Power Quality Improvement of Grid Using STATCOM Based PV System

Bharat Singh Chauhan [1], Vishal Nagar [2], Priyanka Jangid [3]
[1, 2, 3] Department of Electrical Engineering, Rajasthan Technical University, Kota, Rajasthan, India 324010
Email: [1] Bharatsinghchauhan021@gmail.com, [2] Vishalnagar3005@gmail.com, [3] Priyankajangid2702@gmail.com

***Abstract*—— Most of the three-phase systems are designed for a balanced condition. but normally, under operating conditions, three-phase system always has a certain amount of voltage imbalance. Due to the imbalance of voltage, the distribution system is affected. This affects the stability, reliability, power quality, and efficiency of the distribution system. To prevent this problem and improve power quality, this paper presents a simulation study of grid-connected PV with D-STATCOM. For that grid connected with D-STACOM modal has been created in MATLAB software. Investigation has been carried out at different loading conditions with different penetration level. D-STACOM serve as the grid connected converter to achieve power coordination, voltage stabilization and power quality enhancement. According to the voltage imbalance, PV penetration increased until the system reached into balance condition. The two types of control strategies of VSC(STATCOM) first is inner control strategy and another outer control strategy are used.**

Keywords— power quality, Grid connected PV, D-STATCOM, distribution system, Reactive power.

I. INTRODUCTION

Many nations are currently working to integrate renewable energy sources into their current electrical grids due to factors like rising electricity demand, a lack of high transmission and distribution losses, reliability issues, fossil fuels, and more. An attempt has been made by the Indian government to compile global energy statistics as well as India's energy framework. This essay examines some International Energy Agency (IEA) policies that support the development of sustainable energy using renewable resources [1]. Distributed generation, which provides electricity close to residential or commercial users, reduces transmission and distribution costs. Solar photovoltaic (PV) systems, among other micro-sources, are gaining rapid adoption due to their ability to provide sufficient DC voltage and their decreasing capital costs. A 7 kW PV plant has been analyzed and designed for in-depth study [2]. DC sources can be converted using different methods, such as buck-boost converters, depending on demand. Several topologies, including ultra-boost converters [3] and multilevel converters [4], are now available to meet growing power needs. A detailed performance analysis of a DC-DC boost converter using a Proportional-Integral-Derivative (PID) controller has also been conducted [5]. In addition, there are several PV System distributed all over the world, mostly in Europe, with 1.4 million system in Germany alone as well as North America with 440000 systems in the united state. These systems currently contribute about 1% to worldwide electricity generation. The main reason behind that is huge resource availability, small operating cost and operational flexibility. Solar panels are also soundless, clean and they can be located on vacant spaces like rooftops of building also. [6]. On the other hand, a significant growth in the use of non-linear loads in the distribution system has led to various problems of power quality, including high reactive power burden, load imbalance, & so on. This issues attract researchers to carry out the research work with this problem. The specialised power devices frequently used to improve these power quality concerns are distributed static compensators. [7]. In addition to distributed generation, Load frequency control (LFC) is essential for keeping the grid stable, especially with renewable energy sources. STATCOM (Static Synchronous Compensator) helps manage voltage and frequency shifts. The Firefly Algorithm can fine-tune how STATCOM operates, reducing frequency changes and improving performance, ensuring the grid stays reliable even with varying power demands [8]. The traditional reactive power compensation approach, which increases the additional investment in power equipment, uses reactive power compensation devices, including as SVC, SVG, and STATCOM, to correct the reactive power in order to improve the voltage stability of the grid terminals. with the findings of research, the main structure of a photovoltaic inverter & D-STATCOM is completely consistent, as a result photovoltaic power generation system can be equipped to supply reactive power through the distribution network of terminals, Voltage source converter (VSC) development for grid photovoltaics is therefore essential. [9] Employs D-STATCOM to enhance voltage control, hence boosting power system stability, and to solve the issue of voltage & frequency mismatches in the low voltage distribution network. The result of the simulation demonstrate that D-STATCOM helps to ensure system stability and power system performance. With a large penetration of photovoltaic systems, the D-STATCOM possesses the means to enforce adherence to rules and avoid violations of network operational restrictions [10].

