Power Quality Improvement with Renewable Energy Source Integration, using Fuzzy Logic Controlled D-STATCOM

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Abstract: - This paper addresses Power Quality (PQ) issues that prevail at point of common coupling (PCC) of Photo Voltaic (PV) system integrated to the Distribution System. The system considered for the analysis is IEEE-13 nodes test feeder network integrated with PV and D-STATCOM. A novel fuzzy logic controller (FLC) proposed dynamically controls the gate pulse patterns of D-STATCOM, in turn providing flat voltage profile D-STATCOM is the Voltage source inverter (VSI) also provides reactive power support to the distribution system. PQ issues voltage sag, swell and interruptions are mitigated by the proposed robust FLC by generating gate pulse values considering deviation in voltage as input. Membership functions defined are used to set fuzzy rules thereby determines the firing pulse corresponding to the voltage values sensed at PCC. The proposed control algorithm is tested on IEEE 13 bus distribution system with PV integration in Simulink environment. The results indicate the effectiveness of the controller in reducing error less than 5% and maintaining the voltage near to 1.0 per unit.

Key-Words: - D-STATCOM, Power Quality, Fuzzy Logic Control, Renewable Energy Sources, PV system.

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1 Introduction

Integration of photovoltaic (PV) generation can cause variations in power flow and voltage profiles depending on generation and loading conditions. For distribution-level applications, the Distribution Static Synchronous Compensator (D-STATCOM) is one of the most widely investigated shunt-connected FACTS devices for mitigating voltage-related PQ disturbances [1], [2], [3]. The performance of a D-STATCOM is strongly influenced by the topology of the power converter and its control strategy. Multilevel converters can achieve lower switching losses and improved harmonic performance, making them suitable for high-power PQ compensation applications [4], [5], [6]. The control strategy employed for the D-STATCOM is another important factor determining its dynamic performance. Fuzzy Logic Control (FLC), on the other hand, provides a model-independent control approach based on linguistic rules and expert knowledge. The inherent capability of FLC to handle nonlinearities and uncertainties makes it attractive for the dynamic control of power-electronic compensators [4], [7], [8].In the present work, a D-STATCOM based PQ compensation scheme is developed and investigated on the standard IEEE 13-bus distribution system.

A PV generation unit rated at 17.4 kW is integrated with the distribution network to represent renewable-energy penetration. Unlike the approach presented in [9], where a DC source is considered as the energy source for the inverter-based compensation system [10]. The proposed configuration is therefore intended to simultaneously address PQ disturbances associated with load switching and the integration of distributed PV generation. The effectiveness of the proposed FLC-controlled D-STATCOM is evaluated through simulation studies considering appropriate operating conditions of the IEEE 13-nodes test feeder. The overall configuration of the proposed system is illustrated in Figure 1. The results are used to assess the capability of the proposed D-STATCOM in improving PCC voltage

characteristics and maintaining satisfactory power quality under dynamic operating conditions.

2 System Description

PQ analysis is done for standard IEEE 13-nodes test feeder shown in Figure 1 [9], [10], [11]. The developed simulation model comprises of one active three-phase grid source, four three-phase loads, a PV subsystem, two battery energy-storage units, power-electronic converter interfaces, and a STATCOM-based voltage compensation system. The proposed fuzzy-logic controller regulates the compensating converter to improve the voltage profile during network disturbances and fault conditions. Table 1 summarizes the details of the test system.

Table 1. Test system details

Sl.No	Parameter	Description
1	Three phase AC source	1No,100MVA,13.8kV,X/R=7
2	PV system	1No,17.3kW,V_{oc}=406V, V_{mp}=336 V per cell
3	Battery Source for D-STATCOM	2 Nos, Nominal Voltage =25V , Capacity= 16 Ah per cell
4	Three Phase loads	4 Nos Load 1- 50 MW,30 MVAR Load 2 -50 MW, 32 MVAR Load 3 -50 MW Load 4 -165 MW, 56 MVAR

Source: Compiled by the authors for the proposed test system.

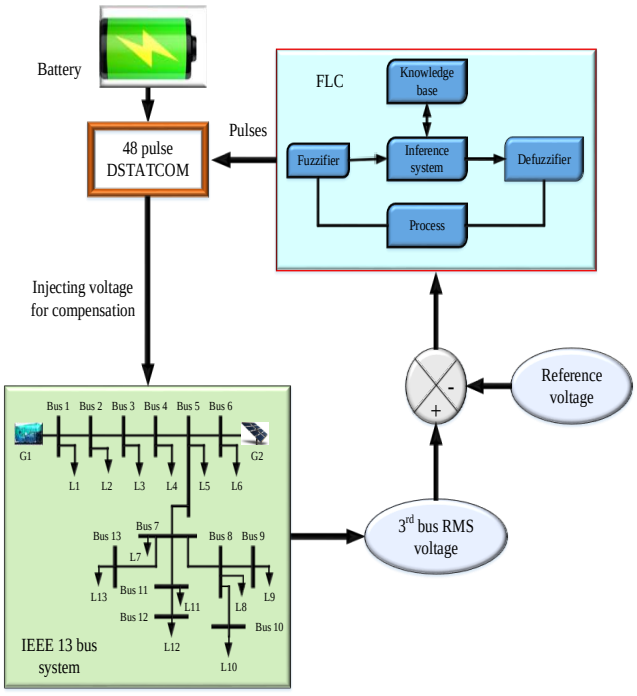


Fig. 1: Schematic of proposed PQ Mitigation model
Source: Created by the authors.

