

Research Article

Design of a Synchronous Reference Frame Controlled Fuzzy Logic Based Distribution Static Compensator to Enhance Distribution System Power Quality

Rekha Sampath¹, Lokesh Mallaiah², Ashwini A V¹, Sathish K R³, Mahesh M⁴ and Kavyashree S³

¹Electrical and Electronics Engineering, Sir M. Visvesvaraya Institute of Technology, Bengaluru, 562157, Karnataka, India

²Electrical and Electronics Engineering, Seshadripuram Institute of Technology, 571311, Karnataka, India

³Electrical and Electronics Engineering, ATME College of Engineering, Mysuru, 570028, Karnataka, India

⁴Electrical and Electronics Engineering, the National Institute of Engineering, Mysuru, 570008, Karnataka, India

Article history

Received: 13-02-2025

Revised: 03-05-2025

Accepted: 14-05-2025

Corresponding Author:

Lokesh Mallaiah

Electrical and Electronics

Engineering, Seshadripuram

Institute of Technology

571311, Karnataka, India

Email: drlokeshmallaiah@gmail.com

Abstract: The demand for enhanced power quality in distribution systems has increased due to the widespread utilization of various AC loads, including rectifiers, inductive loads, and variable speed drives. When these nonlinear loads are combined with renewable energy sources, harmonics are introduced in the system. These can affect the way other equipment in the network works and leave the system vulnerable to disturbances. Integrating DSTATCOM can address these power quality issues. The conventional PI controller is inadequate for addressing power quality challenges in dynamic power systems. This is due to its limited ability to handle nonlinear and time-varying dynamics, which are common in modern power systems. Consequently, the fuzzy logic controller-based DSTATCOM is engineered to address dynamic and multiple power quality issues. The efficacy of the suggested configuration against conventional PI regulators and assess its robustness and efficiency are evaluated. Through MATLAB simulation studies, the fuzzy logic controller-based DSTATCOM demonstrates superior performance in mitigating power quality issues by improving voltage profile, power flow, and power factor by compensating reactive power and reducing harmonic issues, and the results are compared to traditional PI controllers. This innovative solution offers improved stability and reliability in dynamic power systems, making it a promising alternative for enhancing overall system efficiency.

Keywords: Distributed Static Synchronous Compensator, Reactive Power Compensation, Power Quality Synchronous Reference Frame, Fuzzy Logic Controller, PI Controller, Solar Photovoltaic

Introduction

Motivation and Background

In contemporary society, there exists a substantial necessity to preserve electrical energy and improve its use across diverse uses. Conversely, there is an escalating necessity to investigate alternate energy sources to satisfy the swiftly rising demand. There is a growing awareness of the necessity for high-quality electricity to guarantee a productive and dependable energy supply. As a result, several efforts are underway to enhance electricity quality (Korhan and García Márquez, 2023). In the pursuit of an alternative energy source, Solar Photovoltaic (SPV) systems have

demonstrated significant potential in addressing these challenging difficulties. SPV systems are becoming acknowledged as a feasible substitute for conventional power generating techniques. The interconnection of SPV plant into the power grid has emerged as a vital focus of research, fostering an environmentally friendly and longer-lasting future (Reddy et al., 2018). The primary challenge of SPV integration is the necessity to uphold stability, dependability, and power quality. One effective solution to the problem is to utilize the latest power electronic equipment, namely the DSTATCOM.

When it comes to reactive power compensation, harmonic reduction, load unbalancing, voltage fluctuations, and current harmonics in the distribution network, the DSTATCOM works better than other

specialized power devices. The amalgamation of SPV systems with DSTATCOM enhances the advantages of both technologies, hence augmenting the overall efficacy of the grid (Kandpal et al., 2017; Ridzwan et al., 2022). Conversely, SPV systems provide several problems to the grid, requiring effective management to optimize the utilization of renewable energy resources and ensure uninterrupted grid operation. DSTATCOM enhances stability by providing reactive power to the system, compensating for voltage variations, and maintaining system voltage within prescribed limits in the presence of renewables (Naz et al., 2021). Irregularities in SPV systems result in PQ issues, such as harmonics, voltage sags, swells, and flicker, which can adversely affect sensitive equipment linked to the grid. Advanced control algorithms for DSTATCOM identify and alleviate PQ issues by injecting voltages and currents (Khadse and Beohar, 2024). Additionally, SPV systems refuse to operate at a unity power factor, which increases line losses and reduces system efficiency. Use of DSTATCOM compensates reactive power demand, improves power factor, which improves overall power transfer capability, reducing losses.

DSTATCOM possesses the capability to dynamically regulate and control reactive power flow while enhancing the usage of renewable energy sources. The SRF control methodology necessitates a PI controller to manage the voltage at the DC link. The PI controller requires accurate mathematical model parameters, which may be difficult to get (Nandagopal et al., 2023). The adoption of a fuzzy logic-based controller for DSTATCOM has garnered significant interest. The advantages of a fuzzy over a PI controller are its independence on precise mathematical representation values (Ghantimath and Vinayak, 2021).

Consequently, DSTATCOM based on SPV systems have the capability to mitigate the issues related to SPV integration. By using DSTATCOM's features, voltage can be controlled, PQ issues can be fixed, reactive power can be managed, and voltage flicker can be reduced. This ensures that adding SPV systems to the grid is safe and effective.

Related Work

A unique fitness function based on multiple objectives, dependent on specific various characteristic of performance of the system is presented (Saw et al., 2022). The metrics for performance encompass line losses, node voltage, the short circuit current level, and reliability of the system. Furthermore, the financial aspect of the system has been evaluated, including multiple expenditures associated with operating and maintenance cost. The concept of DG-Based Distribution Networks was developed. (Hassan et al., 2020). The review looks at three nature-inspired algorithms that can be used as multi-objective optimization methods to improve the technical

and financial viability of power distribution systems by adding more RES.

A comprehensive study on various challenges associated with the rapid use DGs is proposed in (Wankhede et al., 2022). This includes RES as a preeminent crucial element of the smart grid. A Hybrid genetic algorithm based on harmony search and flexible particle swarm optimization to find the best layout (size and placement) of DGs is used in Sharma and Pandey (2016). The technique aimed to extract maximum benefits by optimal DG planning. The research concentrated on the multi-objective fitness function, which is constructed by taking into account various indices

A fractional-order sliding mode control mechanism enabled DSTATCOM, that functions by either introducing or soaking up a defined quantity of reactive power is introduced (Ahmed et al., 2021). Sayahi et al. (2020) suggested a DSTATCOM control method derived from Direct Power Control to show how the voltage profile affects operation in steady state and under different conditions, such as voltage sags.

Many researchers have suggested modifications to the IRPT. The reactive component of current but noted that IRPT performs poorly during transient disturbances is emphasized in Salmerón et al. (2023). The behavioural study of DSTATCOM using traditional PI controller with five various control strategy and the author only concentrated on harmonics to mitigate SRF found to be better response to the dynamics (Chenchireddy et al., 2021).

A literature analysis indicates that supply voltage changes significantly affect the voltage at DC link. The traditional PI controller, frequently employed to manage DC link voltage, typically encounters overshoot and undershoot and may not produce adequate outcomes under varying parameters and load situations. Research persists in addressing the detrimental impacts of power electronics in micro grids, with multifunctional Distributed Generators (DG) emerging as a novel approach for power quality improvement.

The suggested DSTATCOM uses SRF to balance both linear and nonlinear loads in the distribution system. It does this by using a Fuzzy Logic Controller (FLC) that can deal with nonlinearity and input values that aren't clear. The developed DSTATCOM is intended to optimize the voltage profile, provide reactive power compensation, reduce harmonic distortions, and improve the system power factor.

Objectives and Contributions

This paper presents a detailed modelling of VSC-based DSTATCOM employing an SRF control algorithm to improve PQ issues in distribution systems integrated with SPV. The performance of FLC DSTATCOM is compared with conventional PI controllers. The proposed work highlights the following contributions:

- An in-depth analysis of power quality factors in the distributed generation context has been provided
- A synchronous reference frame control-based 5 MVA DSTATCOM equipped with a FLC has been designed and developed
- Two scenarios, one with PV integration and the other without, were employed to evaluate the performance of the DSTATCOM under imbalanced loads and to assess system efficiency
- The efficacy of the suggested system is compared to a tuned PI controller with DSTATCOM across several scenarios
- The developed DSTATCOM regulates system voltage, mitigates harmonic distortions, and enhances power factor in the distributed system.

Modelling of DSTATCOM

A DSTATCOM comprises a coupling transformer, an inverter, and a DC capacitor. It efficiently produces or absorbs reactive power, thereby stabilizing the voltage of the transmission line. Fig. 1 depicts the setup of the DSTATCOM. The PWM approach eliminates harmonics from the converter output. The control parameters for power flow consist of the disparity in voltage magnitude and phase angle between the AC system and VSC. When the VSC and the AC system possess identical magnitudes, the reactive power flow is null. When the voltage magnitude of the ac system is inferior to that of the VSC, reactive power commences to flow.

The shunt current injected by DSTATCOM for voltage regulation through reactive power management is given by:

$$I_{Sh} = I_L - I_S \quad (1)$$

$$I_{Sh} = \frac{I_L - (V_{th} - V_t)}{Z_{th}} \quad (2)$$

Since DSTATCOM is connected in a shunt to the system, it is essential to regulate the power flow and is represented by:

$$P_i = \sum_{m=1}^n V_i^2 G_{ii} - V_i V_m (G_{im} (\cos \theta_i - \theta_m) + B_{im} (\sin(\theta_i - \theta_m))) \quad (3)$$

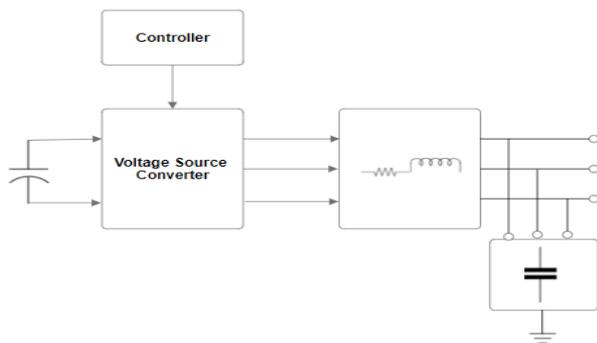


Fig. 1: Structure of DSTATCOM

$$Q_i = \sum_{m=1}^n -V_i^2 B_{ii} + V_i V_m (G_{im} (\cos \theta_i - \theta_m) - B_{im} (\cos(\theta_i - \theta_m))) \quad (4)$$

P_i and Q_i can be varied by varying the phase voltages and currents. Hence, the power flow control is achieved using a SRF.