This study presents a grid-connected PV modeling system that makes use of D-STATCOM. It displays the PV array's I-V & P-V characteristics and offers an overall system diagram. It also looks at DSTATCOM's setup and functioning. D-

Received: 26-09-2024
Revised: 30-12-2024
Published: 31-12-2024

STATCOM is used as the grid-connected converter to coordinate electricity, maintain voltage, and enhance power quality, first simulated a distribution system and determined that there was voltage and current unbalance in the distribution system, and losses were very high [11]. To balance the system, PV with D-STATCOM penetrated to the distribution system. The system's current and voltage were balanced, and losses were also reduced. In this paper, the fundamental control strategy is the dual-close-loop control strategy. Through the separation of active power & reactive power, the inner loop control algorithm is employed to track active power current and reactive power independently. Grid-connected voltage & DC link voltage are managed by the outer loop in the meantime. The simulation results showed that the suggested control technique was effective [12].

II. SYSTEM CONFIGURATION

The main components of the system are a solar photovoltaic array, DC link capacitor, a three phase VSC(D-STATCOM), AC filter, a three phase transformer, and a three phase linear load connected at the distribution end. A schematic diagram of a grid-connected photovoltaic (PV) solar system is shown in Fig. 1.

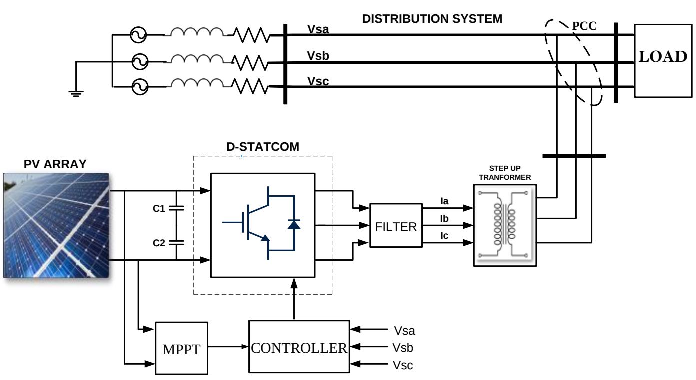

Fig. 1. Basic diagram of grid connected PV system with D-STATCOM

The solar power system are connected to the electrical grid at a point is PCC. The electrical grid is an interconnected electrical network that transports power from suppliers to customers. A solar PV system, MPPT with boost converter, and three-phase voltage source converter (STATCOM) are the main components of the system. [13]. A voltage source inverter, often known as a VSC, is a converter that changes a voltage from DC to AC. An IGBT H- bridge (VSC) act as STATCOM are connected between the harmonics filter and the DC bus capacitor in this system. To preserve the output AC power's power quality, an ac filter is employed. The PV system's output voltage is connected to the distribution system by a step-up transformer [14]. The proposed PV power generating system is controlled by the SRFT (Synchronous Reference Frame Theory). [15]. Its three-phase VSC also balances linear and nonlinear loads, makes adjustments for harmonic currents, and reduces reactive power. The solar photovoltaic system configuration and parameters are explained below.

A. *Solar Power Panel*

The solar-generating system used consists of several interconnected modules forming an array. Generally, PV generation is based on the direct conversion of solar energy into electrical energy, known as the photovoltaic effect. Most of this conversion is carried out by the fundamental components of a photovoltaic solar cell [16]. The simplified electrical circuit of a photovoltaic solar panel is shown in Fig.

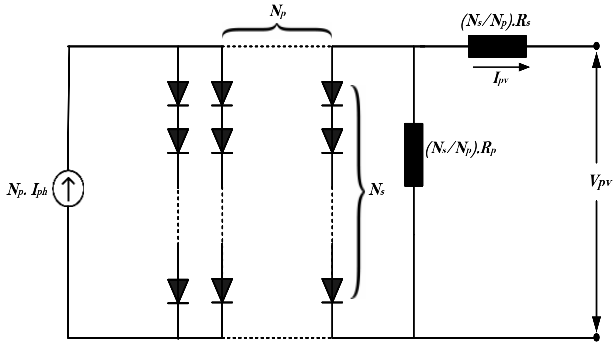

Fig. 2. Equivalent circuit diagram of solar cell

Using Kirchhoff's fundamental laws on the given circuit, the PV panel output current can be calculated mathematically as follows:

$$I_{pv} = N_p I_{ph} - N_p I_{rs}\left[\exp\left(\frac{q}{K_b.T_o.A}\right)\left(\frac{V_{pv}}{N_s}\right) -1\right] \qquad (1)$$

