerges as a critical aspect in effectively addressing power quality concerns within distributed generation systems [10]. Researchers leveraging the IEEE-13 nodes test system illuminate the nuances of power quality analysis [11]. The superiority of fuzzy and neural network controllers over classical PI controllers is underscored through comprehensive studies [12-15]. A paradigmatic example, grounded in PSCAD, meticulously illustrates the intricacies of integrating photovoltaic systems, fostering a deeper understanding of operational dynamics and controllable parameters [16]. A comprehensive review traverses the terrain of power quality challenges within grid-tied Solar PV Systems, unraveling sophisticated mitigation techniques to enhance system performance and reliability [17]. The research landscape expands to explore the efficacy of a Static Synchronous Series Compensator (SSSC) within an IEEE 9-bus system [18]. The allocation of a Unified Power Flow Controller (UPFC) proves pivotal in augmenting system performance, guided by the active power flow sensitivity index [19]. The research trajectory persists with an unwavering focus on bolstering power system performance through the implementation of an SSSC, orchestrated by a PI-based controller [20]. An invaluable compass is provided for engineers and researchers navigating the realm of solar PV power performance forecasting, facilitating real-time decision-making in the intricate design and implementation of on-grid PV systems [21].

The expedition continues with a comprehensive review encapsulating the evolution of power system harmonic analysis methodologies [22]. The evaluative lens scrutinizes the efficacy of a shunt compensator within a proposed two-machine system, navigating through MATLAB simulations [23]. Optimization algorithms, epitomized by Ordered FPA and Optimized TCA, carve a path toward heightened efficiency in maximum power point tracking (MPPT) within PV systems [24, 25]. The proposed optimal microgrid design, a synergistic amalgamation of solar PV, diesel generators, and battery banks, emerges as a paragon of superior performance, validated through simulations employing HOMER Pro software [26]. Specific studies are dedicated to unraveling the harmonic impact of PV systems on grid power quality, ranging from simulations assessing Total Harmonic Distortion (THD) [27], innovative solutions for adjusting inverter filter settings [28], to investigations of the impact of higher PV penetration on static and transient stability within large power systems [30]. In the Geelong region of Australia, simulations provide insights into the effects of varying solar PV penetration on the distribution network, with a keen focus on power quality issues [31]. Simultaneously, the Rockhampton distribution network sets the stage for a study proposing an optimized STATCOM as a potent tool for mitigating adverse harmonic impacts arising from large-scale renewable energy integration [32].

This research paper is organized in following sections:

1. Inroduction to research work
2. Assumptions made during the modeling process and limitations of the study
3. Novelty of Contribution
4. System under study
5. Design of the system under study
6. Result analysis and discussions
7. Conclusion
8. Acknowledgments
9. References

Assumptions made during the modeling process and limitations of the study:

1. The assumed irradiation profile for the Solar PV system ranges between 1200W/m^2 to 1400W/m^2.
2. The study does not account for the system's performance under lower irradiance levels.
3. The simulation incorporates a controlled load profile designed for study purposes; however, it is acknowledged that the system's behavior may differ when subjected to real-time varying load profiles.

Novelty of Contribution:

The novelty of the described research is grounded in its comprehensive strategy for addressing and mitigating power quality challenges associated with the integration of a 0.3MW solar PV system into the grid. Several distinctive elements contribute to the uniqueness of this work:

1. Innovative System Configuration and Components:
The integration features a 0.3MW solar PV system equipped with advanced components, including a sophisticated MPPT tracker and a controlled load. The utilization of a DC-DC boost converter for both voltage regulation and MPPT tracking, coupled with the incorporation of a Static Var compensator for mitigation, constitutes a novel system configuration.

2. Sophisticated Simulation using PSCAD Software:
This study employs PSCAD software for simulation, providing a precise and detailed representation of the dynamic behavior of the solar PV system within the grid. This advanced simulation tool enhances the reliability of the findings and enables a realistic evaluation of power quality parameters.

3. Consideration of Environmental Input Parameters:
By integrating input parameters such as irradiance and temperature into the simulation, the research captures the dynamic nature of solar PV generation. This approach introduces complexity and realism, reflecting the variability of environmental conditions that influence power generation.

4. Thorough Power Quality Analysis:
The study surpasses conventional analyses by FFT analysis for THD measurement and evaluating voltage imbalances. This detailed examination provides a nuanced understanding of the harmonic characteristics and overall power quality of the system.

5. Innovative Mitigation Strategy with Static Var Compensator:
The introduction of a Static Var compensator at the inverter output for THD mitigation represents a novel and effective strategy. This intervention significantly contributes to the management of power quality issues in grid tied solar PV systems. In summary, originality of this work is evident in its holistic and detailed approach to power quality analysis, encompassing advanced system components, realistic simulation, and the implementation of an innovative mitigation strategy. Together, these elements advance the understanding and management of PQ challenges in integration of solar PV systems into distributed generation networks.

2 System under study [16]

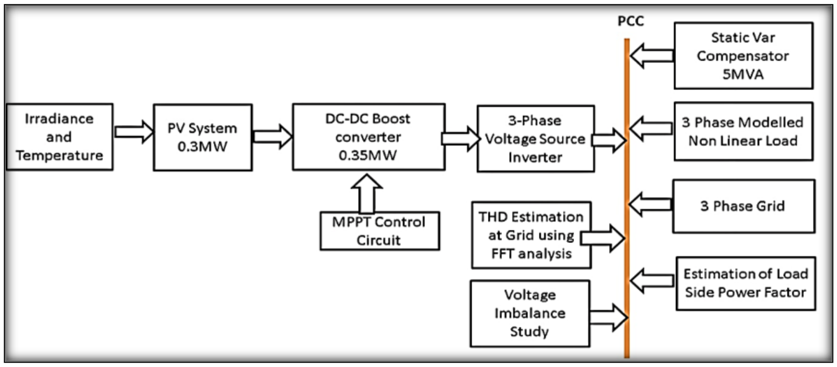

Figure. 1. Block diagram of grid connected 0.3MW solar Photo Voltaic System.