Synchronous Reference Frame Control Theory

The three phase SRF control algorithm based on Parks and Clarkes transformation with voltage controlled PWM technique is designed as shown in Fig. 2. Sine and cosine signals are produced using a three-PLL by allowing the load current to pass through the park transformation. The components of direct-quadrature current are then allowed to pass through low pass filters to obtain i_{ld} and i_{lq} . SRF controller takes out only i_{ld} and i_{lq} components, thereby separating harmonics out of the source signal. The direct and quadrature axis currents consist of both elementary and harmonic components, which are given in (5-6):

$$I_{ld} = i_{ddc} + I_{dac} \quad (5)$$

$$I_{lq} = i_{qdc} + I_{qac} \quad (6)$$

The obtained i_{ddc} and i_{qdc} are sent back into the frame to derive alpha and beta components and are given by:

$$\begin{bmatrix} i_{\alpha dc} \\ i_{\beta dc} \end{bmatrix} = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} i_{ddc} \\ i_{qdc} \end{bmatrix} \quad (7)$$

From the above matrix, three phase reference currents can be obtained, and compensation of reactive power can be achieved.

Supervision of the self-sustaining VSC is achieved using the SRF theory and is derived from the current transformation in a synchronous rotating d-q frame. The source current reference in the d-q frame is initially transformed into the α - β frame and subsequently into the a-b-c frame by using the subsequent equation:

$$\begin{bmatrix} I_{sa} \\ I_{sb} \\ I_{sc} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos \omega t & \sin \omega t \\ \cos(\omega t - 2\pi/3) & \sin(\omega t - 2\pi/3) \\ \cos(\omega t + 2\pi/3) & \sin(\omega t + 2\pi/3) \end{bmatrix} \begin{bmatrix} I_{sd} \\ I_{sq} \end{bmatrix} \quad (8)$$

Fuzzy Logic Controller Design

A FLC is developed to control the distribution system, especially during dynamic conditions. The active and reactive power control is achieved by controlling I_d and I_q respectively. Thereby, it controls the DC link voltage. A FLC with a Mamdani Sugeno model consisting of two inputs and a single output is implemented.

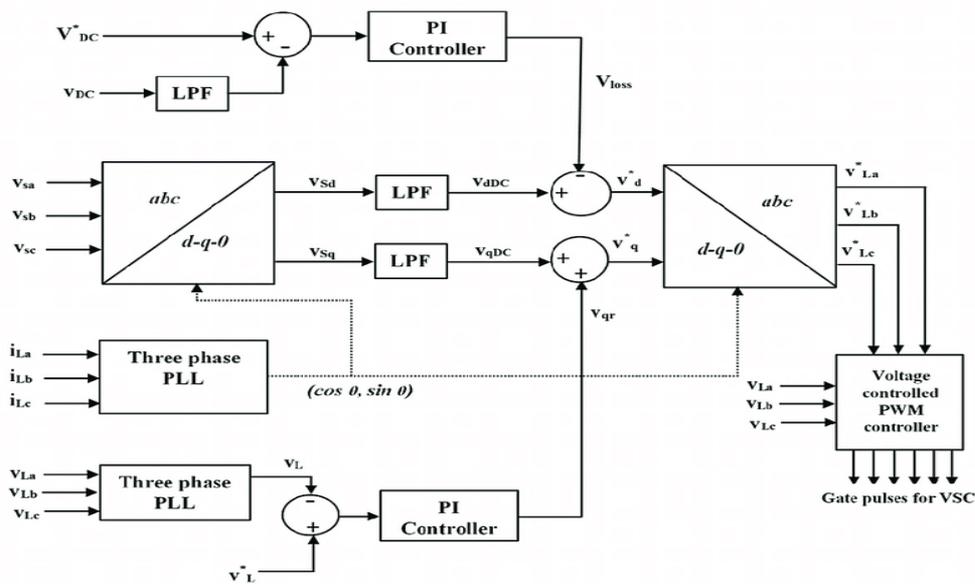


Fig. 2: Block Diagram of SRF Theory

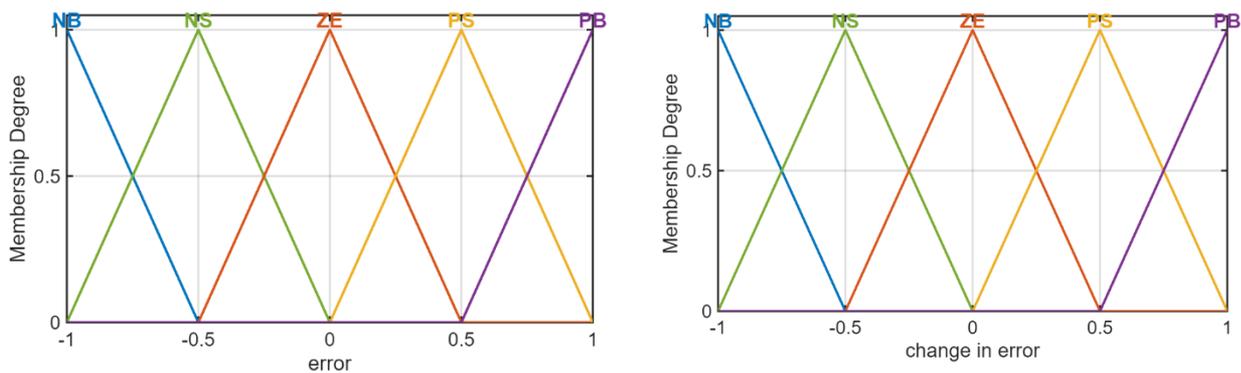


Fig. 3: Function for membership of errors and changes in errors

Table 1: FLC rules

e/Δe	PB	PS	ZE	NS	NB
PB	PB	PB	PS	PS	ZE
PS	PB	PS	PS	ZE	NS
ZE	PS	PS	ZE	NS	NS
NS	PS	ZE	NS	NS	NB
NB	ZE	NS	NS	NB	NB

The data inputs to the fuzzy algorithm consist of error and the change in error. The inputs and outputs are depicted using a triangular membership function, illustrated in Fig. 3. The rules within the framework of fuzzy inference are presented in Table 1.

Simulation Parameters and Methods

Distribution System Description

The study utilizes a standard three-phase distribution network with a rated line-to-line voltage of 11 kV and operating frequency of 50 Hz. The system configuration comprises a primary AC source, a transformer,

interconnected busbars (B1 and B2), RL and nonlinear loads, and integration points for both DSTATCOM and a solar PV system. The DSTATCOM operates in two distinct modes: Unity Power Factor (UPF) correction mode and Zero Voltage Regulation mode. The schematic of the simulated network is presented in Fig. 4.

DSTATCOM Design Specification

Table 2 provides the technical ratings and component selection criteria for the DSTATCOM used in simulation. Values are chosen for effective reactive power compensation, harmonic filtering, and robust operation under dynamic loading.

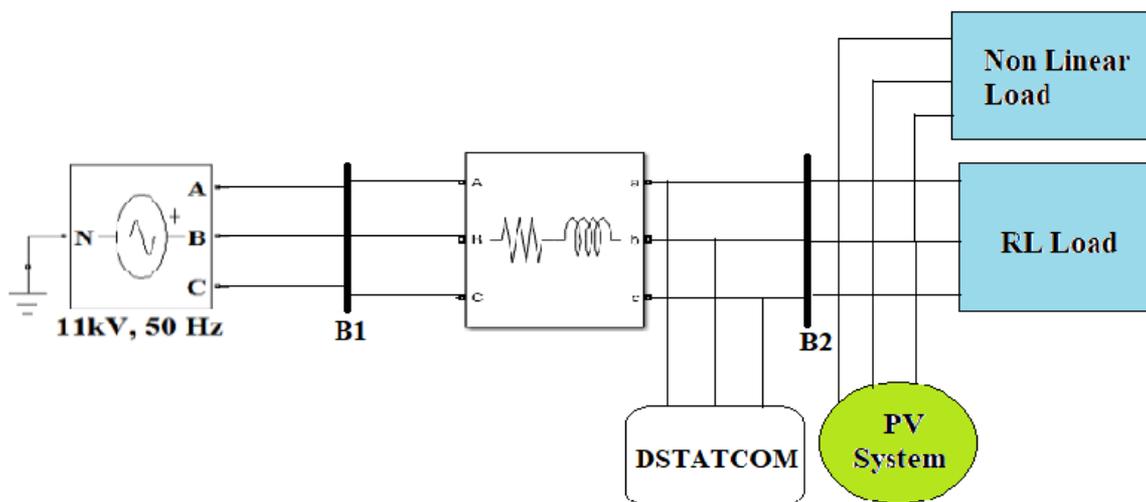


Fig. 4: Proposed System Configuration

Table 2: DSTATCOM Design Data

Sl. No	Quantities	Ratings	Description
1	Rated apparent Power	20MVA	Rated DSTATCOM capacity
2	V_{L-L}	11kV	Line-to-line RMS voltage
3	Frequency	50Hz	System operating frequency
4	Feeder Impedance	$Z_s=1+j0628\Omega$	Models line resistance and reactance
5	DC capacitor	500 μ F	Filters DC link voltage fluctuations
6	Ripple Filter	R= 0.4 Ω , C= 100 μ F	Suppresses high-frequency harmonics

Table 3: Controller Data

Sl. No	Quantities	Ratings	Description
1	Power Converter	IGBTs/Diodes	Fast-switching devices for inverter topology
2	Power Switching Frequency	10kHz	Ensures precise modulation and reduced harmonics
3	PI controller	$K_i = 50$ & $K_p = 0.5$	Tuned for optimal dynamic response
4	Nonlinear load	Three phase bridge rectifier and series RL load with R=100 Ω , L=1H	Simulates typical industrial harmonic sources
5	Linear load	$Z=50 +j60 \Omega$	Represents standard resistive-inductive load
6	Inverter parameters	3phase multilevel IGBT based inverter with 3 legs,6 pulse and having 500Hz carrier frequency	Enables fine-tuned voltage control

Controller and Converter Data

Table 3 lists the controller and power electronic hardware parameters assigned for effective performance benchmarking between PI and Fuzzy Logic controllers.

The inverter configuration is chosen for its capability to produce balanced three-phase voltages and facilitate the SRF control methodology. PI gains are tuned based on system step-response and desired settling time.

