Fuzzy Logic Control of D-STATCOM for Power Quality Improvement in Distribution Networks with Non-Linear Loads

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Abstract

Voltage stability and reactive power management are two issues that arise when photovoltaic (PV) devices are integrated into the power grid. In this study, a grid-connected photovoltaic system that has been upgraded with a Static Synchronous Compensator (STATCOM) to boost reactive power compensation and preserve grid stability is examined. The suggested method ensures power quality and lowers voltage fluctuations by effectively managing the flow of active and reactive power. To maximize STATCOM performance under changing load and sunlight circumstances, a fuzzy based control technique is proposed that allows for dynamic compensation. This will improves the overall power factor, reduce voltage variances, and improve overall grid performance. The proposed work is justified by the simulation results. The MATLAB/Simulink results show that PV-STATCOM integration has the potential to be a workable solution for contemporary power networks dealing with rising penetration of renewable energy.

Keywords: Reactive Power Compensation, D-STATCOM , Fuzzy Logic Controller, Power quality Improvement .

I. INTRODUCTION

Power quality (PQ) has become a critical concern in modern electrical distribution networks due to the increasing penetration of non-linear and time-varying loads such as power electronic converters, arc furnaces, uninterruptible power supplies, and adjustable speed drives. These loads introduce harmonics, voltage sags/swells, flicker, and reactive power disturbances, thereby degrading the overall system efficiency and reliability [1], [2]. To mitigate such issues, the use of custom power devices (CPDs) has been proposed as a viable solution. Among them, the Distribution Static Compensator (D-STATCOM), a shunt-connected voltage source converter (VSC), has gained widespread attention for its ability to inject reactive power and compensate for load disturbances in real time [3], [4]. D-

STATCOMs are particularly effective in maintaining voltage regulation, improving power factor, and reducing total harmonic distortion (THD) at the point of common coupling (PCC) [5]. The performance of D-STATCOM is largely dependent on the effectiveness of its control strategy. Conventional controllers such as the Proportional-Integral (PI) controller are simple to implement but often fail to provide satisfactory dynamic performance in the presence of system non-linearities, parameter uncertainties, and rapidly varying load conditions [6], [7]. Moreover, these linear controllers require frequent tuning and lack adaptability under diverse operating scenarios.To overcome the limitations of conventional methods, intelligent control techniques such as Fuzzy Logic Control (FLC) have been introduced [8]. FLC provides a non-linear, rule-based approach that does not require an exact mathematical model of the system. It emulates human reasoning by handling imprecision and uncertainties through linguistic rules and fuzzy sets, thus offering improved robustness and adaptability [9]. Compared to traditional controllers, FLCs exhibit faster response times, better steady-state performance, and superior control under uncertain conditions [10]. Several studies have highlighted the application of fuzzy controllers for custom power devices. In [11], the authors demonstrated the effectiveness of a fuzzy logic-based D-STATCOM in voltage sag mitigation. Similarly, in [12], a comparative analysis showed that fuzzy controllers significantly outperformed PI controllers in terms of THD reduction and voltage regulation under non-linear load conditions.

This paper presents a Fuzzy Logic Control strategy for the D-STATCOM to enhance power quality in distribution networks experiencing non-linear loads. The proposed controller is designed to improve voltage profile, minimize THD, and enhance dynamic performance. The system is modelled in MATLAB/Simulink, and its performance is evaluated under various load scenarios. The results are benchmarked against a PI-controlled D-STATCOM to demonstrate the superiority of the fuzzy logic approach. The remainder of the paper is organized as follows: Section II presents the system configuration and modelling of the D-STATCOM. Section III describes the design of the Fuzzy Logic Controller. Section IV provides simulation results and analysis. Section V concludes the paper with key findings and suggestions for future work.