The block diagram of grid connected 0.3MW solar Photo Voltaic System is represented in Figure 1. The irradiance and temperature values are given as inputs to Solar PV system. This output power is feed to boost converter designated to operate at 0.35MW to account for switching losses. The boost converter is controlled through Perturb and observe alogorithm control circuit to ensure maximum power productivity at all the time. This power at maximum power point shall be feed to VSI.The output of the VSI will be connected at point of common contact(PCC).Total Harmonic Distortion(THD) is measured using FFT analysis along with the study of voltage imbalance at Point of Common Contact(PCC),where 3 phase grid and modelled non linear load are also connected. The estimation of power factor is also done at PCC.

3 Design of the system under study

3.1 Irradiance and temperature specifications:

The 0.3MW grid tied PV system is feed with irradiance and temperature inputs as follows:

Table 1. Irradiance and temperature inputs to Solar PV system.

S.N	**Parameter**	**Initial Value**	**Minimum Value**	**Maximum Value**
1	Irradiance	1200W/m^2	1200W/m^2	1400W/m^2
2	Temperature	20.5°C	20.5°C	35.5°C

These parameters represented in Table 1encompassing irradiance and temperature, are pivotal to the investigation outlined in the study. It is noteworthy that the specified values for each parameter delineate the range and boundaries within which the simulation and analysis are conducted.

3.2 PV System specifications

The PV system parameteres are represented in Table 2:

Table 2. PV system parameters [16].

S.N	Parameter	Maximum Value
1	Single PV Cell Voltage(Voc)	0.6V
2	Single PV Cell Current(Isc)	2.5A
3	No.of cells connected in series per module	36
4	Single Module Voltage	36*0.6=21.6V
5	No.of module in series per array	22
6	Single array Voltage Voc	22*21.6.=475.2V
7	No.of module strings in parallel per array	250
8	Array Current Isc	250*2.5=625A
9	Array Maximum Power Pmpp	Voc*Isc=0.297MW

3.3 Boost Converter design and specifications

The configuration of boost converter is represented in Figure.2.V_L represents the output voltage of the PV system as an input to the boost converter.V_H represents the output voltage of boost converter which acts as an input to the voltage source inverter.

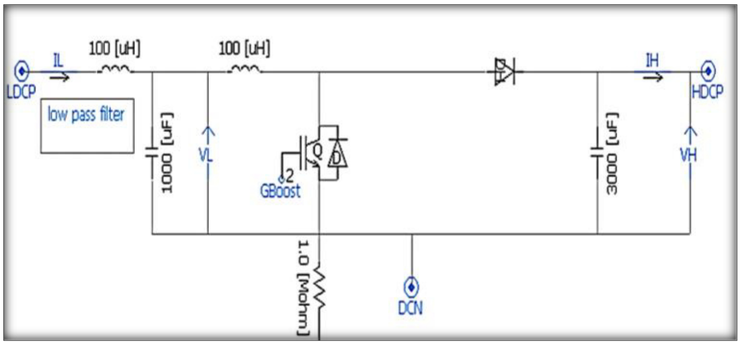

Figure 2. Configuration of boost converter.

A low pass filter is implemented by connecting an inductor at the input of the converter. Furthermore, energy storage is facilitated through shunt-connected capacitors, with a capacity of 1000µF at the input and 3000µF at the output. To control the ON and OFF switching of current flow, an IGBT (Insulated Gate Bipolar Transistor) is employed in conjunction with a grounding resistor. The system is characterized by specific operating parameters: a Pref (preferred) value set at 0.3MW, representing the desired power level, and a Plimit, indicating the rated Maximum Power Point Tracking (MPPT) power, configured at 0.35MW. These parameter settings establish operational thresholds, ensuring effective control over power flow within the system. It is essential to underscore that the incorporation of the inductor, capacitors, IGBT, and associated components collectively contributes to the efficient functioning of the converter. This integration allows for energy storage, effective filtration, and controlled switching, aligning with the specified power preferences and limitations.

Converter Specifications:

Inductor (L):	100µH
Capacitor (Cin)	1000 µF
Capacitor (Cout)	3000 µF
Switching Device	IGBT
Switching Control	Grounding resistor
Rated Power (Plimit)	0.35MW
Reference Power (Pref)	0.3MW
Converter Type	Boost Converter

Converter Design methodology:

1. **Calculate Switching Frequency (fsw):** Choose a switching frequency based on the application. A common starting point is 10 kHz.
2. **Duty Cycle (D):** Calculate the duty cycle using the formula:$D=1-(Vout/Vin)$
3. **Select Switching Components:** Choose IGBT and diode components capable of handling the calculated duty cycle, switching frequency, and power requirements.
4. **Input Filter Design:** The input inductor (L) acts as a low pass filter. Its value should be chosen to provide sufficient filtering. The cutoff frequency is given by $fc=1/2\pi\sqrt{LC}1$
5. **Energy Storage Capacitors:** Choose input and output capacitors based on the voltage and energy storage requirements. Ensure they can handle the maximum input and output voltages.
6. **IGBT Control:** Implement a control strategy for the IGBT. This may involve PWM control scheme. The grounding resistor helps in controlling the ON and OFF states.
7. **Protection Circuitry:** Implement protection mechanisms such as overvoltage protection, overcurrent protection, and thermal protection to ensure the reliability and safety of the converter.
8. **System Efficiency:** Optimize the converter design for efficiency, taking into account losses in the components and control circuitry.
9. **Testing and Simulation:** Simulate the design using appropriate simulation tools to ensure its functionality and performance meet the specifications.