Where

I_{pv} = output photovoltaic current;
V_{pv} = Output Photovoltaic Voltage;
I_{ph} = Photo electric current;
I_{rs} = diode reverse saturation current;
K_B = Boltzmann constant;
q = elementary charge;
A = diode identify factor;
T_0 = cell's operating temperature;
T_s = cell's temperature under standard condition(298k);
N_P = Number of parallel connected cells;
N_s = Number of serial connected cells.

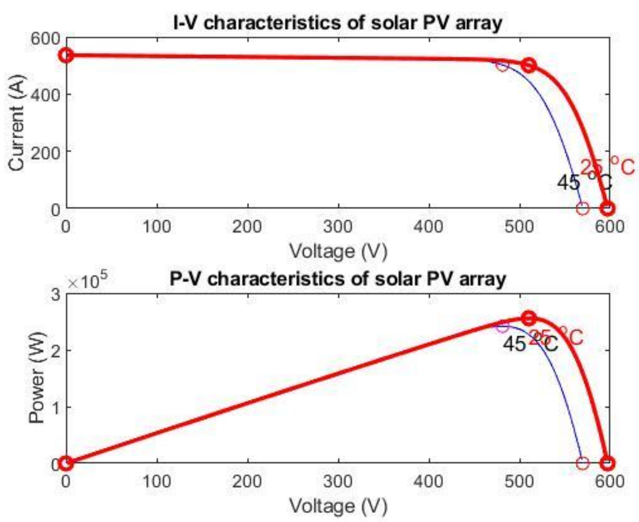

Fig-3: I-V AND P-V characteristics of PV array

In this paper PV array delivers a maximum of 250 kW at 1000w/m2 sun irradiance. The array is made up of seven strings of 88 series-connected modules that are linked in parallel to produce the right output voltage and current. As a result, one module can carry an open circuit voltage (V_{oc}) of 85.3 volts & a short circuit current (I_{sc}) of 6.09 amperes. hence the maximum current at maximum power point I_{mp} (A) and maximum voltage at maximum power point V_{mp} (V) of each module are 5.69A and 72.9V. [17] The I-V & P-V characteristics of solar cell are shown in fig. (3).

PV's inherent voltage of 272 volts DC at maximum power is raised to 500 volts by the boost converter. For this converter to supply the necessary voltage at maximum output power, an MPPT system is used, which automatically modifies the duty cycle [18-20].

B. *Principle of D-STATCOM*

Suppressing voltage sag by controlling bus voltage is the fundamental function of a D-STATCOM. As so, depending on the bus voltage, the DSTATCOM functions as either a capacitor or an inductor.

In essence, D-STATCOM is a specialized power device. It is employed in the distribution network to regulate power flow and enhance transient stability. The D-STATCOM is a specialized power device that is connected in series with the power system and is based on a voltage or current source inverter. D-STATCOM's primary duties include voltage regulation, harmonic current correction, reducing the magnitude of voltage sag, and flicker prevention. The connection of D-STATCOM to the distribution network is shown in Fig. 4.

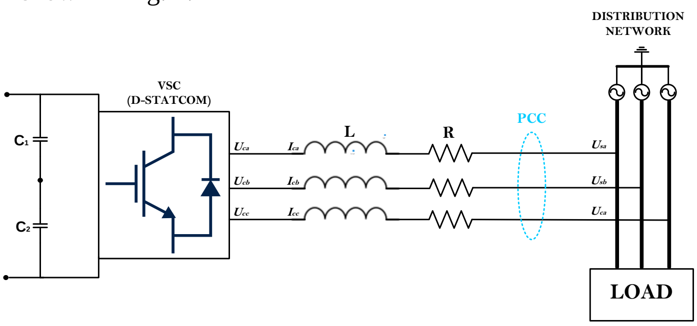

Fig 4: Basic circuit diagram of D-STATCOM

In this paper for VSC, a 6-armed H-bridge converter is used. It is also seen as a 3-level NPC (neutral point clamped) converter [21-22].