3 PV System Integration and D-Statcom

3.1 PV System Integration

The PV subsystem is represented using an equivalent electrical circuit of PV cells and is supplied with an insolation-dependent input. The PV output is measured in terms of voltage, current, and generated power and is interfaced with the AC network through a power-electronic converter.

PV system is integrated to the system at bus 6. It comprises of 2 panels in parallel, each made up of 11 PV cells connected in series which gives out open circuit voltage of 406V, maximum power point voltage of 336 V per cell and output power 17.3 kW. Each array is modeled using a solar-equivalent electrical circuit with a predefined maximum-power-point operating voltage. A universal bridge converts DC output of PV system into grid voltage. Impact of static and dynamic shading conditions of PV panels on bus voltage are also studied during which PQ issues arise which are mitigated by injecting the power from the battery source using proposed FLC. The Simulink model of PV system is as shown in Figure 2.

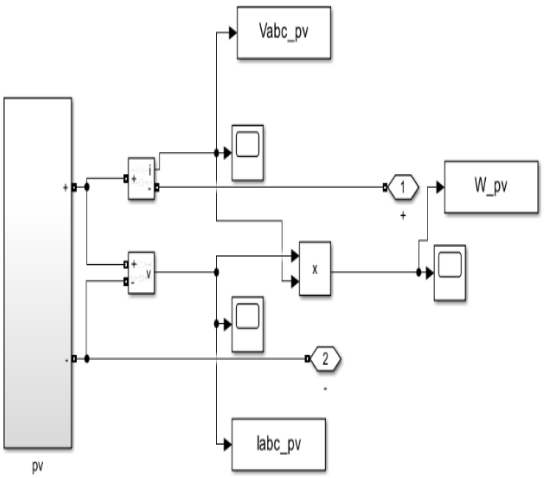


Fig. 2: PV system Simulink model
Source: Created by the authors using MATLAB/Simulink.

3.2 D-STATCOM

D-STATCOM a static counterpart of synchronous condenser performs the regulation function in a robust manner. Major attributes of STATCOM are quick response time, higher flexibility in operation under various conditions. It regulates bus voltage magnitude by absorbing or generating reactive power to grid dynamically [3], [8]. A typical D-STATCOM is as shown in Figure 3. The D-STATCOM regulates the PCC voltage by controlling the converter output voltage, which

establishes a compensating current through the coupling impedance. The quadrature component of the compensating current provides the required reactive-power exchange with the distribution system.

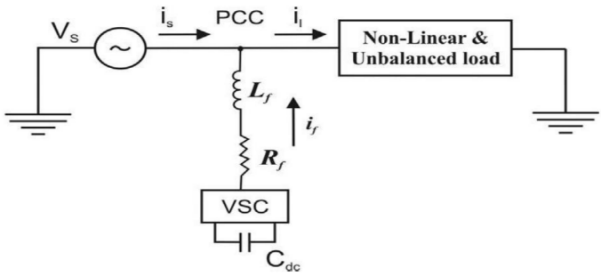


Fig. 3: Typical D-STATCOM
Source: Adapted by the authors from [3]

Mathematically let three phase voltage at PCC be $V_{sa,}V_{sb,}\ V_{sc}$, and converter voltages be $V_{ca,}V_{cb,}\ V_{cc}$ and converter currents be $I_{ca,}I_{cb,}\ I_{cc}$. For each phase, applying
KVL across the coupling impedance gives

$$V_{sa} - V_{ca} = R_f I_{ca} + L_f \frac{dI_{ca}}{dt} \quad (1)$$

$$V_{sb} - V_{cb} = R_f I_{cb} + L_f \frac{dI_{cb}}{dt} \quad (2)$$

$$V_{sc} - V_{cc} = R_f I_{cc} + L_f \frac{dI_{cc}}{dt} \quad (3)$$

In general,

$$L_f \frac{dI_{abc}}{dt} = V_{cabc} - V_{sabc} = R_f I_{cabc} \quad (4)$$

Considering three phase *abc* to *dq* transformation.

$$V_{sd} - V_{cd} = R_f I_{cd} + L_f \frac{dI_{cd}}{dt} \quad (5)$$

$$V_{sq} - V_{cq} = R_f I_{cq} + L_f \frac{dI_{cq}}{dt} \quad (6)$$

Therefore, the converter voltage controls the compensating current. The active and reactive powers are given by

$$P = \frac{3}{2}\left(V_d I_d + V_q I_q\right) \quad (7)$$

$$Q = \frac{3}{2}\left(V_q I_d - V_d I_q\right) \quad (8)$$

To align with voltage at PCC, d-axis component has to be considered, which makes $V_q = 0$, thus

$$P = \frac{3}{2}(V_d I_d) \ ; \ Q = \frac{3}{2}\left(-V_d I_q\right) \quad (9)$$