II.   SYSTEM DESCRIPTION

The block diagram depicted in   shows a reactive power compensation system designed to improve power quality at the point of common coupling where nonlinear load connected to gird. A D-STATCOM is a controlled reactive source, which includes a Voltage Source Converter (VSC) and a DC-link capacitor connected in shunt, capable of generating and/or absorbing reactive power. It is shunt connected at the distribution side of the power systems.
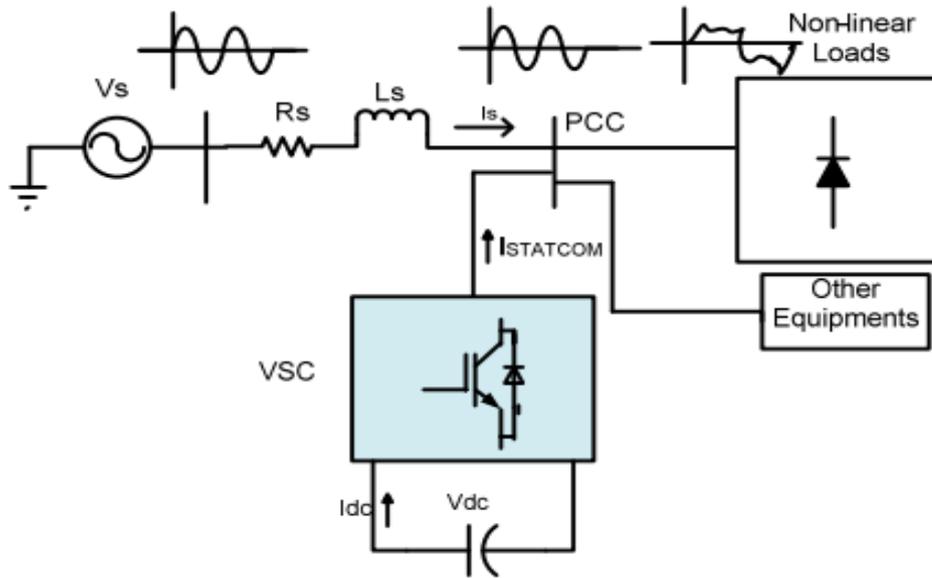
Figure 1:Power system with D-STATCOM

The operating principles of D-STATCOM are based on the exact equivalence of the conventional rotating synchronous compensator [13]. The AC terminals of the VSC are connected to the Point of Common Coupling (PCC) through an inductance, which could be a filter inductance or the leakage inductance of the coupling transformer, as shown in **Error! Reference source not found.**. The DC side of the converter is connected to capacitor, which carries the input ripple current of the converter and reactive energy storage element. This capacitor could be charged by voltage source or inverter. When AC output voltage of inverter is equal to terminal voltage, then there is no reactive power exchange. It there difference between these voltages the only reactive power exchange occurs. The control strategies studied in this paper are applied with a view to studying the performance of a D-STATCOM for reactive power compensation and harmonic mitigation. Configuration and operation of DSTATCOMD-STATCOM has 3-phase voltage source converter, capacitor at DC side of inverter is connected with the electrical system at the PCC. The instantaneous controllable3-phase output voltage is generated from DC voltage at fundamental frequency. The pulse is generated by hysteresis current controller which takes the difference of reference current and actual source current and minimize the error and controls the current and generate 3-phase output voltage and injects capacitive or inductive current according to the nature of load [14].

III. CONTROL OF PROPOSED SYSTEM WITH CONVERNTIONAL CONTROL

A. Mathematical modelling for reactive shunt compensated system with non-linear load

Converter Side Equations: *In the synchronous rotating reference frame (d-q):*

$$V_{sd} = R_s i_d + \frac{L_s di_d}{dt} - L_s \omega i_q + v_{od} \qquad (1)$$

$$V_{sq} = R_s i_q + \frac{L_s di_q}{dt} + L_s \omega i_d + v_{oq} \qquad (2)$$

Where:

V_{sd}, V_{sq} are d-q components of grid voltage at PCC

i_d, i_q are d-q components of inverter (D-STATCOM) output current

v_{od}, v_{oq} are d-q components of inverter output voltage

R_s is the resistance of coupling inductor

L_s is the inductance of coupling inductor

ω is angular frequency of the grid

In grid-synchronous reference frame, we typically align the grid voltage such that:

$V_q = 0, \quad V_d = |\,V\,|$

Then , $P_{grid} = \frac{3}{2} V_d i_d, Q_{grid} = -\frac{3}{2} V_d i_q$

The mathematical modelling for the proposed system is as shown below. Total instantaneous power drawn by non-linear load is represented as,

So the Power balance equation become:

$$P_{grid} + P_{DSTATCOM} = P_{load} \qquad (3)$$

$$Q_{grid} + Q_{DSTATCOM} = Q_{load} \qquad (4)$$

Where:

- P_{grid}, Q_{grid}:   Real and reactive power from the grid

- $P_{DSTATCOM}, Q_{DSTATCOM}$: Power handled by the D-STATCOM

- P_{load}, Q_{load} :Total load power, including harmonic distortion effects

Non-linear loads inject harmonic currents and cause distorted voltages. Therefore, the load power has to be separated into:

- Fundamental active power (P_1)

- Fundamental reactive power (Q_1)

- Distortion power (D) due to harmonics

And distortion compensation (harmonics) is handled only by the D-STATCOM, since grid cannot compensate:

$$P_{grid} + P_{DSTATCOM} = P_1 + P_{harm} \qquad (5)$$

$$Q_{grid} + Q_{DSTATCOM} = Q_1 \qquad (6)$$

$$D_{STATCOM} = D_{load} \qquad (7)$$

The apparent power (S) becomes:

$$S = \sqrt{P_1^2 + Q_1^2 + D^2} \qquad (8)$$

The D-STATCOM in presence of non-linear load aims to:

- Supply reactive power Q_1

- Cancel out harmonic currents (to improve power quality)

- Maintain unity power factor and voltage at PCC

  In other words

  $$P_{DSTATCOM} = P_{sh} - P_{loss} \qquad (9)$$

  $$Q_{DSTATCOM} = Q_1 + Q_{sh} \qquad (10)$$

  Where P_{sh} is the shunt power generated by the STATCOM, $P_{DSTATCOM}$ is reactive power delivered by the STATCOM. P_{loss} is the losses in the STATCOM.

B. Conventional Control strategy
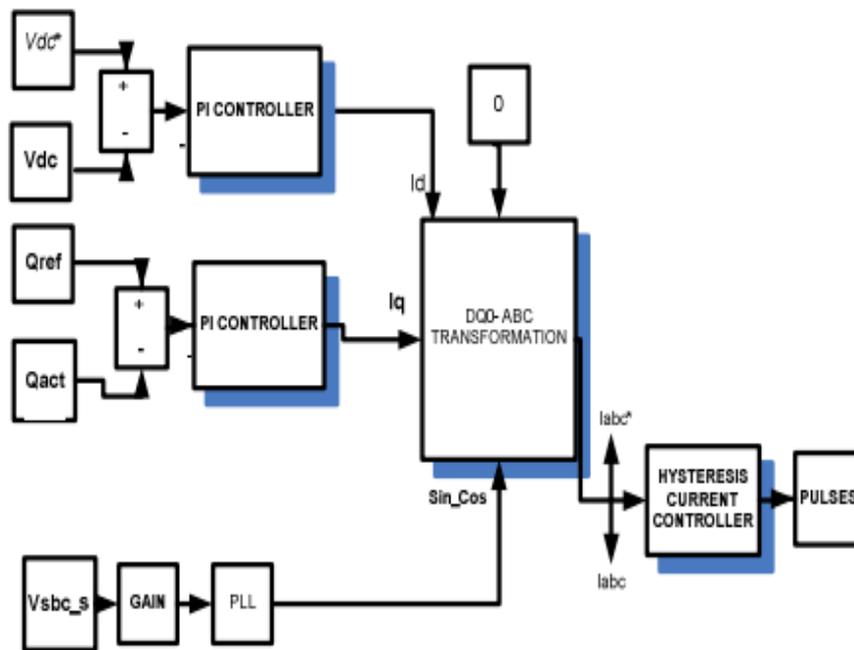
Figure 2:Control Strategy to generate pulses

From the single line diagram Figure 2

$$I_s(t) = I_L(t) + I_{STATCOM}(t) \qquad (9)$$

When the phase of $V_{STATCOM}$ is in quadrature with $I_{STATCOM}$ without injecting real power the D-STATCOM can achieve the voltage sag mitigation. The shunt injecting current $I_{STATCOM}$ and 5 in Figure 2, can be expressed as equation (9) and (10)