3.4 MPPT-Perturb and Observe algorithm

Figure. 3 represents block diagram representation of MPPT-Perturb and Observe algorithm. Vpv(Solar PV Voltage and Ipv(Solar PV Current) are given as reference to the MPPT block.The Perturb and Observe MPPT block generates

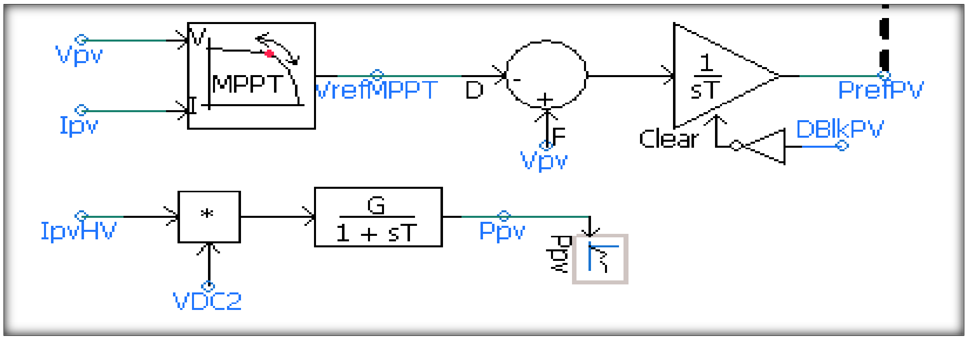

Figure. 3. Block diagram representation of MPPT-Perturb and Observe algorithm.

VrefMPPT which is compared with Vpv using a comparator.In case of mismatch, the transfer function 1/sT takes corrective action to generate PrefPV which is feed to 0.3MW boost converter to regulate power output.
The Perturb and Observe (P&O) algorithm is a popular MPPT technique used in photovoltaic (PV) systems to optimize the operation of solar panels and extract the maximum power from them. Here's a brief description of the P&O algorithm and a simplified flowchart:

Perturb and Observe (P&O) Algorithm:

1. Initialization:Set an initial operating point (voltage or current) for the PV system.
2. Perturbation: Increase or decrease the operating point (voltage or current) by a small step size.
3. Power Measurement:Measure the power output of the PV system at the perturbed point.
4. Comparison:
    - Compare the power at the perturbed point with the power at the previous operating point.
    - If the power has increased, continue perturbing in the same direction.
    - If the power has decreased, change the perturbation direction (reverse the direction).
5. Update Operating Point:Update the operating point based on the perturbation direction determined in the previous step.
6. Iteration:Repeat steps 2-5 until the maximum power point is reached or a stopping criterion is met

Flow chart of MPPT-Perturb and Observe algorithm:

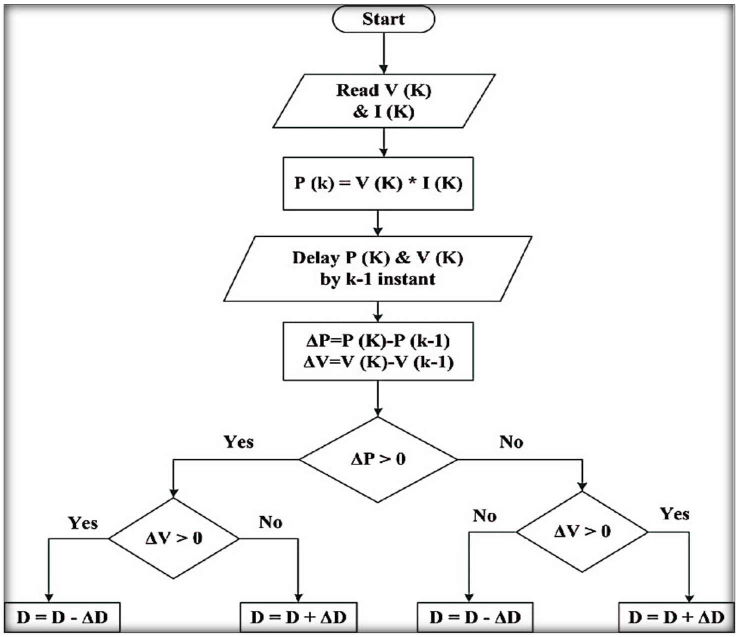

Figure 4. Flowchart of MPPT-Perturb and Observe algorithm.

3.5 Inverter specifications

The system configuration involves VSI connected at the output of the boost converter. The boost converter generates an output DC voltage, denoted as Vdc, which is then supplied to a three-phase inverter. Three-phase inverter plays the crucial role of converting the DC voltage into three-phase AC power.The inverter comprises six IGBT switches, each activated by firing control signals GG1, GG2, GG3, GG4, GG5, and GG6 respectively. These control signals are responsible for regulating the switching of the IGBT switches, allowing precise control over the conversion of DC power to AC power.To mitigate high-order harmonics and enhance the quality of the generated AC power, an LCL filter is incorporated into the system. The primary function of the LCL filter is to attenuate high-frequency components and suppress harmonics, ensuring a cleaner and more sinusoidal output waveform. This contributes to improved power quality and reduces the potential for interference and distortion in the electrical system. In summary, the integration of a voltage source inverter, boost converter, three-phase inverter, and an LCL filter collectively forms a system designed to efficiently convert DC voltage to three-phase AC power while addressing high-order harmonics for enhanced power quality.