Simulation Environment and Test Scenarios

Simulations are conducted in MATLAB R2021a using Simulink and Control System Toolboxes. The test system is subjected to two main scenarios:

- (a) Without PV integration
- (b) With PV integration

Each scenario includes three cases:

- Base case (no DSTATCOM)
- DSTATCOM with PI controller
- DSTATCOM with Fuzzy Logic controller

PQ disturbances are simulated using planned events: Constant RL load 1 is connected to the feeder throughout the simulation, and non-linear load is coupled to the test system at $t = 3$ sec to inject harmonics. The source is programmed in such a way that the voltage sag occurs for duration of 0.2 sec between 1 and 1.2 sec and is followed

by a voltage swell. All key PQ metrics voltage profile, power factor, and harmonic distortion (THD) are measured at the PCC for consistency.

Results and Discussion

This section presents the simulation-based evaluation of DSTATCOM performance for power quality (PQ) enhancement in a three-phase distribution system, both with and without PV integration. DSTATCOM's performance is evaluated by simulating in MATLAB/Simulink R2021a. Critical PQ indicators - voltage profile, THD_V , THD_I and power factor were assessed under defined disturbance scenarios.

Scenario 1. Test System Without PV

Test System Without DSTATCOM (Base case)

Initially, the test system consists only of a linear load. Intentionally, a voltage sag is created between 1 and 1.2 sec; the voltage drops from 1 pu to 0.89 pu, and the settling time is 0.014 sec, as illustrated in Fig. 5. At 2 seconds, a nonlinear load is connected by closing the circuit breaker. The system's power flow is depicted in Fig. 6. It consists of four subplots, showing real and reactive power flow of grid, SPV, DSTATCOM, and load over time. In this case, the output of DSTATCOM and

SPV is zero; only the grid supplies the connected linear and nonlinear load.

The connection of the nonlinear load at 2 sec introduces harmonics into the system, causing disturbances, as shown in Fig. 7. The THD_V and THD_I are 13.07 and 15.42%, respectively, with a power factor of 0.78 as shown in Fig. 8. The DC link voltage V_{dc} exponentially decreases to zero, which is not at all regulated due to the disablement of a DSTATCOM represented in Fig. 9.

Test System With DSTATCOM Using PI Controller

In this simulation, the DSTATCOM is integrated into the test system, and the results are presented. The voltage profile has been improved from 0.89 pu to 0.99 pu between 1 and 1.2 sec. The PI controller takes 0.14 sec to compensate the voltage as shown in Fig. 10. Hence, the voltage sag condition is successfully addressed by the DSTATCOM. The flow of active and reactive power is depicted in Fig. 11. It is obvious that the grid supplies the load's active power and the DSTATCOM supplies the reactive power. Hence it also achieves the unity power factor shown in Fig. 12.

The harmonics induced into the system are suppressed by DSTATCOM, and the voltage harmonics are reduced to 9.58% and the current harmonics to 12.64%, as mentioned in Fig. 13.