H-bridge VSC synthesizes voltages voltages u_{ca}, u_{cb}, and u_{cc} from DC voltage using forced-commutated power electronic devices (GTO, IGBT, or MOSFET). The three-phase system voltage is represented by U_{dc}. u_{sa}, u_{sb}, and u_{sc}, and the three-phase voltage produced by the H-bridge VSC is represented by u_{ca}, u_{sb}, and u_{sc}.

As per Fig. 1, the voltage equation appears as follows:

$$\begin{bmatrix} u_{ca} \\ u_{cb} \\ u_{cc} \end{bmatrix} - \begin{bmatrix} u_{sa} \\ u_{sb} \\ u_{sc} \end{bmatrix} = L\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + R\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \text{.......... (2)}$$

The d-q components of 3-phase voltage & current can be obtained by Park transformation. then, Equation (2) is transformed using the dq coordinate system as shown below.

$$L\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} R & -\omega L \\ \omega L & R \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} u_{cd} & u_{sd} \\ u_{cq} & u_{sq} \end{bmatrix} \text{.... (3)}$$

Active and reactive power control strategies can be suggested based on equation (3). The detail control strategy is discussed at part C.

C. *Solar Three Phase Distribution Grid under Unbalanced Condition*

The model has performed as predicted under balanced conditions, but in fact, most distribution networks have a degree of imbalance. Before penetration of PV, At the point of common coupling, the voltage for each phase was different. According to the IEEE standard (IEEE 1159) [23-24], an imbalance of more than 2% is considered to be at a high degree of imbalance, and the network typically needs corrective assessment. Before penetration of PV, The voltage & current imbalance of grid are shown in fig. (5). Due the imbalance of current and voltage system work with high losses. The system losses are shown in fig (6)

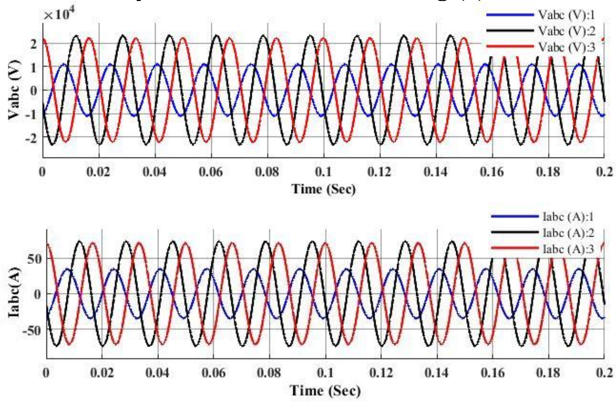

Fig. 5. Voltage and current imbalance of grid

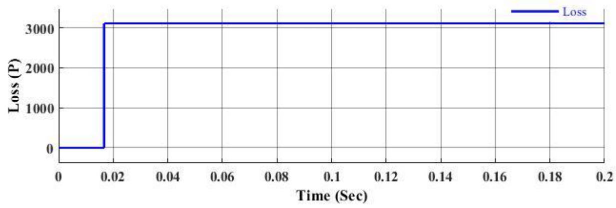

Fig. 6. system losses before PV penetration

III. PROPOSED CONTROL STRATEGY

VSC controlled strategy of VSC controller shown in fig. 7.

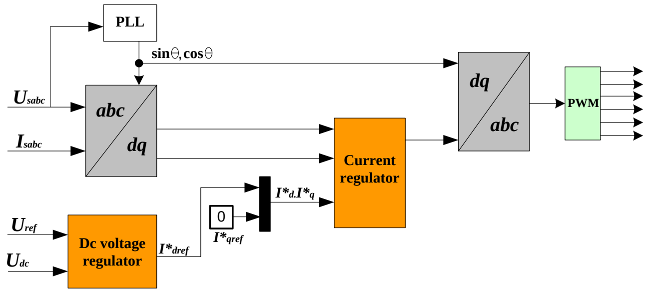

Fig. 7. VSC (D- STATCOM) control strategy

As previously indicated, the VSC controller requires voltage & current data on the PCC (U_{sabc} & I_{sabc}), current data for local loads ($I_{loadabc}$), & DC link voltage data of the VSC (U_{dc}). In the VSC controller, there are two control loops: an internal AC current control loop & an external DC voltage control loop. The outer loop controls the DC link voltage to a reference value (U_{ref}), while the inner loop controls the AC current to a reference value (I^*_d, I^*_q). therefore, simulation results will show that this is useful to decrease THD (Total Harmonic Distortion) of output current.