3.6 Load Modelling

Block diagram representation of the controlled load modelling is shown in Figure.5. The determination of load resistance, inductance, and capacitance is established through an assessment grounded in the active and reactive power control delivered to the load. In this context, the estimation of these parameters is intricately linked to the precise management of both active power (real power) and reactive power supplied to the load.

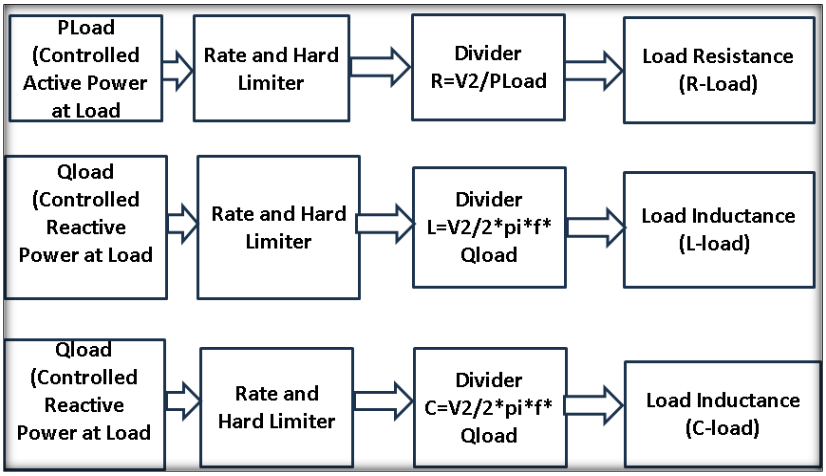

Figure 5. Block diagram representation of the controlled load modelling.

3.7 Three Phase grid specifications

Specifications of three phase AC grid are as follows:

Table 3. Three phase grid specifications.

S.N	Parameter	Value
1	Source Impedance	R-R_L Type
2	Base MVA	50MVA
3	Base Voltage(L-L RMS)	0.5Kv
4	Base frequency	50Hz
5	Postitive sequence impedance	0.25Ώ
6	Postitive sequence impedance phase angle	80°
7	Series resistance	1 Ώ
8	Parallel Resistance	1 Ώ
9	Parallel inductance	0.1H
10	Zero Sequence impedance	1 Ώ

4 Result analysis and Discussions

4.1 PV System performance Characteristics

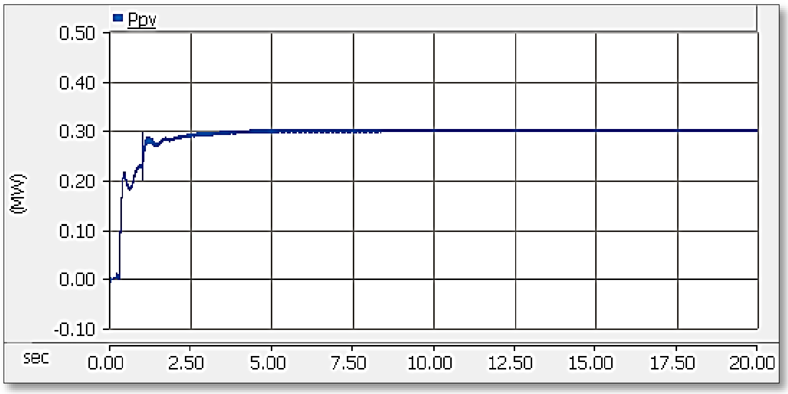

Figure 6. Power (P_{pv}) characteristics of Solar PV system.

As revealed in Figure 6, Photovoltaic Power (Ppv) rises gradually from 0MW and settles down at 0.3MW which is also the rated PV system capacity. In other words, the solar PV system is producing the rated designated power constantly. As represented in Figure 7, the PV system voltage is observed to be constant at around 0.6kV and as shown in Figure 7, the current produced by PV system initially undergoes transients and then settles at 500A

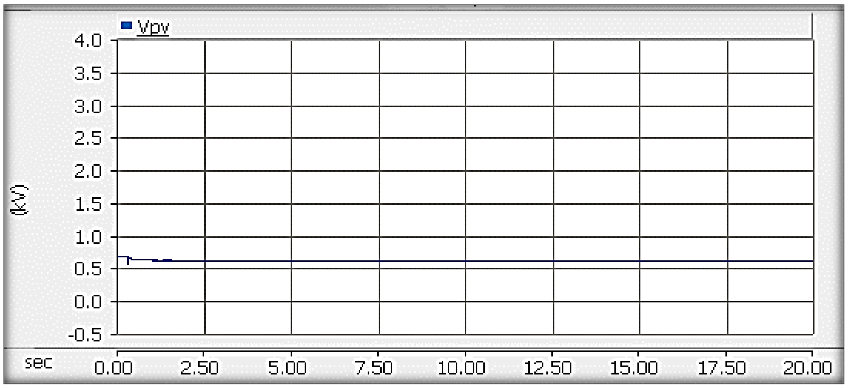

Figure 7. V_{pv} characteristics of Solar PV system.