Multilevel converter voltage equations are given by

$$V_{cd} = M_{cd}\, V_{DC} \ \ \& \ \ V_{cq} = M_{cq}\, V_{DC} \quad (10)$$

$$M_{cd} = d - axis Modulation\ Index$$
$$M_{cq} = q - axis Modulation\ Index$$

Considering basic 6 pulse VSI topology, it comprises of 6 switches S_1, S_2, S_3, S_4, S_5, S_6 where in S_4, S_5, S_6 have complementary switching conditions with respect to S_1, S_3, S_2 given by

$$S_4 = 1 - S_1;\ S_5 = 1 - S_3;\ S_6 = 1 - S_2 \quad (11)$$

The switching sequence of the topology along with magnitude of phase voltage impressed across each of them is summarized in the Table 2.

Table 2. Switching sequence of basic 6 pulse VSI

State	S_1	S_3	S_2	V_a	V_b	V_c
1	1	0	0	$2\,v_{dc}/3$	$-v_{dc}/3$	$-v_{dc}/3$
2	1	1	0	$v_{dc}/3$	$v_{dc}/3$	$-2\,v_{dc}/3$
3	0	1	0	$-v_{dc}/3$	$2\,v_{dc}/3$	$-\,v_{dc}/3$
4	0	1	1	$-\,2v_{dc}/3$	$v_{dc}/3$	$v_{dc}/3$
5	0	0	1	$-\,v_{dc}/3$	$-v_{dc}/3$	$2\,v_{dc}/3$
6	1	0	1	$v_{dc}/3$	$-2\,v_{dc}/3$	$v_{dc}/3$

Source: Prepared by the authors based on the six-pulse VSI switching sequence

4 Fuzzy Logic Control Mechanism

The proposed FLC based D-STATCOM model is designed to analyze the performance under interruption and PV shading conditions. Standard IEEE bus system is taken to analyze the PQ issues mitigation process. D-STATCOM with battery is placed between buses 3 and 2 bus. FLC controller is designed to control the compensator working process. The proposed model effectively compensates the PQ issues at all circumstances which are validated using MATLAB/SIMULINK tool. . Inputs to FLC are error in voltage at bus 3 with respect to reference voltage (V_{ref}), typically 1 per unit (p.u) and incremental change in error which are represented as [7], [8].

$$e(t) = V_{ref} - V_{BUS3} \quad (12)$$

$$\Delta e(t) = e(t) - e(t - \Delta t) \quad (13)$$

Based on values in Table 2, the fuzzy rules are framed. Error values are provided as an input of FLC model, which analyze the error signal and refer the rule to make an output. For the given system 10 fuzzy rules has been framed which changes the gate pulse triggering pattern of each of the 6 pulse VSI based on the error measured as

given in equation 12. A FLC controller is designed to generate the switching patterns of D-STATCOM. The output of gate pulse of FLC is summarized in Table 3. Simulink model of FLC makes use of bell-shaped membership function for input and trapezoidal membership function for output with Mamdani Fuzzy Inference System (FIS). [7], [8].

Table 3. Gate pulse pattern to D STATCOM

Error (input)	Gate Pulse Variation (output)
Negative Large (NL)	-67.5^0 to -52.5^0
Negative Big (NB)	-52.5^0 to -37.5^0
Negative Medium (NM)	-37.5^0 to -22.5^0
Negative Small (NS)	-22.5^0 to -7.5^0
Negative Very Small (NVS)	-15^0 to -7.5^0
Zero (ZE)	-7.5^0 to 7.5^0
Positive Very Small (PVS)	-7.5^0 to 22.5^0
Positive Small (PS)	22.5^0 to 37.5^0
Positive Medium (PM)	37.5^0 to 52.5^0
Positive Big (PB)	52.5^0 to 67.5^0

Source: Proposed by the authors for the fuzzy logic controller

Based on these patterns delay is added to each inverter and voltage magnitude is maintained within acceptable limits for several dynamic conditions in the system which are discussed in section 6. The entire switching mechanism is explained in the sequence mentioned below

Bus voltage → error → FLC → firing-angle/modulation command → pulse generator → phase-shifted converters → 48-pulse D-STATCOM.

The Simulink model of the proposed 48-pulse D-STATCOM is shown in Figure 4 (Appendix).

Table 4 (Appendix) shows the fuzzy rules which is used for proposed FLC. Based on these rules, the FLC controller generates a pulse signal for D-STATCOM which inject voltage to compensate the load demand. The Simulink structure of proposed model is illustrated in Figure 5 (Appendix), [7], [8].

5 Results

The proposed model was validated under the following cases.

Case 1: Interruption condition
Case 2: Static shading condition
Case 3: Dynamic shading condition

Case 1: Interruption Condition

This is most crucial PQ issues for power system these issues occur at the supply voltage is decreased to less than 0.1 p u. This cause system failure, components malfunction and equipment failure. The error value during interruption is shown in Figure 6 and Figure 7 shows the observed waveform of proposed model which injects voltage during the period of interruption.