A. *DC link voltage control*

For DC link voltage control comparing the reference DC voltage U_{dref} with the actual DC voltage U_{dc}, through the PI regulator, the output is active power reference current I_{dref} , Reactive power reference Current I_{qref} is typically set to zero, indicating that the system can keep the maximum power factor. I_q ref is adjusted from the grid-connected point via an AC voltage regulator, taking into account decreasing output current harmonics.

B. *Algorithm for regulating current*

Fig. 8. shows the active and reactive current control diagram.

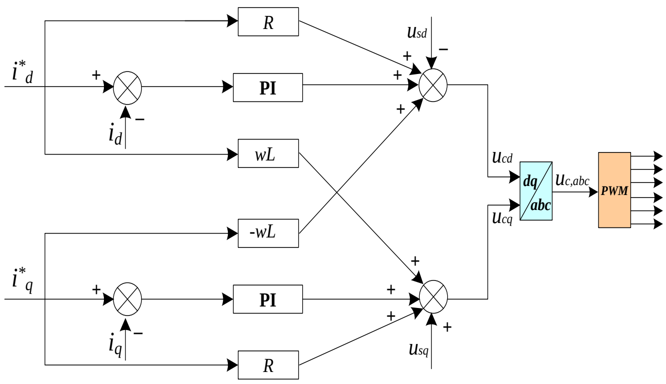

Fig. 8. Current control strategy

In this strategy, if VSC (d-STATCOM) performs local load reactive power compensation, I_d and I_q should contain current data information from local loads. Otherwise, the PCC voltage won't be stable. This is the major reason for the VSC controller acquiring local load current. on the other hand, local loads current acquisition is flexible. Only the local areas where current data may be easily acquired are compensated for reactive power by VSC (d-STATCOM). The grid or other local reactive power compensation devices will make up the difference for others. This fully complies with the power compensation principle.

IV. SIMULATION RESULT

The operation of the proposed PV system with D-STATCOM for power quality improvement was verified using MATLAB/Simulink software.

The control process started by measuring system voltage and current at the point common coupling, and also losses to calculate unbalance condition of system voltage and current. The main task of simulation is to evaluate the performance of proposed control strategy to control system unbalance to balance condition and decrease the system losses.

The total simulation time taken is 0.2 sec. The simulation result shows the after PV penetration system balance condition. At the point of PCC, the decreased imbalance voltage of the system after 100 kW penetrate PV with D-SATACOM are shown in Fig. (9). Similarly, the decreased imbalanced current of the system are shown in Fig. (10). In Fig.(9)&(10), the curves of output 3-phase AC voltage & current are less smooth and not in same phase. And it just shows the curves from 0 to 0.2s. System losses after penetration of the 100 kW PV system are decreased, as shown in fig. (11). But this result are not fulfilled the condition of balanced system, so that to balanced the system PV penetration increased and analysis the result.