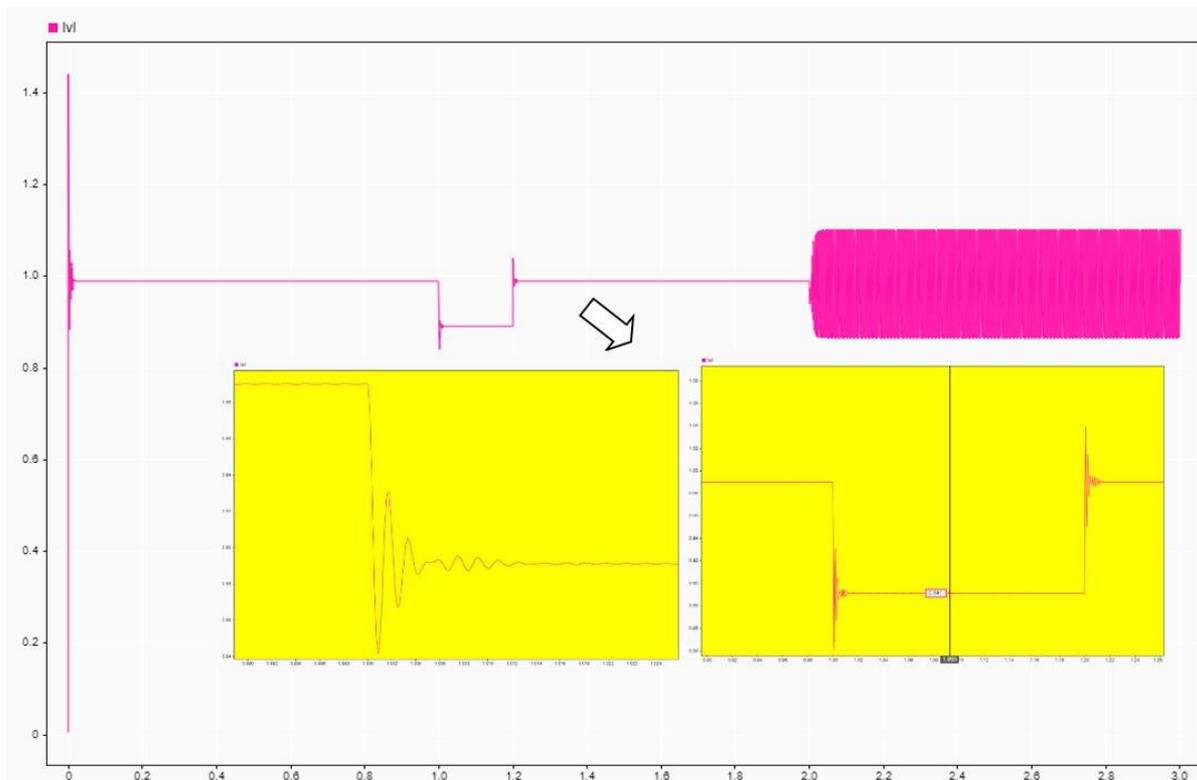


Fig. 5: Voltage at PCC in PU without DSTATCOM

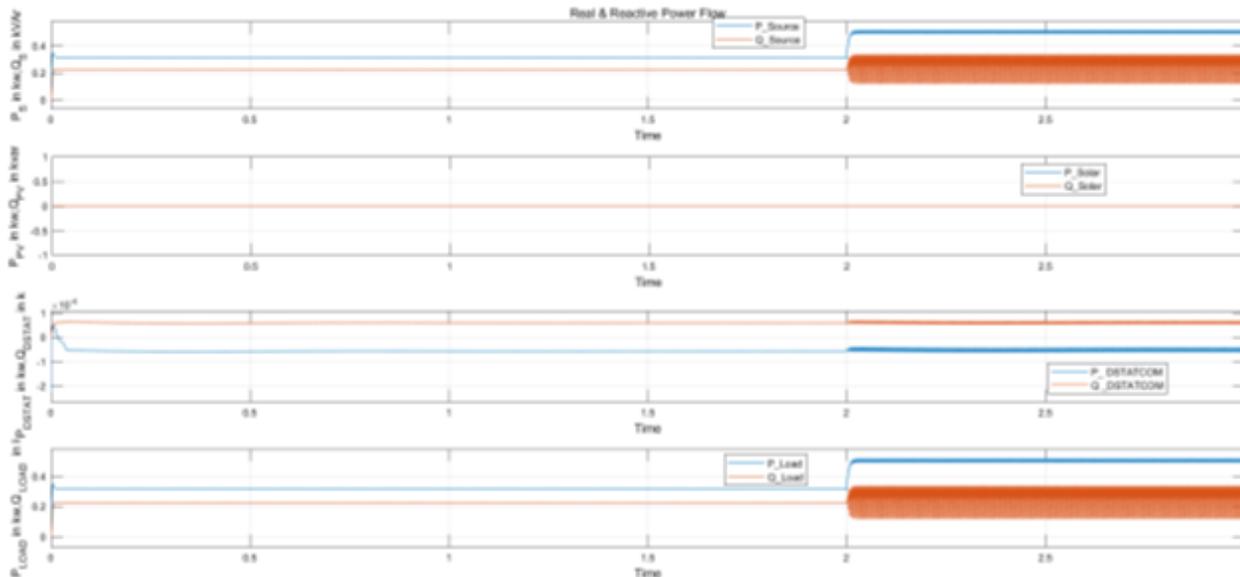


Fig. 6: Power flow in the system without DSTATCOM

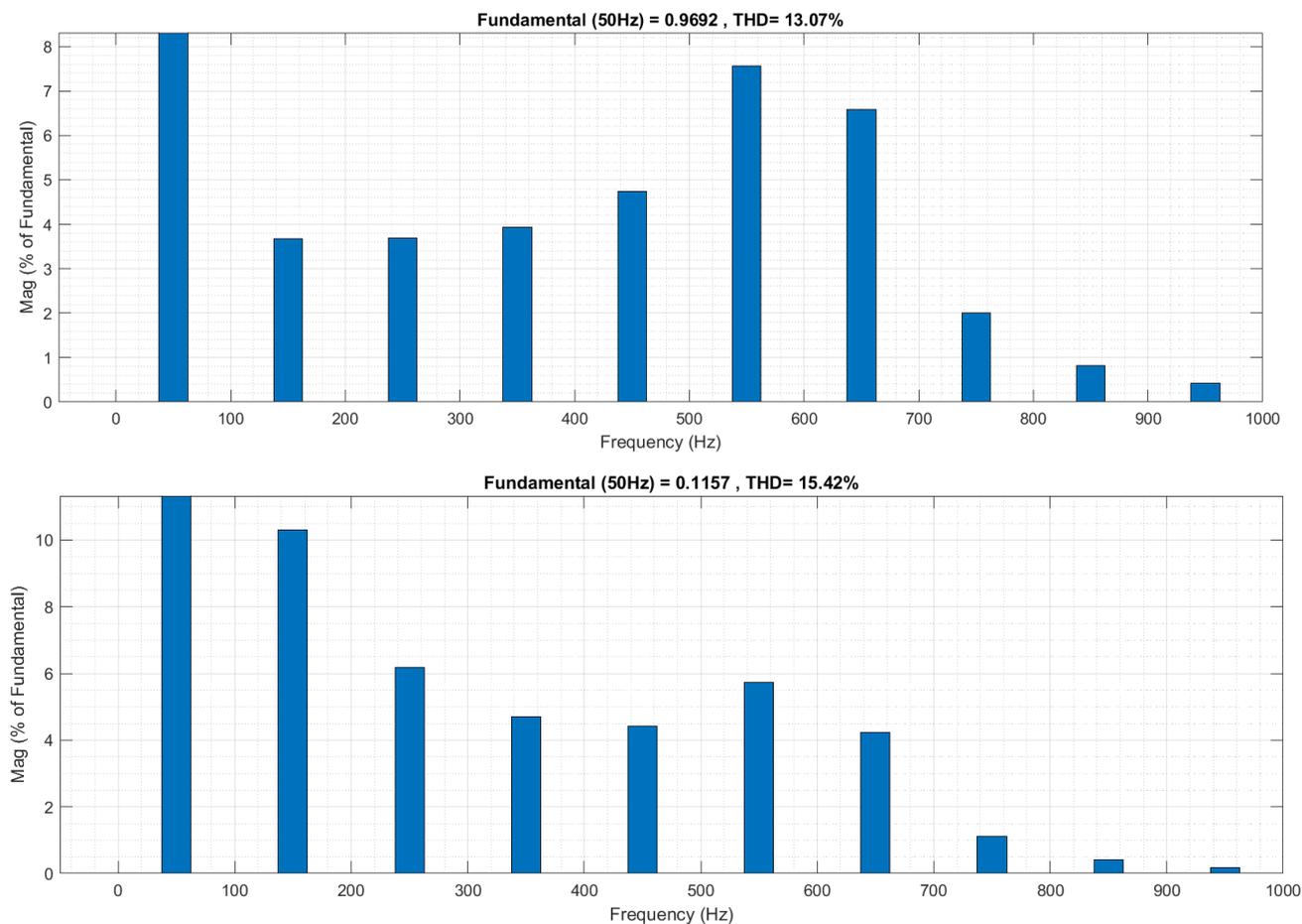


Fig. 7: Voltage and current harmonics without DSTATCOM

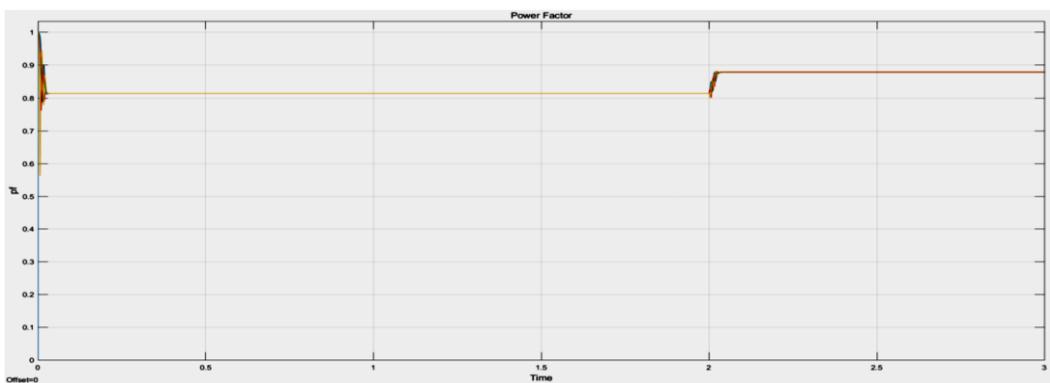


Fig. 8: System power factor without DSTATCOM

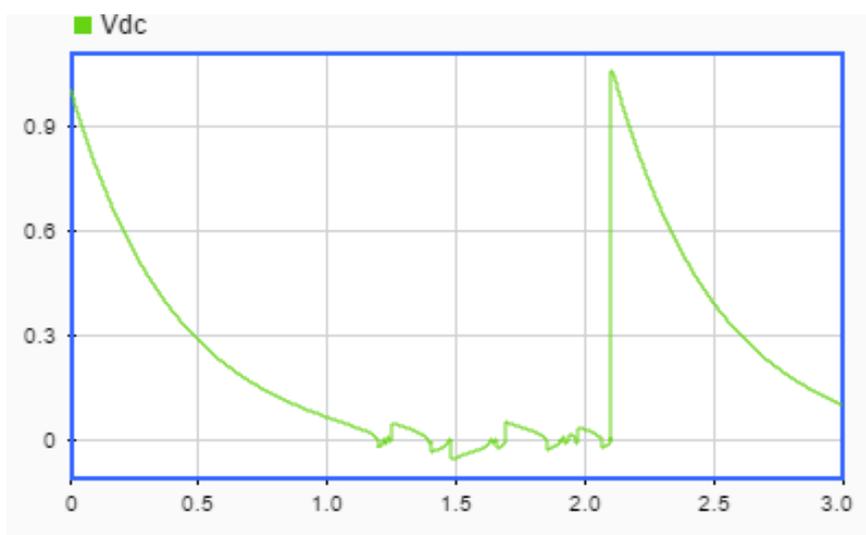


Fig. 9: System V_{dc} without DSTATCOM

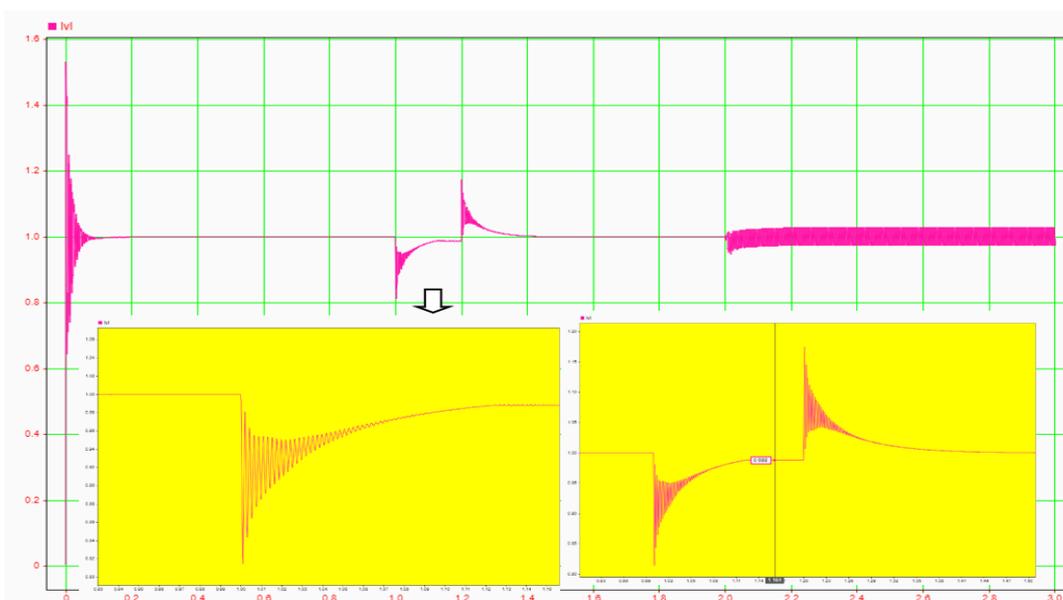


Fig. 10: Voltage at PCC in PU with DSTATCOM using PI controller

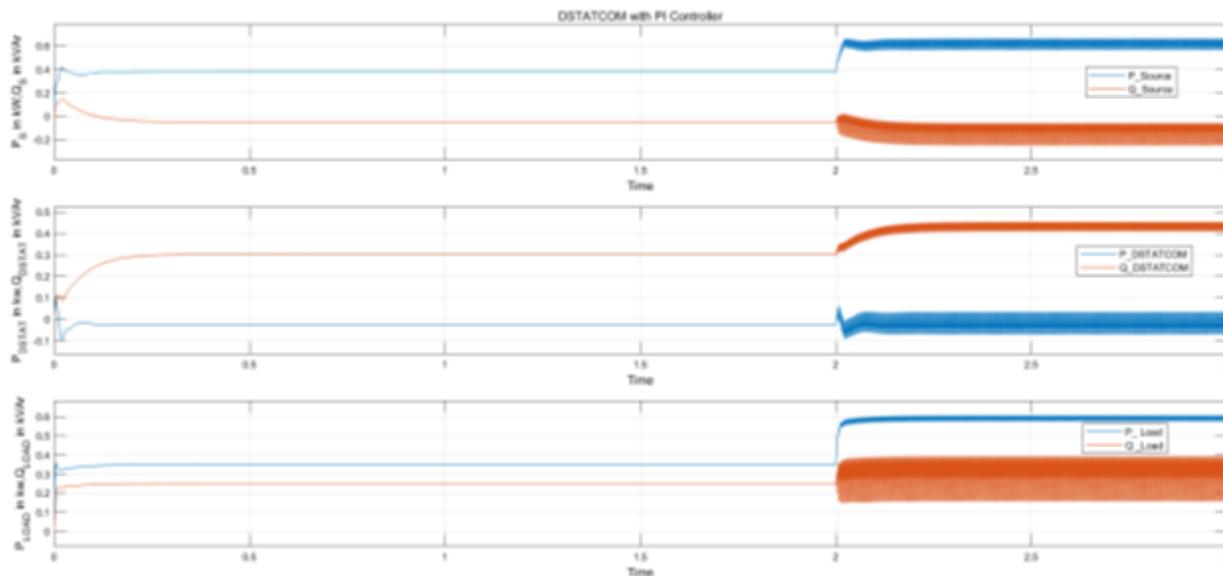


Fig. 11: Power flow in the system with DSTATCOM

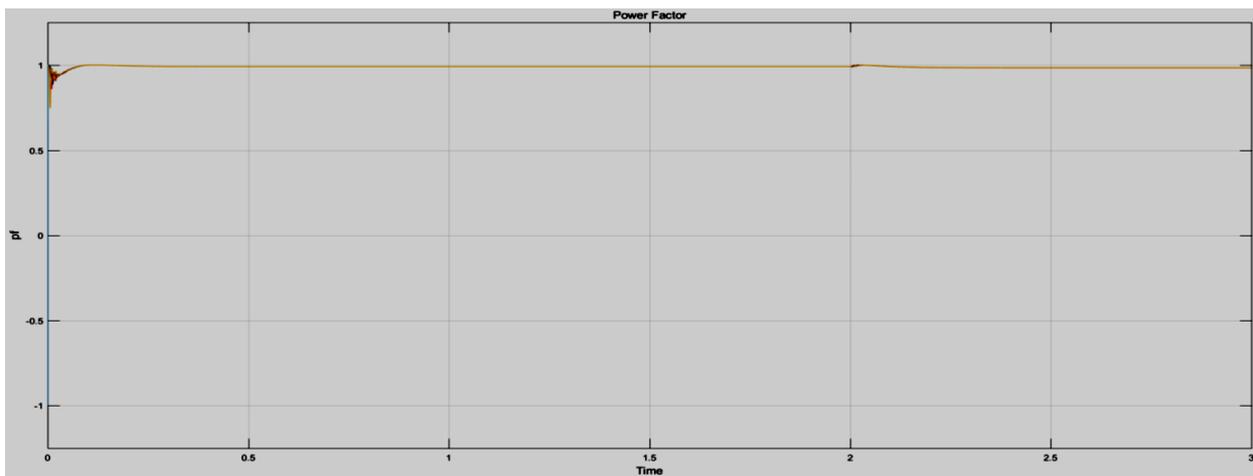
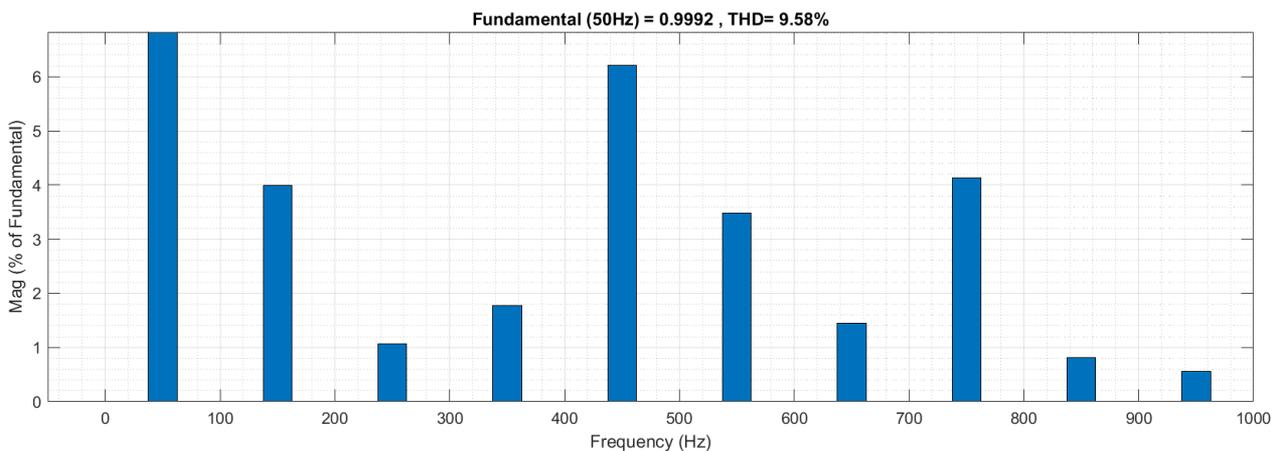