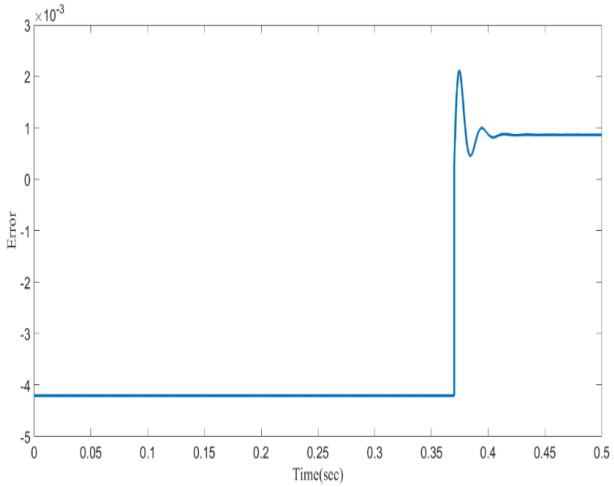


Fig. 6: Analysis of error at interruption fault
Source: Simulation results obtained by the authors

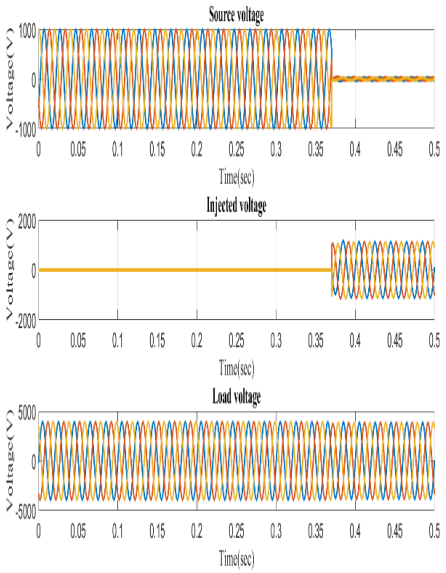


Fig. 7: Voltage compensation during Interruption
Source: Simulation results obtained by the authors

Case 2: Static Shading

The PV irradiance was reduced to 800 W/m^2, because the shading was in static form. During this period, the PQ disturbance sag, swell, and interruption are analyzed for a small duration and variations in source voltage which is compensated by injected voltage from D-STATCOM to maintain voltage profile at Bus 6 are plotted in Figure 8, Figure 9 and Figure 10. The power variation of PV at this condition was provided in Figure 8. The

representation shows the proposed model provide a better working process at static shading condition.

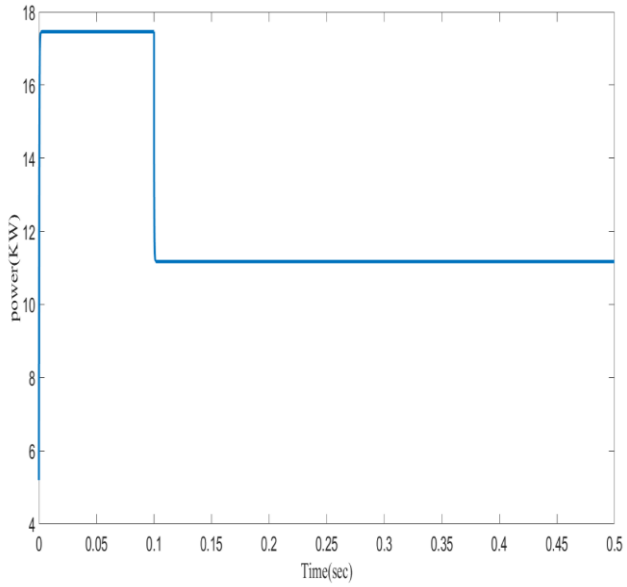


Fig. 8: Analysis of PV power at static shading condition
Source: Simulation results obtained by the authors.

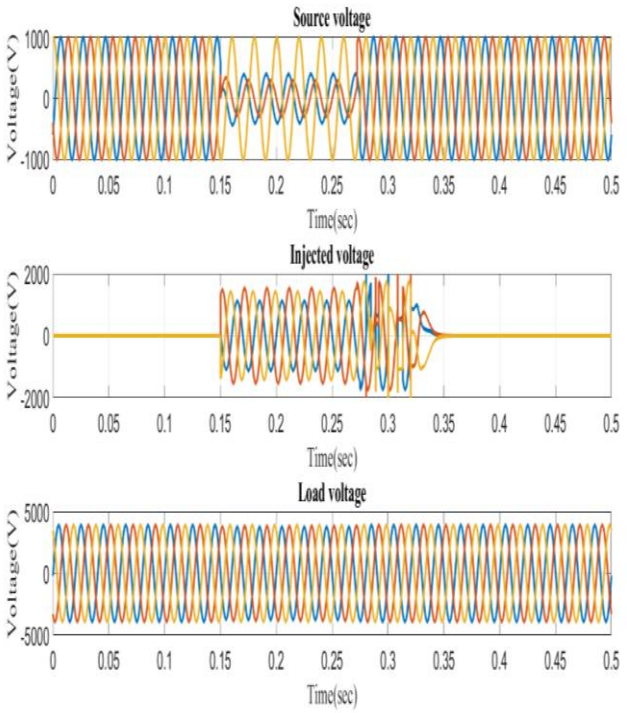


Fig. 9: Analysis of sag compensation under static shading
Source: Simulation results obtained by the authors.