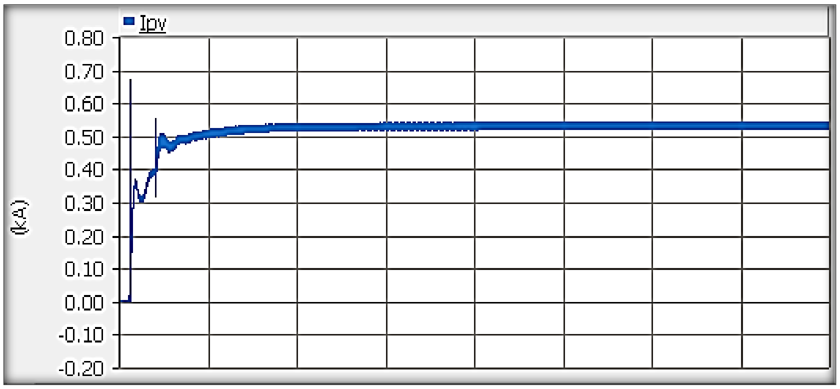

Figure 8. I_{pv} characteristics of Solar PV system.

4.2 Boost Converter control Charcteristics

The DC-DC boost converter has following characteristics:

1. Pref, Pdc and Plimversus time characteristics
2. V_L, V_H versus Time characteristics
3. I_{dclink}, I_L versus Time characteristics

Where,

1. P_{ref} is the reference power set at MPPT algorithm i.e., 0.3MW
2. P_{dc} is the actual power generated by PV System in turn feed to DC-DC boost converter i.e.,0.3MW
3. P_{lim} is the maximum power set limit of DC-DC boost converter
4. V_L -> boost converter input voltage
5. V_H -> boost converter output voltage
6. Idclink is the current delivered by DC-DC boost converter
7. I_L ->load current

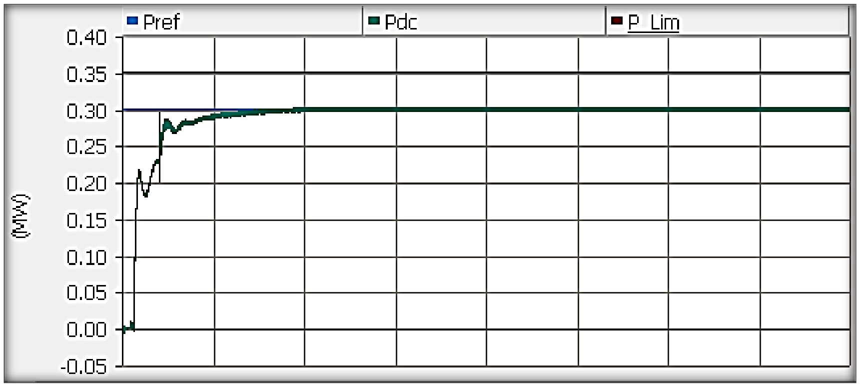

Figure 9. Power Characteristics of boost converter.

As represented in Figure 9, value of P_{dc} rises from 0MW and settles at 0. 3MW.The Pref and Plim are observed to be 0.30MW and 0.35MW respectively.

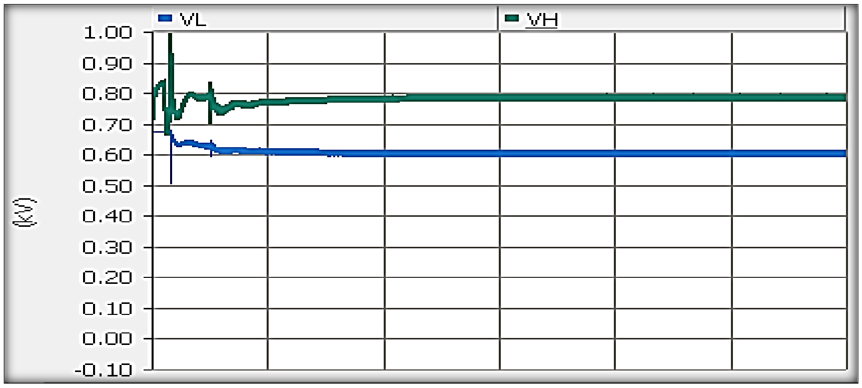

Figure 10. Voltage Characteristics of boost converter.

As represented in Figure 10, the input voltage (VL) to boost converter is observed to be 0.66KV and output voltage (VH) is observed to be 0.7KV.

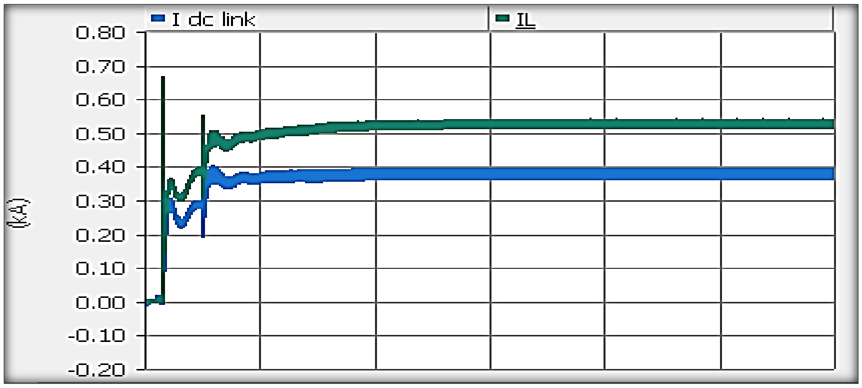

Figure 11. Current Characteristics of boost converter.