Fig. 12: System power factor with DSTATCOM



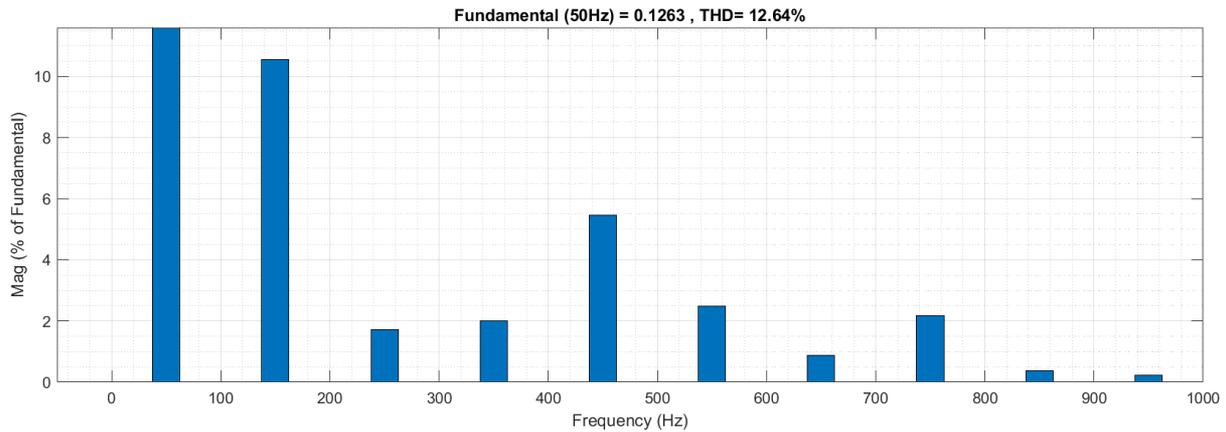


Fig. 13: Voltage harmonics and Current harmonics with DSTATCOM

The voltage at DC link V_{DC} is fixed to 1 p.u., and the response demonstrates that the PI controller maintains V_{DC} at 1 p.u. in all the conditions as seen in Fig. 14.

DSTATCOM With FLC

In this scenario, DSTATCOM with FLC is connected in shunt to improve the PQ of the system. The voltage profile has been improved from 0.89 pu to 0.99 pu between 1 and 1.2 sec. The PI controller takes 0.12 sec to compensate the voltage, which is faster than the traditional PI controller, as illustrated in Fig. 15. The system's real and reactive power flow in the presence of DSTATCOM enabled with FLC is represented graphically in Fig. 16. The load is drawing real power from the mains and reactive power from the DSTATCOM, lowering the grid's burden in all conditions. Thereby it achieves UPF as represented in Fig. 17. Voltage and current harmonics are as shown in Fig. 18, respectively. Voltage harmonics are 7.57 and current harmonics are 3.06%. It can be seen from Fig.19 that the

power factor is at 1 p.u. during normal operating conditions and when sag is created. Hence, it can be clearly say that DSTATCOM effectively improves power factor.

Scenario 2: Test System With PV Integration

In this scenario, a 100kW PV model with perturb and observe based MPPT technique is interfaced into the grid through a power converter at the PCC in order to assess the system's PQ and thereby the behaviour of DSTATCOM in the presence of DGs.

Test System Without DSTATCOM

In this scenario, the test system operates without a DSTATCOM to study its behaviour with a nonlinear load in the presence of SPV. Due to the integration of SPV, the operating voltage level at the PCC is increased to 0.91 PU between 1 and 1.2 sec. Fig. 20 illustrates the test system's power flows at various times to show that the grid and SPV both supply the real power. The grid is the only source of reactive power required by the load.