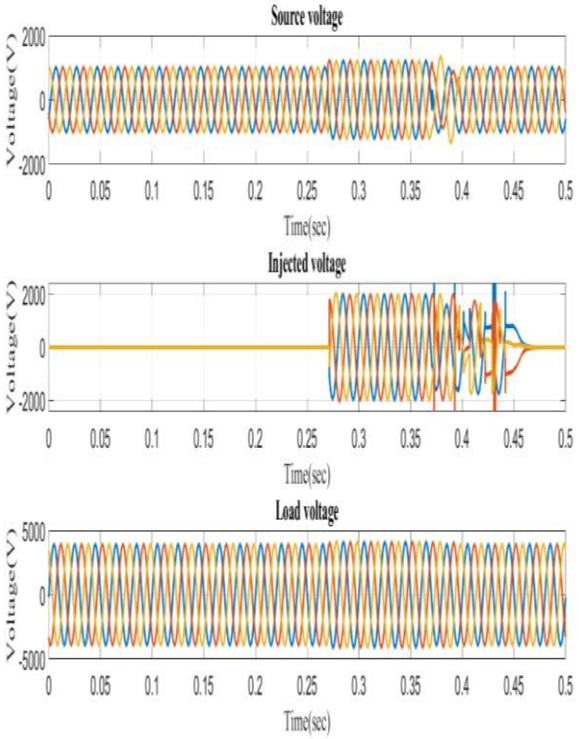


Fig. 10: Analysis of swell compensation under static shading condition
Source: Simulation results obtained by the authors.

Case 3: Dynamic shading condition

In this period, the PV irradiance is not constant, it is varied by 700 W/m^2, 800 W/m^2, 1000 W/m^2, and 900 W/m^2 in dynamic form (temporary shading). During this period, the PQ disturbance sag, swell and interruption are analyzed and variations in source voltage which is compensated by injected voltage from D-STATCOM to maintain voltage profile at Bus 6 are plotted plotted in Figure 12, Figure 13 and Figure 14, also the Power variation of PV at this condition was showed in Figure 11.

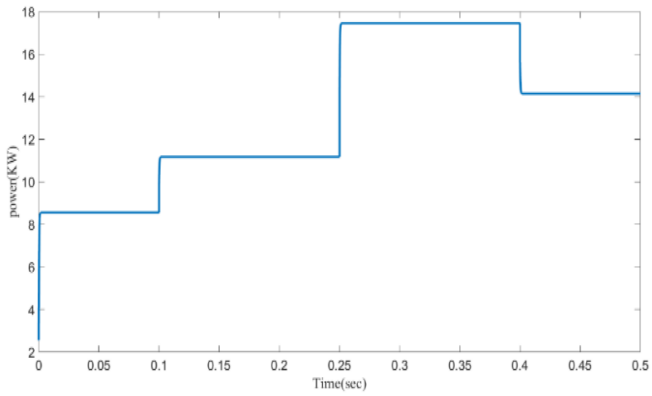


Fig. 11: Analysis of PV power at dynamic shading condition
Source: Simulation results obtained by the authors.

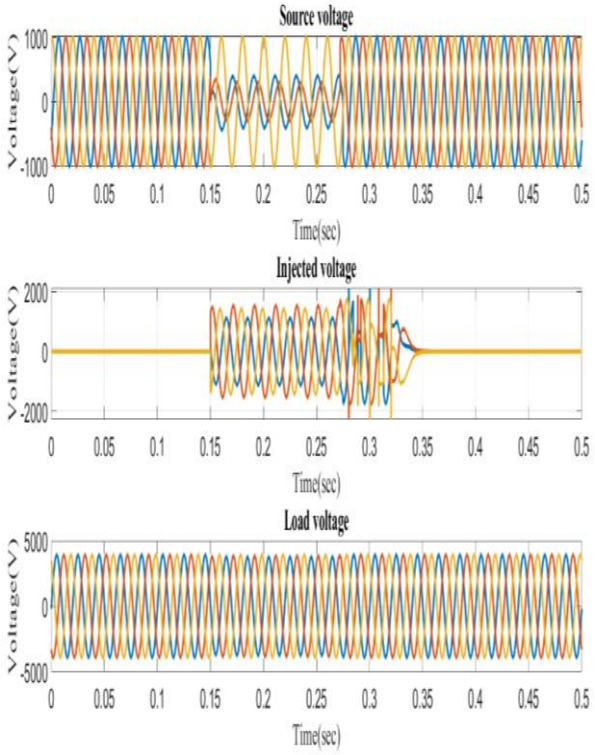


Fig. 12: Analysis of sag compensation under Dynamic shading condition
Source: Simulation results obtained by the authors.