As represented in Figure 11, the actual current (dc link current) delivered by boost converter is 0.40KA and the load current IL is observed to be 0.50KA.

4.3 Control Charcteristics of Voltage source inverter(VSI)

VSI is used in grid tied PV applications because of the following reasons:

1. Capability to maintain improved power factor without use of capacitor bank
2. Turning off the switches naturally i.e., without use of forced commutation system

The Voltage Source converter has following characteristics:

1. Voltage Profile
2. Current Profile

Design of LCL Filter at the output of the inverter for harmonic mitigation would be important as the power will be feed to grid directly and presence of harmonics would create power quality issues at grid and load side.
Also, the FFT analysis would reveal order and magnitude of harmonics at the output of the inverter and would guide the pathway for design of LCL filter to mitigate the same.

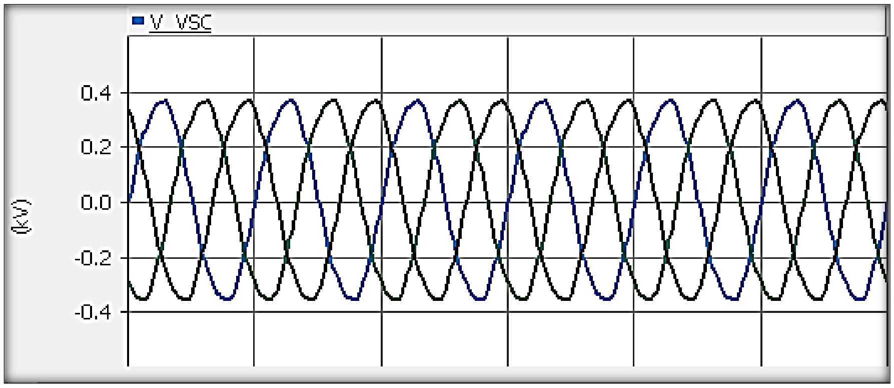

Figure 12. Voltage Profile of Voltage source inverter.

As represented in Figure 12, the output voltage of the inverter is revealed to be 400V.The voltage is slightly distorted and harmonic analysis would reveal the magnitude and order of the harmonics.

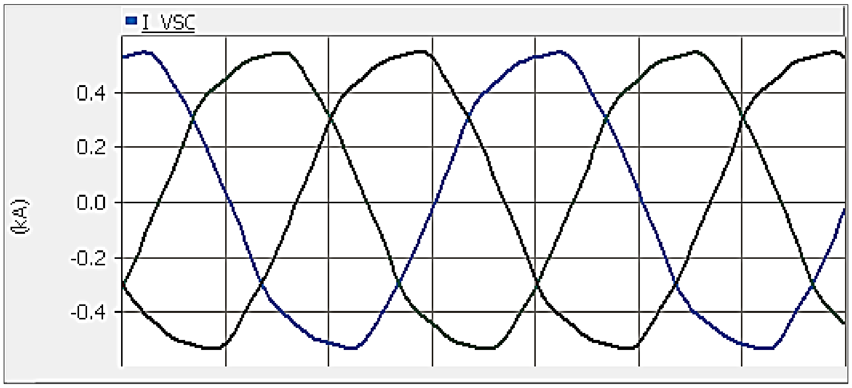

Figure 13. Current Profile of VSI.

As represented in Figure 13, Inverter output voltage is observed to be 500A.The current is slightly distorted and harmonic analysis would reveal the magnitude and order of the harmonics.

4.4 Grid voltage and current charcteristics

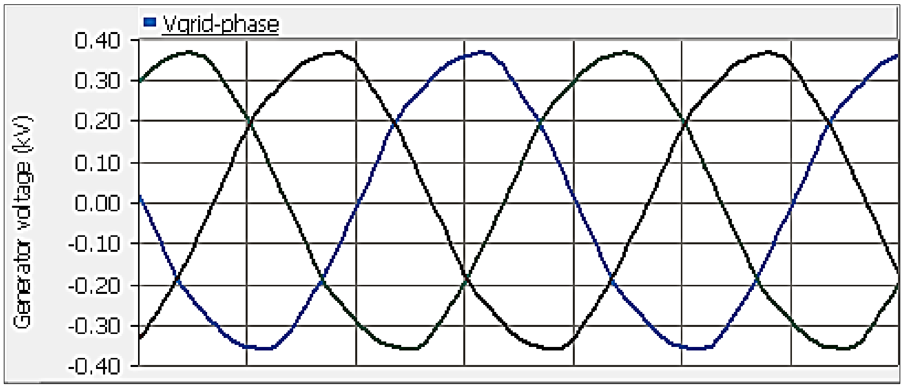

Figure 14. Grid Voltage Profile.

The grid voltage profile is represented in Figure 14, Voltage imbalance study is conducted for comprehensive analysis of the voltage unbalance problem. As seen from Figure 14, the voltage is slight imbalance i.e pure sinusoidal nature of the grid voltage is compromised. This non sinusoidal nature is mainly due to harmonics injected by voltage source converter wherein harmonic analysis would reveal the magnitude and order of the harmonics.