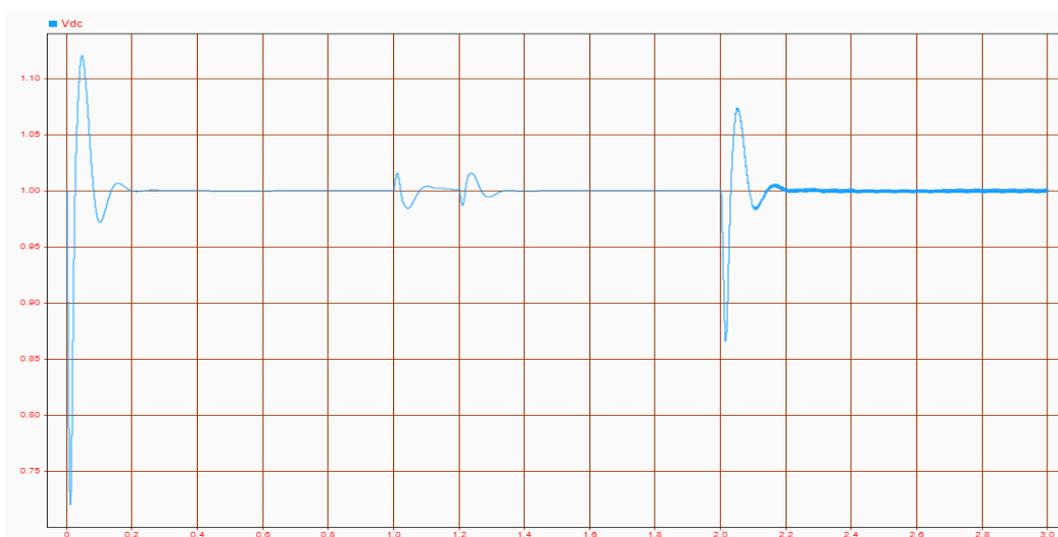


Fig. 14: System V_{dc} with DSTATCOM using PI controller

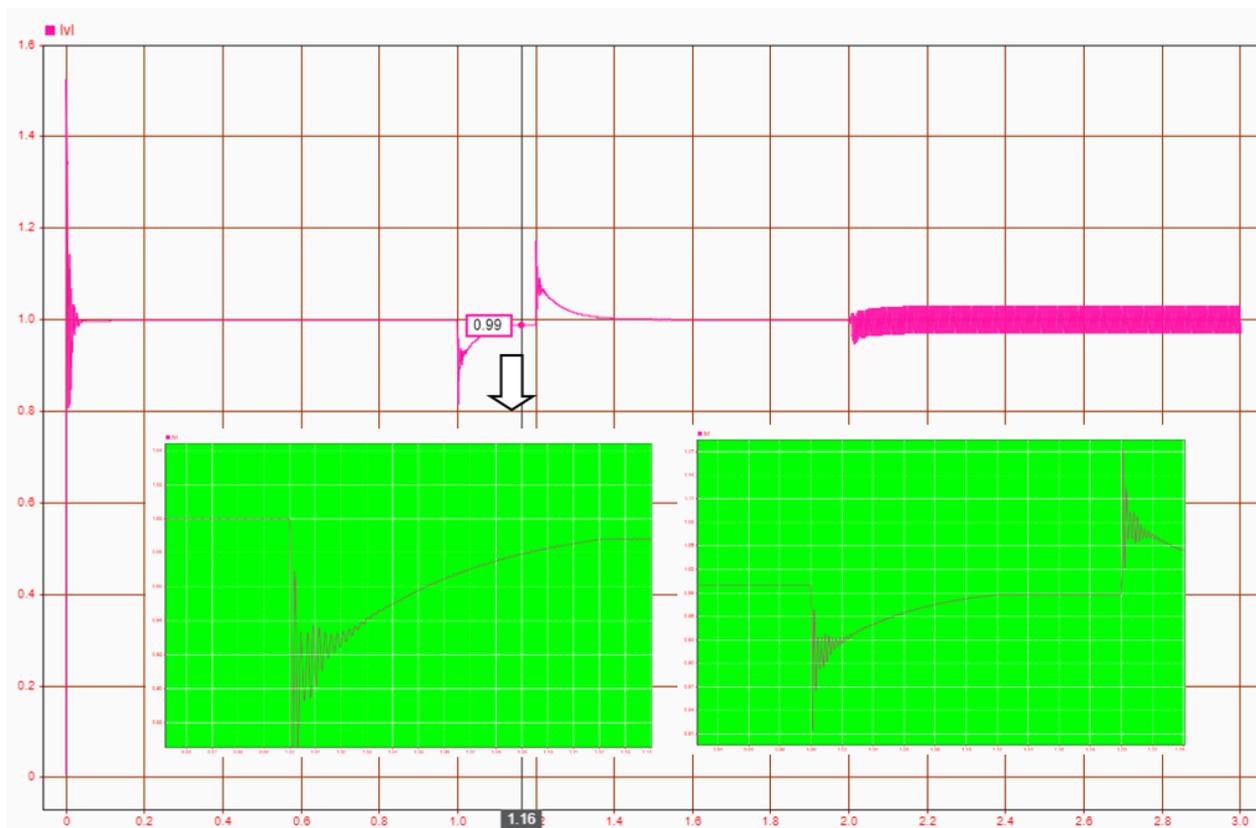


Fig. 15: Voltage at PCC with DSTATCOM using FLC

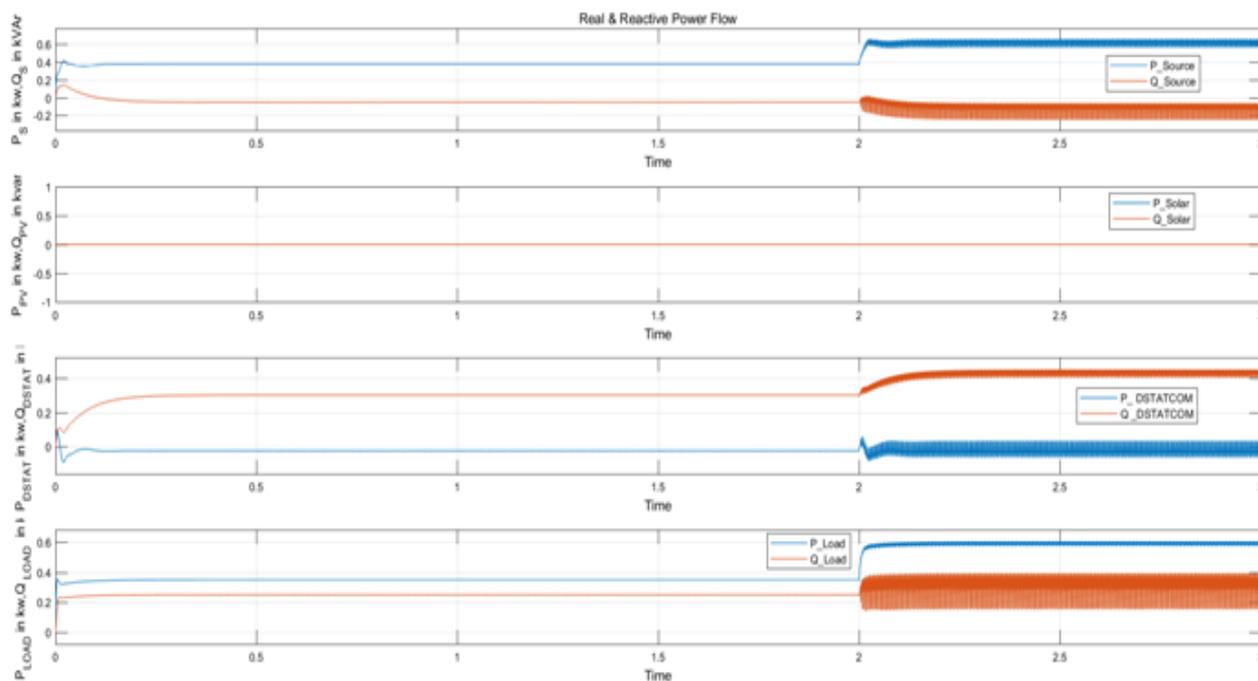


Fig. 16: Active and Reactive Power flow with DSTATCOM

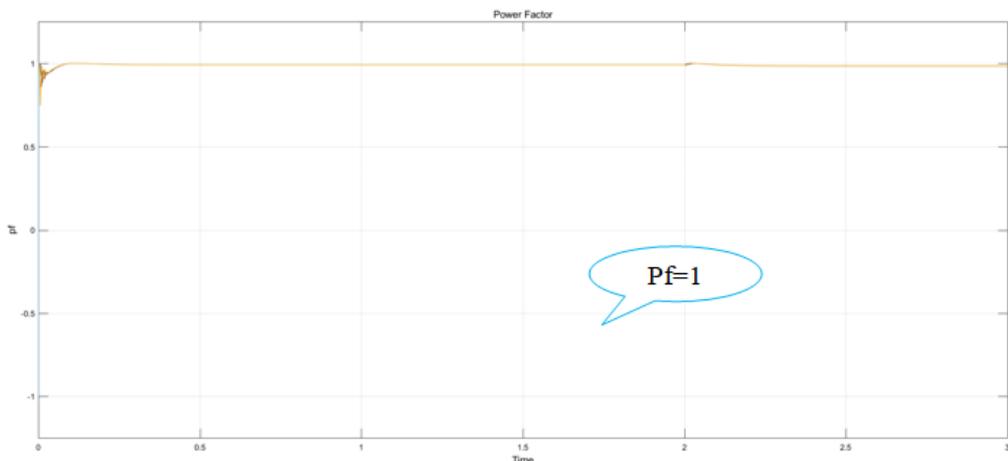


Fig. 17: Power Factor with DSTATCOM

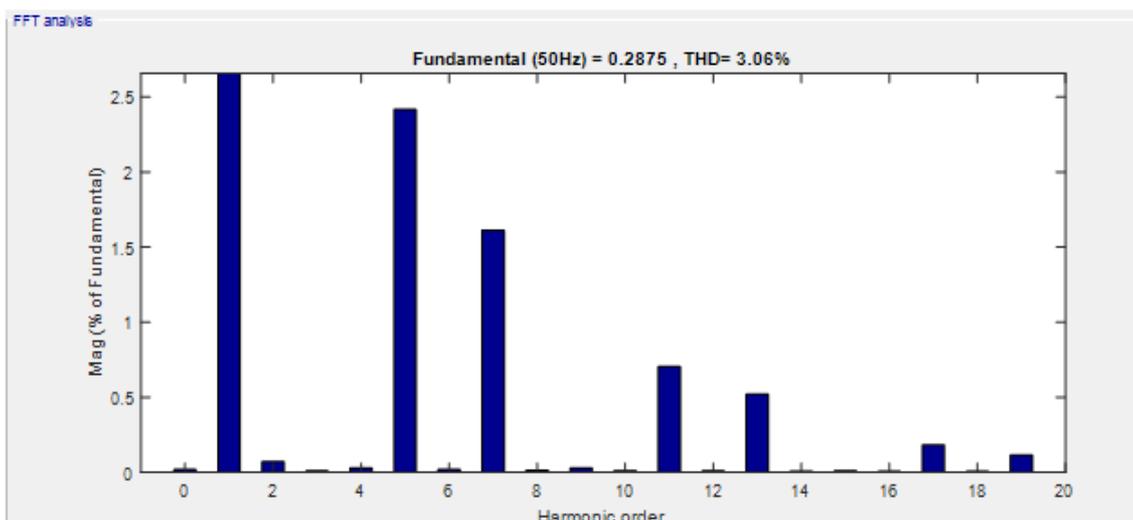
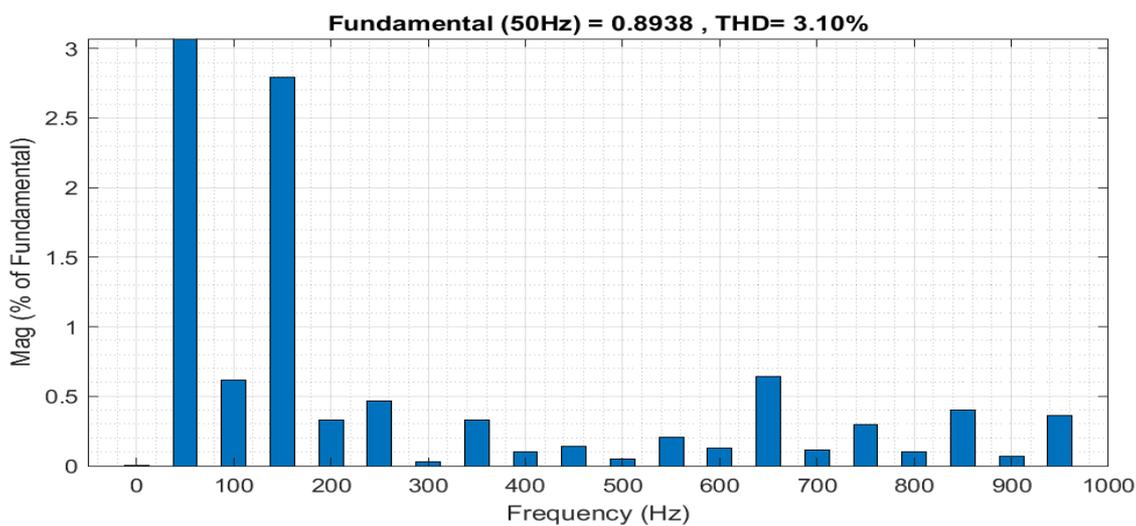


Fig. 18: Voltage and current THD using FFT window with DSTATCOM using FLC



Fig. 19: V_{dc} with DSTATCOM using FLC

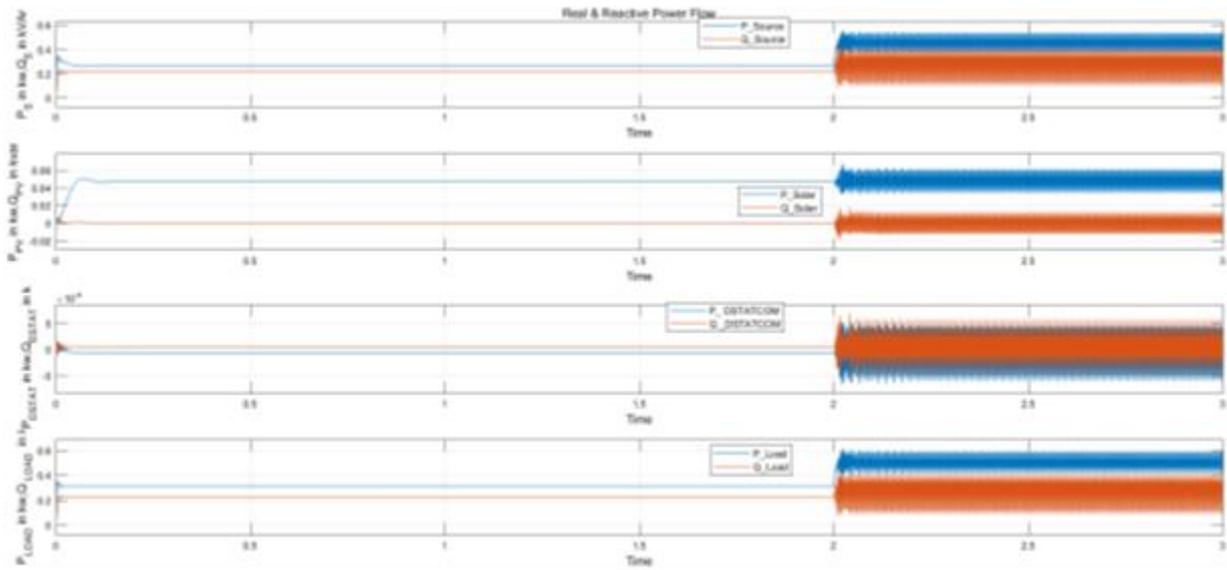


Fig. 20: Active and Reactive Power flow with PV

The nonlinear load is connected at 2 seconds, and the voltage and current harmonics increase to 13.06% and 22.02% due to interface SPV through power converters, as shown in Fig. 21. The power factor of the system is 0.82, shown in Fig. 22.