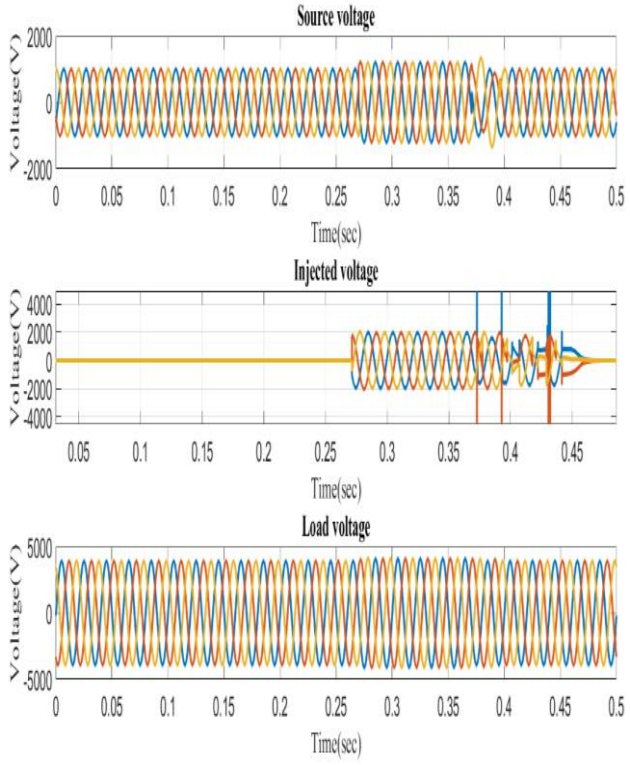


Fig. 13: Analysis of swell compensation under Dynamic shading condition
Source: Simulation results obtained by the authors.

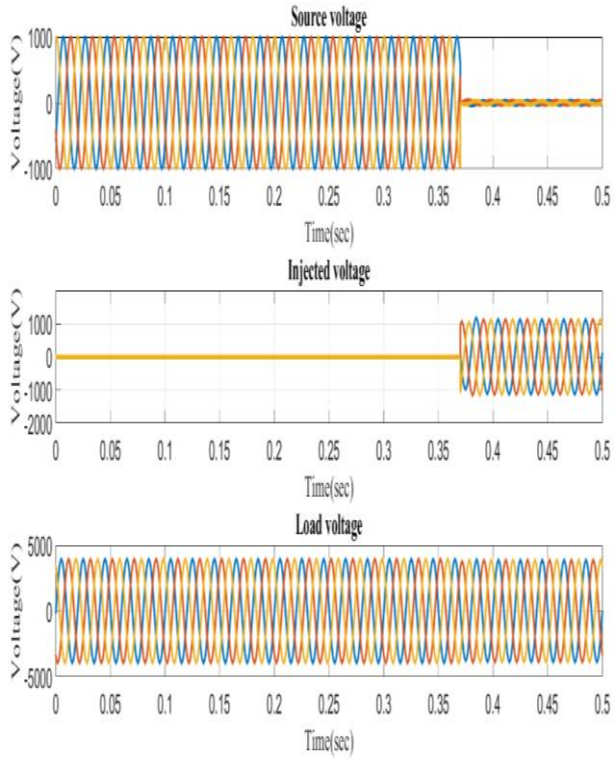


Fig. 14: Analysis of Interruption under Dynamic shading condition
Source: Simulation results obtained by the authors.

6 Conclusion

This paper presented a Fuzzy Logic Controller (FLC)-based 48-pulse D-STATCOM for enhancing power quality in a 13-nodes test system integrated with a 17.3 kW photovoltaic (PV) renewable energy source. The proposed compensator, regulated by a Mamdani FIS with 10 fuzzy rules mapping voltage error at Bus 3 to a gate-pulse variation spanning -67.5° to +67.5° across a 6-pulse to 48-pulse phase-shifted converter arrangement (±3.75° per transformer stage), was designed to dynamically regulate the point of common coupling (PCC) voltage by providing rapid reactive power support during power quality disturbances. The effectiveness of the control approach was validated under three operating conditions: supply interruption (source voltage dropping below 0.1 p.u.), static PV shading (irradiance reduced to 800 W/m²), and dynamic PV shading (irradiance varied across 700, 800, 1000, and 900 W/m²). Simulation results demonstrated that the FLC-controlled D-STATCOM successfully mitigated voltage sag, voltage swell, and interruption phenomena, restoring the PCC voltage to approximately 1.0 p.u. with a steady-state tracking error of less than 5% in all three cases. Furthermore, the integration of the two 25 V, 16 Ah battery-supported D-STATCOM

units ensured continuous voltage support during variations in solar irradiance, thereby improving system reliability and operational stability under fluctuating renewable generation conditions.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work, the author(s) utilized artificial intelligence (AI) technologies solely for the purpose of linguistic refinement and grammatical correction. Following the application of these tools, the author(s) comprehensively reviewed, verified, and edited the resulting text. The author(s) maintain full accountability and responsibility for the accuracy, integrity, and final content of the publication.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