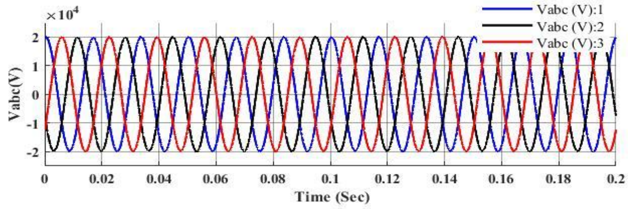

Fig. 9. Decreased imbalance voltage after 100 kW PV penetration

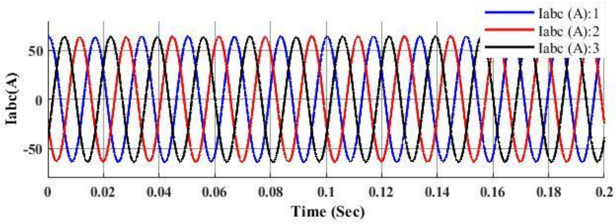

Fig. 10. Decreased imbalance current after 100 kW PV penetration

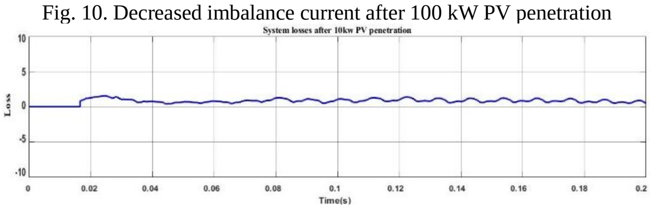

Fig. 11. Decreased losses of system after 100 kW PV penetration

After penetration of a 250 kW PV system, the simulation results are shown below. The balance voltage of the system after a 250 kW penetration of PV with D-SATACOM are shown in Fig. (12). Similarly, the balanced currents of the system are shown in fig. (13). In Fig.(12)&(13), the curves of the output 3-phase AC voltage & current are very smooth. And it just shows the curves from 0 to 0.2s. Actually, they are smooth in all static processes. System losses after penetration of the 250 kW PV system are decreased, as shown in fig. (14).

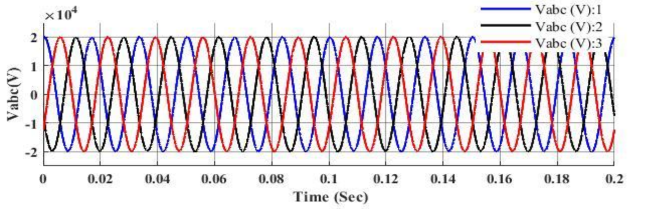

Fig. 12. Balanced voltage after 250 kW PV penetration

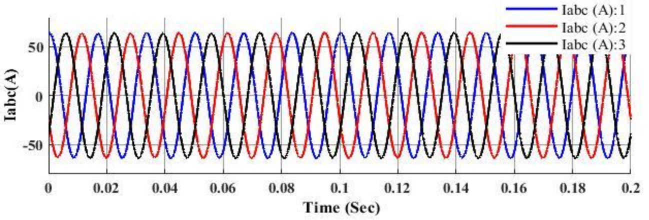

Fig. 13. Balanced current after 250 kW PV penetration

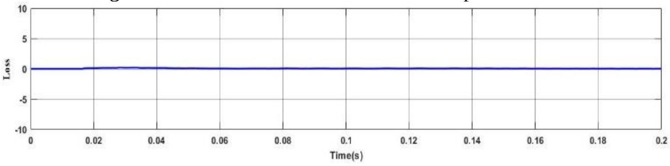

Fig. 14. System losses after 250 kW PV penetration

Figs. 15 and 16 display the output three-phase AC voltage and current from the FFT analysis:

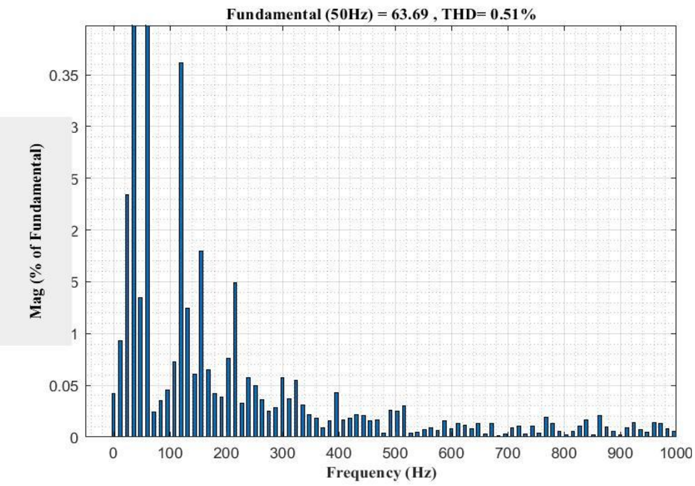

Fig.15. FFT analysis results of output three-phase AC voltage

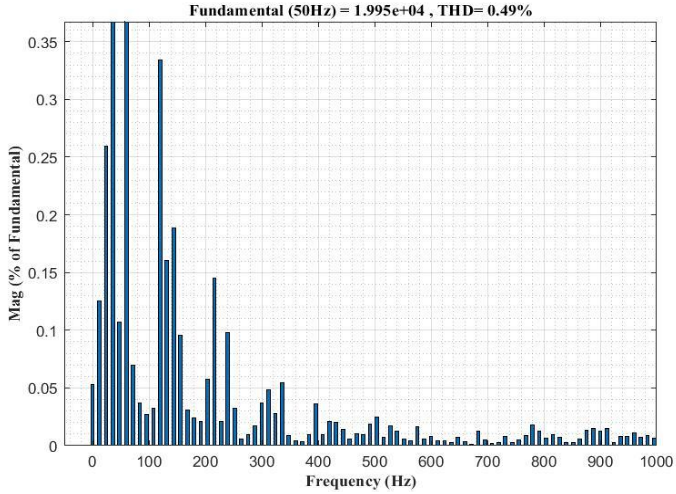

Fig. 16. FFT analysis results of output three-phase AC current

In Figures (15) & (16), the start time is 0.1s and the number of cycles is 4. This is a typical choice of period since the lower output power, the higher the THD in the voltage & current. THD in output voltage is 0.51% and in current is 0.49%. These results satisfy the grid-connected standard. It demonstrates that control strategy of D-STATCOM is effective.

V. CONCLUTION

Grid-connected PV systems will grow in popularity in the future. This work examines the role of D-STATCOM control on the proposed three-phase cascaded H-bridge inverter configuration's operation. In the proposed work, a different concept of the utilization of a PV solar farm as a STATCOM for a weak grid to control the voltage and current fluctuation has been proposed and Results are confirmed using the MATLAB/Simulink software. Moreover, it includes the fluctuation in PCC power output. Regulation in this situation may be able to reduce weak grid problems at the distributed end more significantly. The control strategy is used to enhance the system's performance and power quality. A control strategy for an imbalanced system to improve the power quality and balance the system are proposed. According to the simulation results, a grid-connected PV system with D-STACOM can maintain system voltage and current while reducing system losses and enhancing power quality. This effort is willing to contribute to the evolution of renewable energy power generation and smart grid technology.

REFERENCES

[1] Jayaswal, Kuldeep, D. K. Palwalia, and Aditya Sharma. "Renewable Energy in India and World for Sustainable Development." Power Electronics for Green Energy Conversion (2022): 67-89.

[2] B. S. Chauhan, V. Nagar and A. Bhargava, "Evaluating Solar Power Generation: A 7 kW Photovoltaic System Performance Analysis with PVsyst Simulation," 2023 First International Conference on Advances in Electrical, Electronics and Computational Intelligence (ICAEECI), Tiruchengode, India, 2023, pp. 1-6, doi: 10.1109/ICAEECI58247.2023.10370799.

[3] Jayaswal, Kuldeep, D. K. Palwalia, and Josep M. Guerrero. "A Comprehensive Performance Analysis of a 48-Watt Transformerless DC-DC Boost Converter Using a Proportional–Integral–Derivative Controller with Special Attention to Inductor Design and Components Reliability." Technologies 12.2 (2024): 18.

[4] V. Nagar, K. Jayaswal, P. Chaturvedi, A. Sharma and D. K. Palwalia, "Design and Analysis of High Gain DC-DC Converters for PV Application," 2023 IEEE 11th Region 10 Humanitarian Technology Conference (R10-HTC), Rajkot, India, 2023, pp. 538-543, doi: 10.1109/R10-HTC57504.2023.10461907.

[5] V. Nagar and D. K. Palwalia, "Design and Analysis of Multi-Level Converters in Real-Time Using OPAL-RT Simulators," 2023 International Conference on Electrical, Electronics, Communication and Computers (ELEXCOM), Roorkee, India, 2023, pp. 1-6, doi: 10.1109/ELEXCOM58812.2023.10370726.

[6] E. Roman, R. Alonso, P. Ibanez, S. Elorduizapatarietxe and D. Goitia, "Intelligent PV Module for Grid-Connected PV Systems," in IEEE Transactions on Industrial Electronics, vol. 53, no. 4, pp. 1066-1073, June 2006.

[7] C. Kumar and M. K. Mishra, "An Improved Hybrid DSTATCOM Topology to Compensate Reactive and Nonlinear Loads," in IEEE Transactions on Industrial Electronics, vol. 61, no. 12, pp. 6517-6527, Dec. 2014.