Test System With DSTATCOM Using PI Controller

In this scenario, a DSTATCOM controlled with a conventional PI controller is connected in a shunt to improve the grid's power quality. The voltage profile at PCC is enhanced to 1 pu from 0.91 pu. Fig. 23

illustrates, the system's power flow with the DSTATCOM connected. The load draws real power from the mains and reactive power from the DSTATCOM, reducing the grid's burden under all conditions. The DSTATCOM adequately supplies the system's required reactive power. Thereby the PF is increased to one. Fig. 24 show the voltage and current harmonics, respectively, with voltage harmonics at 3.36 and current harmonics at 16.94%. As seen in Fig. 25, the power factor has been improved to 1 throughout the simulation under all the conditions.

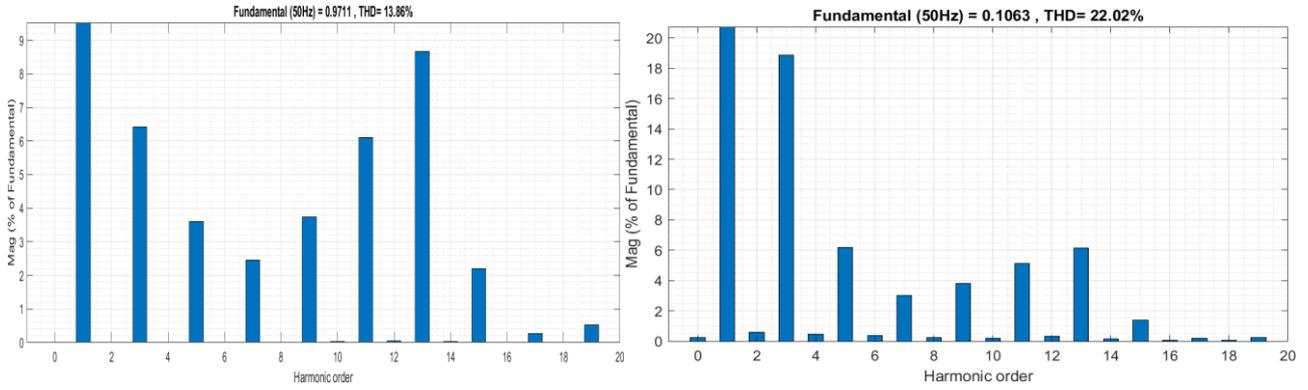


Fig. 21: Voltage and current THD using FFT window

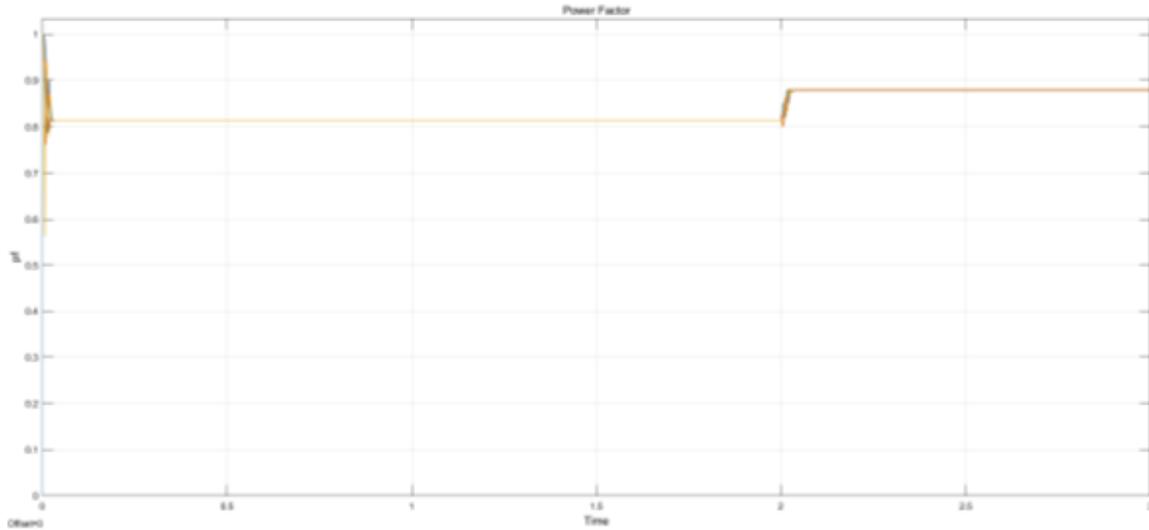


Fig. 22: Power Factor with PV

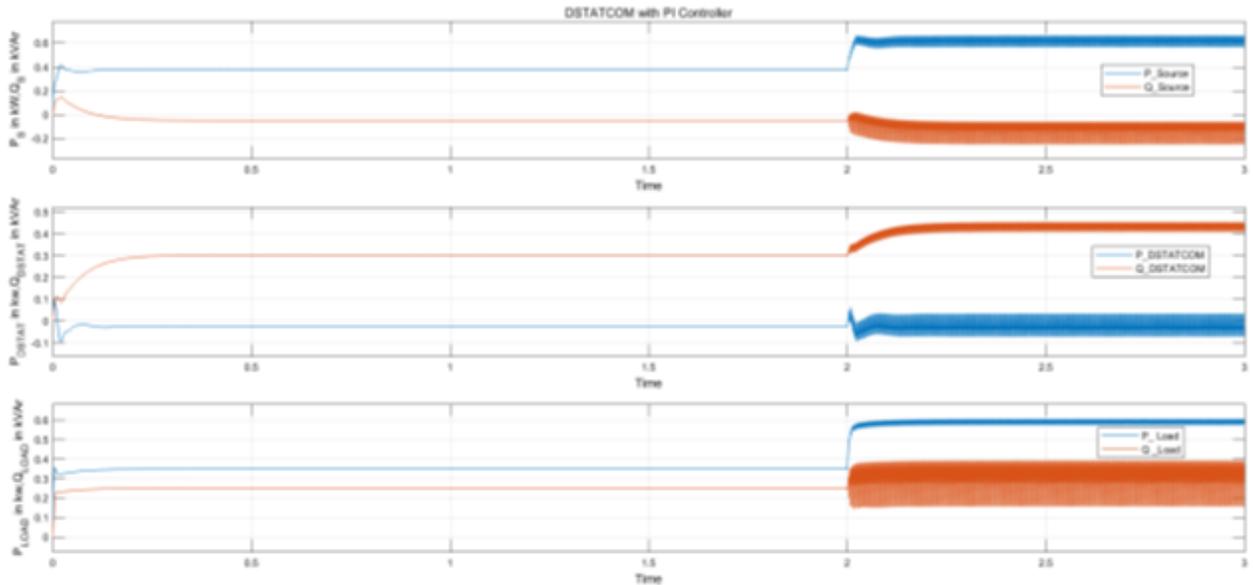


Fig. 23: Power flow with DSTATCOM integrated with SPV

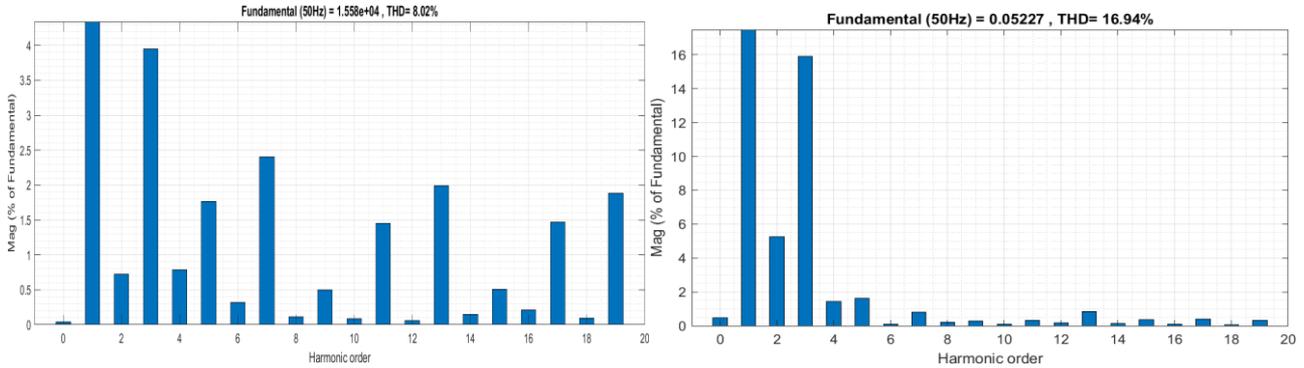


Fig. 24: Voltage and current THD using FFT window

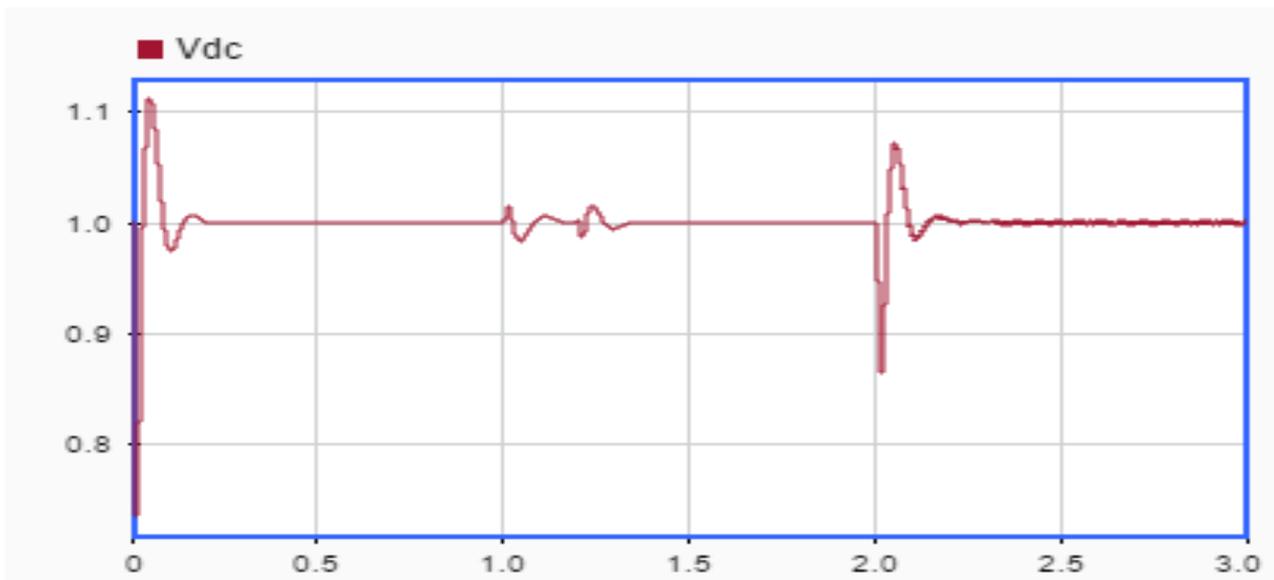


Fig. 25: V_{dc} with PI Controller integrated with SPV

DSTATCOM With FLC

In this scenario, DSTATCOM with FLC is connected in shunt to improve the power factor of the grid. Fig. 26 depicts the system's power flow in the presence of DSTATCOM. The load is drawing real power from the mains and reactive power from the DSTATCOM, lowering the grid's burden in all conditions. The required reactive power for the system is sufficiently supplied by the DSTATCOM. Fig. 27 represents the harmonic analysis using FFT which yields 3.36 of voltage harmonics and 1.89% of current harmonics at PCC. Also, unity power factor is maintained through the simulation shown in Fig. 28. Fig. 29 shows that the DC link voltage of DSTATCOM is 1p. u using a FLC in all conditions.