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Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

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APPENDIX

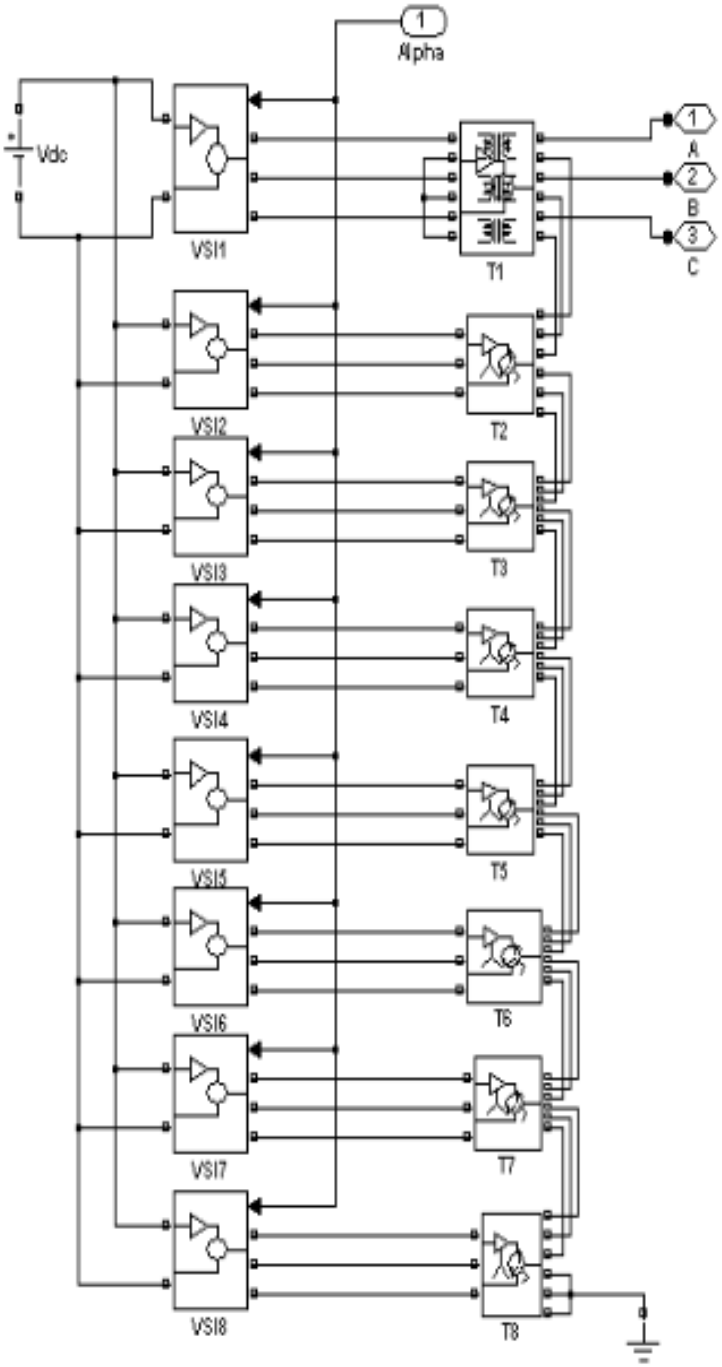


Fig. 4: Simulink model of 48 pulse D-STATCOM
Source: Adapted by the authors in [3].