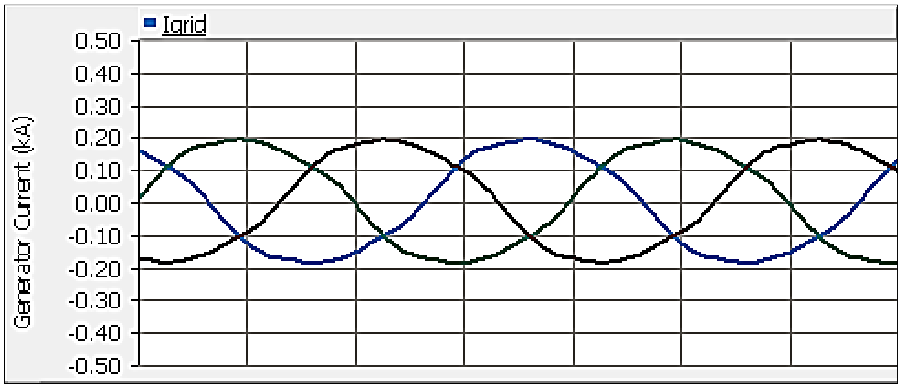

Figure 15. Grid Current Profile.

The grid current profile is represented in Figure 15. As represented in Figure 13, the current is slight imbalance i.e pure sinusoidal nature of the grid current is compromised. This non sinusoidal nature is mainly due to harmonics injected by voltage source converter wherein harmonic analysis would reveal the magnitude and order of the harmonics.

4.5 Power handling Charcteristics

The power handling characteristics mainly consists of following:

1. Active Power characteristics
2. Reactive Power characteristics

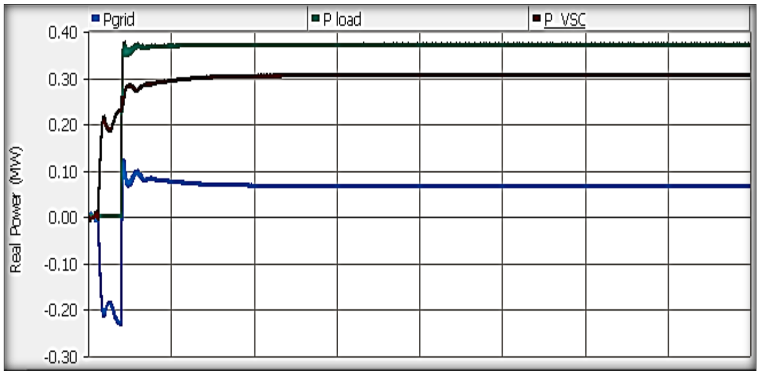

Figure 16. Active power characteristics.

As represented in Figure *16*, 0.36MW is active power delivered to the load, out of which 0.30MW is supplied by Voltage source inverter in turn by PV panel and DC-DC boost converter and 0.06MW by conventional generator i.e grid. reactive power consumed by the load is 0.12MVAr.

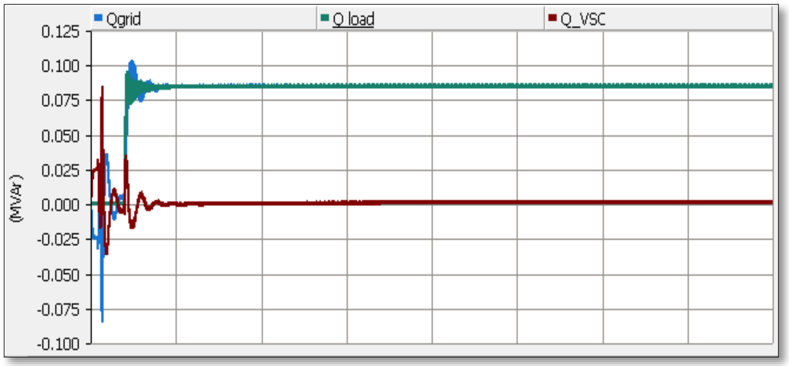

Figure 16. Reactive power characteristics.

4.6 Estimation of Load side frequency and power factor

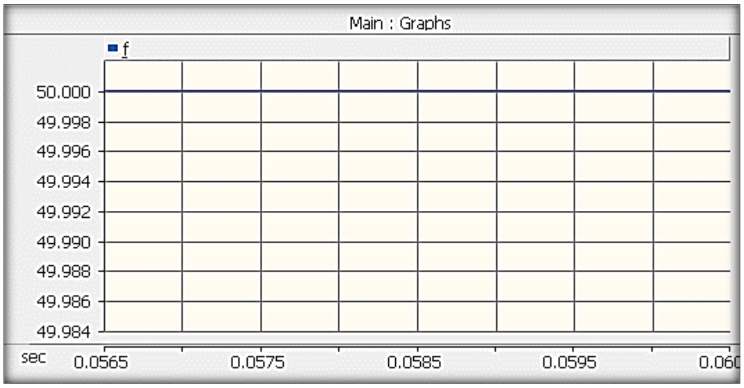

Figure 17. Frequency at load side.

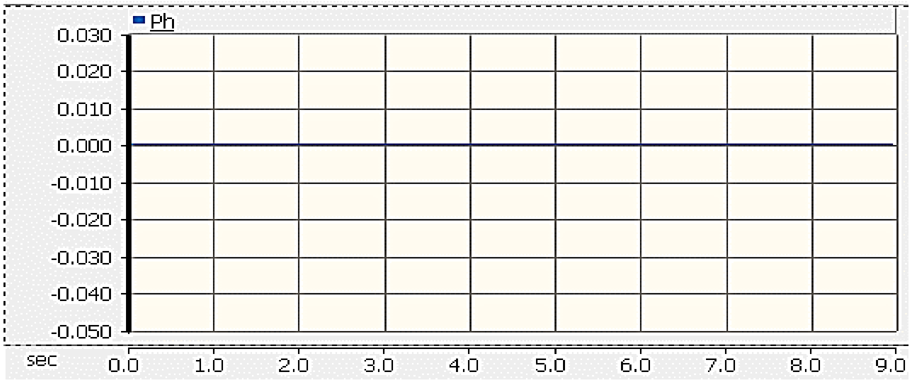

Figure 18. Phase difference at load side.