Comparative Summary

Key performance results from all cases are consolidated in Table 4, highlighting the progressive enhancement of PQ from base case to PI and fuzzy control. The Fuzzy controller consistently outperformed PI control in harmonic suppression, power factor correction, and dynamic voltage recovery

Results demonstrate that the DSTATCOM, especially under fuzzy control, significantly enhances voltage stability, suppresses harmonics, and sustains unity power factor even in the presence of renewables and nonlinear loading. Fuzzy control provides faster compensation, superior harmonic mitigation, and robust V_{dc} regulation compared to PI control. These improvements align with literature reports and validate the potential of intelligent control strategies for PQ improvement in modern distribution networks.

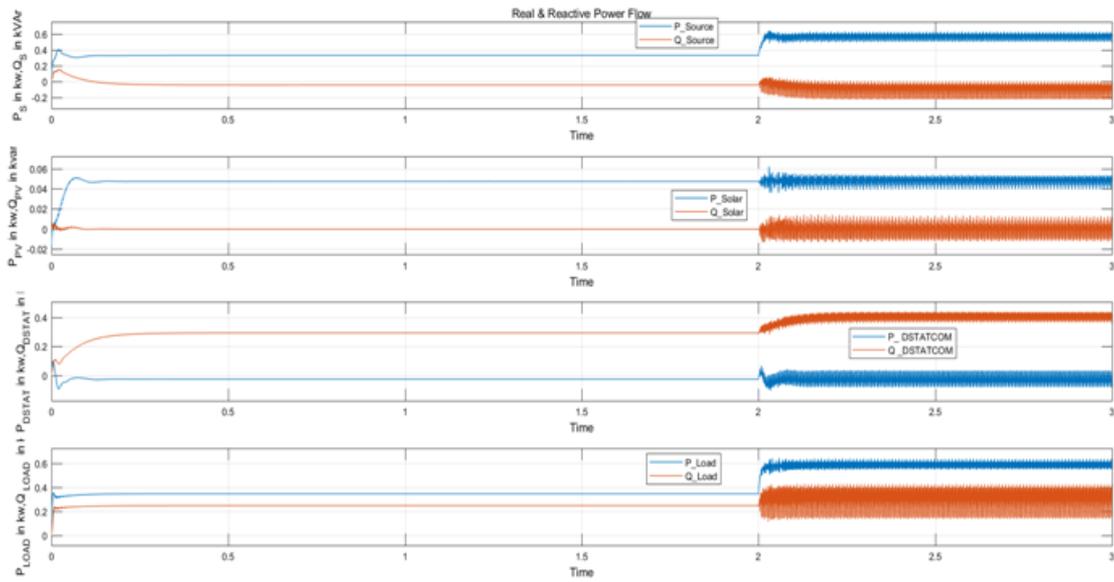


Fig. 26: Power flow with DSTATCOM integrated with SPV

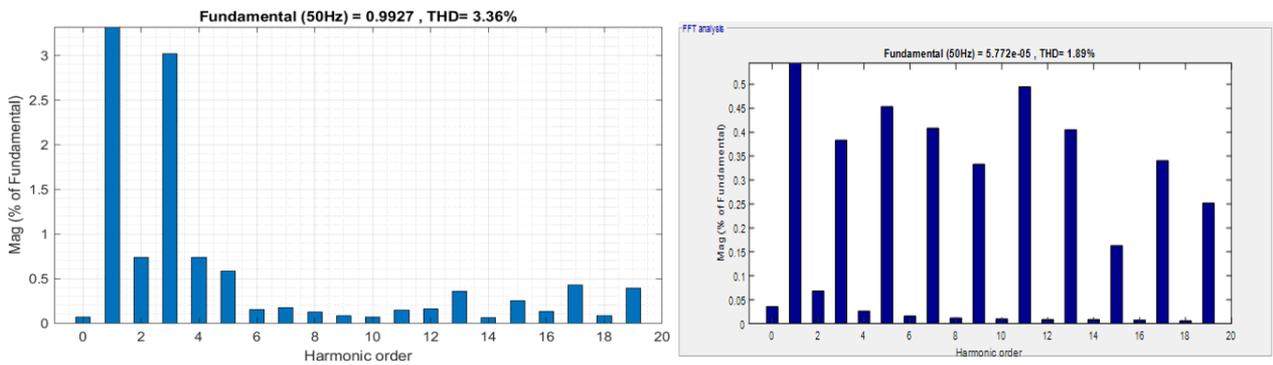


Fig. 27: Voltage and current THD using FFT window

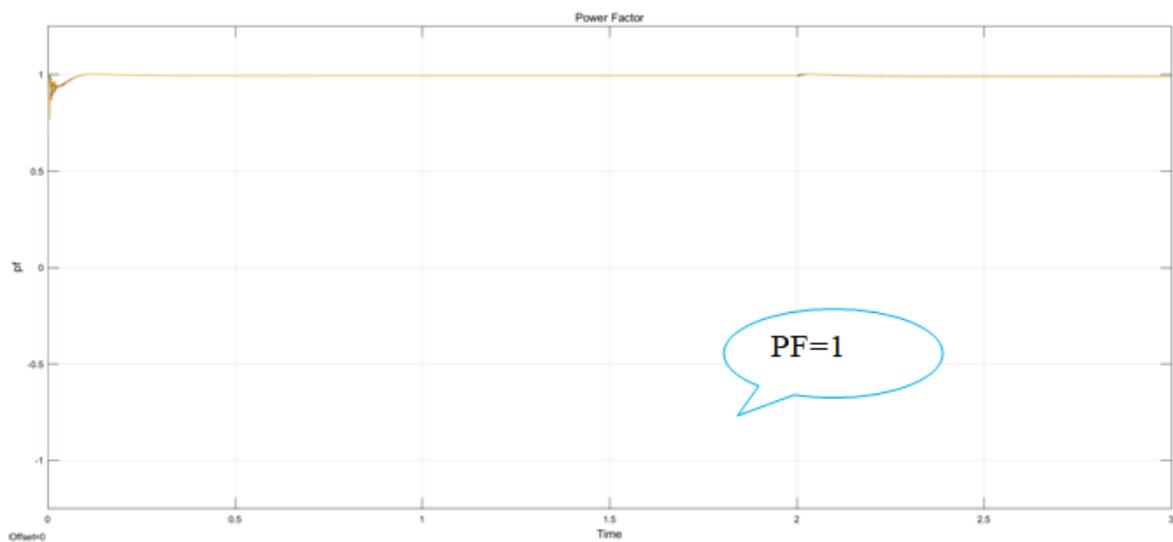


Fig. 28: Power Factor with DSTATCOM integrated with SPV

Table 4: Comparison between PI and fuzzy controlled DSTATCOM

Sl.No	Scenario	THD _v	THD _i	Power factor
1.	Test System	Without DSTATCOM	13.07	15.42
2.		With DSTATCOM	9.58	12.64
3.		DSTATCOM with FLC	3.10	3.06
4.	Test System with SPV	Without DSTATCOM	13.06	22.02
5.		With DSTATCOM	8.02	16.94
6.		DSTATCOM with FLC	3.36	1.89

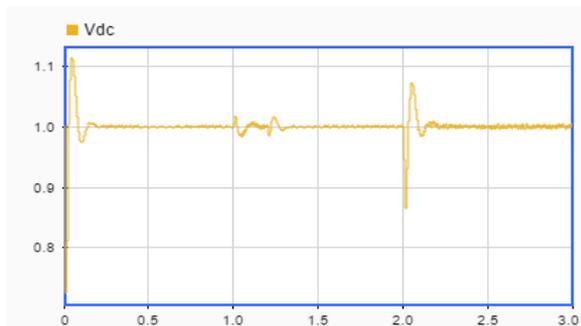


Fig. 29: V_{dc} with Fuzzy Controller

Conclusion

This study presents the design and simulation of a VSC-based DSTATCOM utilizing the SRF control approach to address PQ concerns in distribution systems, both with and without SPV integration, by operating in various modes to manage power flow. The PQ challenges such as voltage sag, harmonics, and power factor are simulated with a nonlinear load and a customizable voltage source. The integration of SPV systems introduces harmonics into the grid and elevates the voltage profile. The DSTATCOM, equipped with a PI controller and a FLC, is utilized to evaluate its efficacy in harmonic mitigation, voltage profile enhancement, and power factor improvement across various scenarios. The simulation outcomes of the proposed FLC are compared with traditional PI controllers and demonstrate efficacy in resolving PQ difficulties. The integration of the VSC-DSTATCOM and a FLC into the distribution system results in substantial enhancements in PQ. DSTATCOM improves PCC voltages and supplies essential reactive power assistance. Future research should focus on developing more comprehensive and adaptable models that incorporate unbalanced and time-varying load conditions more realistically. This includes improving the integration of advanced control techniques such as adaptive fuzzy logic controllers combined with machine learning algorithms to enhance system robustness under diverse operating scenarios.

Acknowledgment

Thank you to the publisher for their support in the publication of this research article. We are grateful for the resources and platform provided by the publisher, which

have enabled us to share our findings with a wider audience. We appreciate the efforts of the editorial team in reviewing and editing our work, and we are thankful for the opportunity to contribute to the field of research through this publication.

Funding Information

This research received no external funding.

Author's Contributions

All authors made a significant contribution to the preparation, development and publication of this manuscript.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues involved.

Data Availability Statement

No datasets were generated or analyzed during the current study.

Conflict of Interest

The author declares no conflicts of interest related to this work.

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