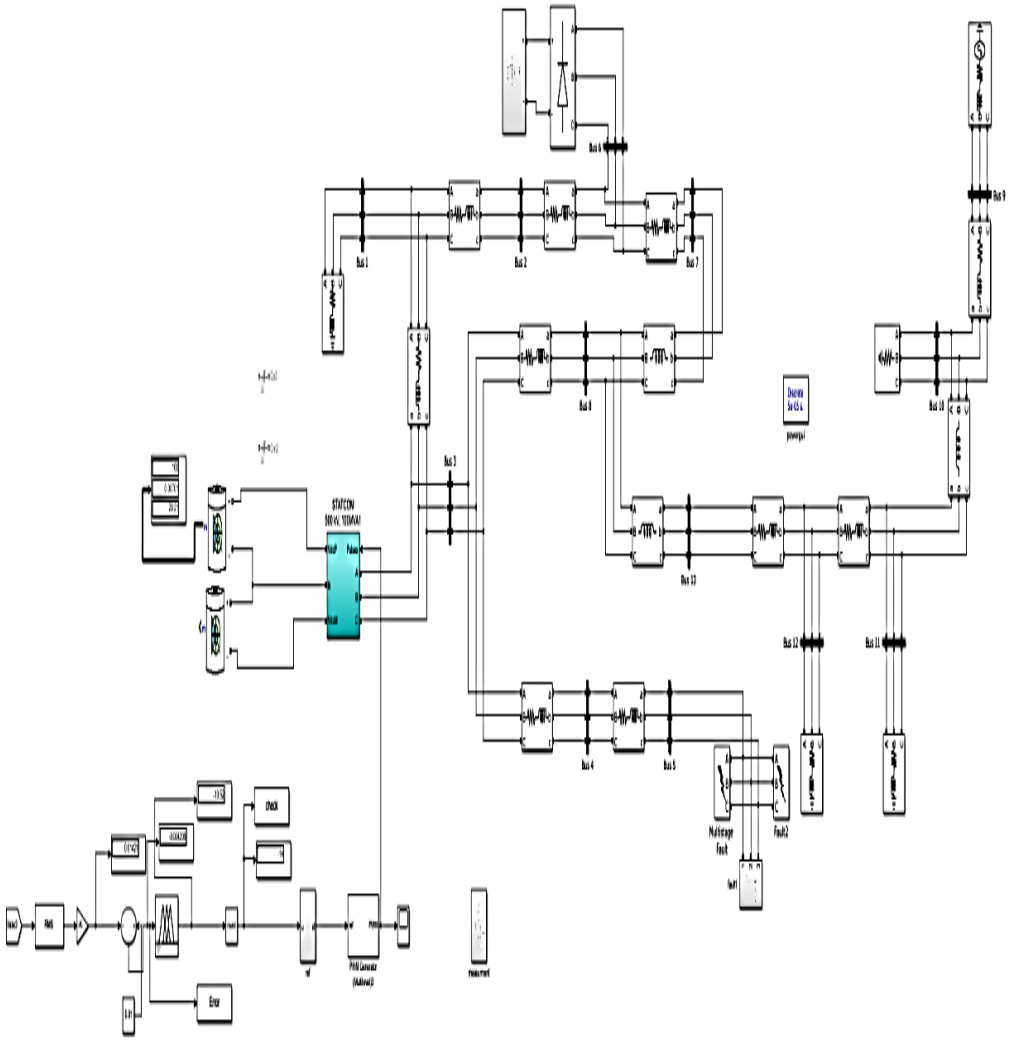


Fig. 5: Simulink model of FLC based D-STATCOM
Source: Created by the authors using MATLAB/Simulink.

Table 4. Fuzzy Rules

E / dE	NL (-0.07, -0.05)	NB (-0.07, -0.05, -0.03)	NM (-0.05, -0.03, -0.02)	NS (-0.03, -0.02, -0.015)	NVS (-0.02, -0.015, -0.005)	ZE (-0.015, -0.005, 0)	PVS (-0.005, 0, 0.02)	PS (0, 0.02, 0.04)	PM (0.02, 0.04, 0.06)	PB (0.04, 0.06, 0.08)	PL (0.06, 0.08, 0.1)
NL (-0.07, -0.05)	NL -67	NL -67	NB -52.5	NB -52.5	NM -37.5	NM -37.5	NS -22.5	NVS -15	NVS -15	ZE -7.5	ZE -7.5
NB (-0.07, -0.05, -0.03)	NL -67	NB -52.5	NB -52.5	NM -37.5	NS -22.5	NS -22.5	NVS -15	NVS -15	NVS -15	ZE -7.5	ZE -7.5
NM (-0.05, -0.03, -0.02)	NB -52.5	NB -52.5	NM -37.5	NM -37.5	NS -22.5	NS -22.5	NVS -15	NVS -15	ZE -7.5	ZE -7.5	PVS 0
NS (-0.03, -0.02, -0.015)	NB -52.5	NB -52.5	NM -37.5	NS -22.5	NS -22.5	NVS -15	NVS -15	ZE -7.5	ZE -7.5	PVS 0	PVS 0
NVS (-0.02, -0.015, -0.005)	NM -37.5	NS -22.5	NS -22.5	NS -22.5	NVS -15	NVS -15	ZE -7.5	ZE -7.5	PVS 0	PVS 0	PS 15
ZE (-0.015, -0.005, 0)	NM -37.5	NS -22.5	NS -22.5	NVS -15	NVS -15	ZE -7.5	ZE -7.5	PVS 0	PVS 0	PS 15	PS 15
PVS (-0.005, 0, 0.02)	NS -22.5	NVS -15	NVS -15	NVS -15	ZE -7.5	ZE -7.5	PVS 0	PVS 0	PS 15	PS 15	PM 22.5
PS (0, 0.02, 0.04)	NVS -15	NVS -15	NVS -15	ZE -7.5	ZE -7.5	PVS 0	PVS 0	PS 15	PS 15	PM 22.5	PM 22.5
PM (0.02, 0.04, 0.06)	NVS -15	NVS -15	ZE -7.5	ZE -7.5	PVS 0	PVS 0	PS 15	PS 15	PM 22.5	PM 22.5	PB 52.5
PB (0.04, 0.06, 0.08)	ZE -7.5	ZE -7.5	ZE -7.5	PVS 0	PVS 0	PS 15	PS 15	PM 22.5	PM 22.5	PB 52.5	PB 52.5
PL (0.06, 0.08, 0.1)	ZE -7.5	ZE -7.5	PVS 0	PVS 0	PS 15	PS 15	PM 22.5	PM 22.5	PB 52.5	PB 52.5	PL 60

Source: Fuzzy rules developed by the authors