As shown in the Figure 17 and Figure 18, the load side frequency and phase difference are observed to be 50Hz and zero degree respectively. The phase difference of zero degree suggests unity power factor at load side which do not seem to be power quality problem. Thus, frequency and power factor at load side are observed to be satisfactory.

4.7 THD analysis

Inverter voltage and current THD estimation is carried out using FFT analysis in PSCAD.

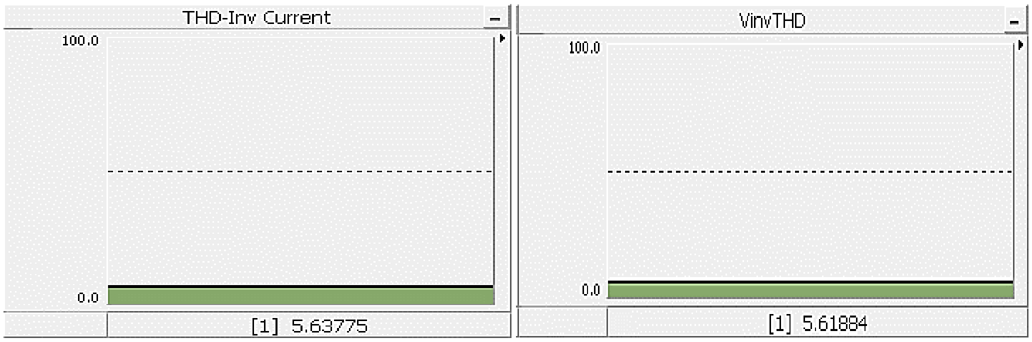

Figure 19. Total harmonic distortion at the output voltage and current of the inverter.

As represented in Figure 19, the values of Total harmonic distortion at Inverter current and voltage are found to be 5.63775% and 5.61884% respectively. The permissible range of the THD in typical power system is 4%. Adequate filter design and reactive power compensation strategy needs to be adopted to maintain THD below 4%.

4.8 Mitigation of Total harmonic distortion in inverter voltage and current

Static Var compensator is connected at the point of common coupling as a mitigation strategy to improve current and voltage THD.Static Var compensator (SVC) is used for shunt reactive compensation which helps to maintain bus voltage magnitude and regulates bus voltage and manage reactive power loading. Static Var compensator is found to reduce THD in inverter current and voltage to 5.11% and 3.15% respectively

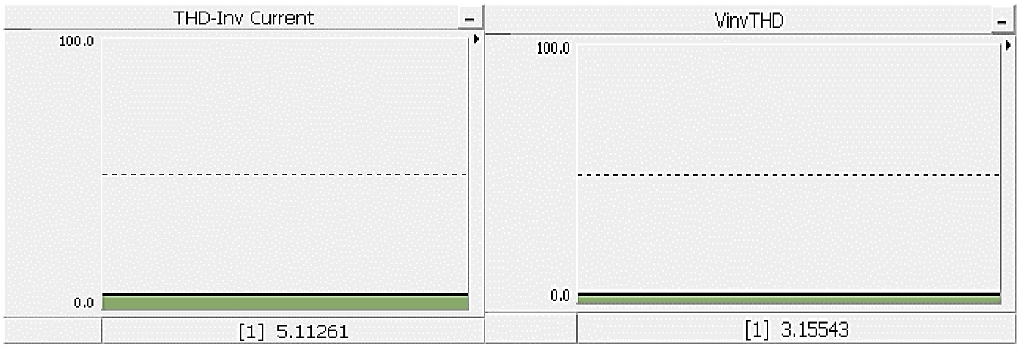

Figure 20. THD at the output voltage and current of the inverter after connection of SVC.

5 Conclusion

In conclusion, the thorough examination of PQ issues within the grid-connected solar PV system has proven pivotal in ensuring the system's effective operation without introducing disruptions to the electrical grid. Acknowledging the potential ramifications of power quality issues on both the solar PV system's performance and interconnected electrical equipment, the study emphasized a comprehensive design, encompassing a PV system with boost converter, inverter, grid connection, and controlled load specifications. The simulation results confirm the consistent generation of the designated power levels by the PV system under irradiance conditions ranging from 1200W/m^2 to 1400W/m^2 and temperatures between 20.5°C and 35.5°C. However, a critical observation highlights distortions in the inverter's voltage and currents, featuring non-pure sinusoidal waveforms, with Total Harmonic Distortion (THD) values measuring 5.63775% and 5.61884%, respectively. In response to these identified PQ issues, the proposed mitigation strategy involves incorporating a Static Var Compensator. This strategic intervention has resulted in significant improvements, notably reducing the THD at the inverter's output. Specifically, the THD values for inverter current and voltage have been successfully lowered to 5.11% and 3.15%, respectively. This outcome not only underscores the effectiveness of the mitigation strategy in addressing the identified power quality issues but also emphasizes its role in enhancing the overall performance and reliability of the solar PV system. The seamless connection between the study's specific results and the proposed mitigation strategy underscores the significance of such interventions in achieving optimal PQ in grid-connected solar PV systems.

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