[8] D. K. Sambariya, P. Jangid and S. Sambariya, "Optimal design of Load Frequency Controller for a Single Area System using Fire Fly Algorithm," 2023 IEEE Renewable Energy and Sustainable E-Mobility Conference (RESEM), Bhopal, India, 2023, pp. 1-6, doi: 10.1109/RESEM57584.2023.10236160.

[9] Hui Li, Yaomei Huang and Junwei Lu, "Reactive power compensation and DC link voltage control using Fuzzy-PI on grid-connected PV system with d-STATCOM," 2016 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC), Xi'an, China, 2016, pp. 1240-1244.

[10] T. -L. Lee, S. -H. Hu and Y. -H. Chan, "Design of D-STATCOM for voltage regulation in Microgrids," 2010 IEEE Energy Conversion Congress and Exposition, Atlanta, GA, USA, 2010, pp. 3456-3463.

[11] Li, Hui, et al. "Modeling, control and simulation of grid-connected PV system with D-STATCOM." 2014 IEEE International Conference on System Science and Engineering (ICSSE). IEEE, 2014.

[12] H. Li, H. Zhang, F. Ma and W. Bao, "Modeling, control and simulation of grid-connected PV system with D-STATCOM," 2014 IEEE International Conference on System Science and Engineering (ICSSE), Shanghai, China, 2014, pp. 27-30.

[13] V. Patel and J. J. Patel, "Power quality improvement of grid using solar photovoltaic farm," 2017 Innovations in Power and Advanced Computing Technologies (i-PACT), Vellore, India, 2017, pp. 1-6.

[14] C. Dai and Y. Baghzouz, "On the voltage profile of distribution feeders with distributed generation," 2003 IEEE Power Engineering Society General Meeting (IEEE Cat. No.03CH37491), Toronto, ON, Canada, 2003, pp. 1136-1140 Vol. 2.

[15] B. Singh, K. Al-Haddad, and A. Chandra, "A new control approach to three-phase active filter for harmonics and reactive power compensation", IEEE Trans. Pow.Sys.,vol.13, no.1, pp.133–138, 1998.

[16] G.K. Singh, Solar power generation by PV (photovoltaic) technology: A review, Energy, Volume 53,2013,Pages 1-13,ISSN 0360-5442.

[17] Soto, W.D., 2002. SA Klein e WA Beckman, «Improvement and validation of a model for photovoltaic devices,». Renewable Energy, 247, pp.78-88.

[18] Yong Yang, Fang Ping Zhao, Adaptive Perturb and Observe MPPT Technique for Grid- Connected Photovoltaic Inverters, Procedia Engineering, Volume 23,2011,Pages 468-473,ISSN 1877-7058.

[19] V. Nagar, A. Sharma and D. K. Palwalia, "Analysis and Optimization of Interleaved Ultra-Boost Converters for Solar PV Applications," *2024 IEEE Third International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES)*, Delhi, India, 2024, pp. 172-176, doi: 10.1109/ICPEICES62430.2024.10719146.

[20] V. Nagar, A. Sharma and D. K. Palwalia, "Design and Analysis of DC-DC Buck Converter with Type III Compensator," *2024 IEEE Third International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES)*, Delhi, India, 2024, pp. 90-95, doi: 10.1109/ICPEICES62430.2024.10719237.

[21] Li, Hui, Yaomei Huang, and Junwei Lu. "Reactive power compensation and DC link voltage control using Fuzzy-PI on grid-connected PV system with d-STATCOM." 2016 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC). IEEE, 2016.

[22] A. Sharma, V. Nagar and D. K. Palwalia, "Analysis and Design of Artificial Neural Network Based Droop Control for Autonomous Hybrid Microgrid," *2024 IEEE Third International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES)*, Delhi, India, 2024, pp. 593-598, doi: 10.1109/ICPEICES62430.2024.10719091.

[23] Smith JC, Hensley G, Ray L. IEEE recommended practice for monitoring electric power quality. IEEE std. 1995:1159-995.

[24] Aditya Sharma and Dheeraj Kumar Palwalia, "Synergistic Application of Particle Swarm Optimization and Gravitational Search Algorithm for Solar PV Performance Improvement", Adv. technol. innov., vol. 9, no. 3, pp. 210–223, Jul. 2024.