$$I_{STATCOM} = I_L - I_S = I_L - (V_{th} - V_L)/Z_{th} \qquad (10)$$

$$\text{Where, } V_L = V_{th} + (I_{STATCOM} - I_L)Z_{th} \text{ and } I_s = -(V_{th} - V_L)/Z_{th}$$

The direct and quadrature axis component of current are:

$$I_d = \left(K_p + \frac{K_p}{s}\right) * (V_{DC}^* - V_{DC}) \qquad (11)$$

$$I_q = \left(K_p + \frac{K_p}{s}\right) * \left(Q_{grid}^* - Q_{grid}\right) \qquad (12)$$

C. Proposed Fuzzi logic Control strategy

Fuzzy Rules: The fuzzy controller uses a set of IF-THEN rules based on the linguistic interpretation of E and ΔE

Membership Functions (MF): These define the linguistic terms (e.g., Negative, Zero, Positive) for E and ΔE, typically using triangular or trapezoidal functions.

The outcome of the fuzzy inference system is the reference component of current on d-axis (I_d^*), Similarly the error and change in error due to reactive power are given as inputs to other fuzzy controller to get the (I_q^*). The block diagram of fuzzy system is shown in
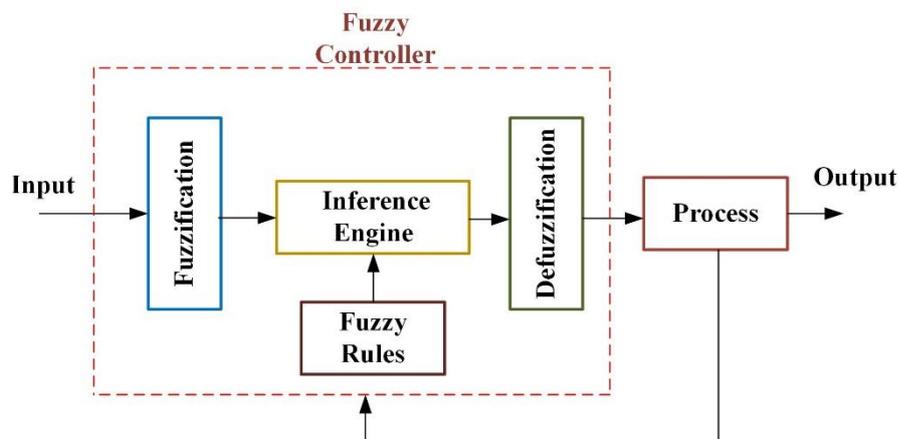

Figure 3: Operation of Fuzzy Control

In the Figure 2, the conventional PI controller is replaced with fuzzy controller such that the error caused by difference between actual and reference DC voltage and change in error is given as inputs to the fuzzy controller.
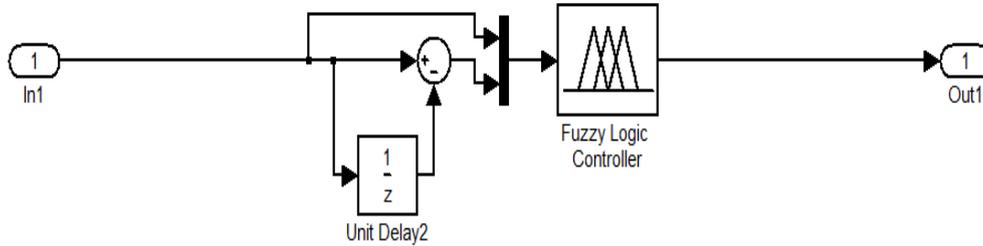

Figure 4: Fuzzy logic control circuit

The d-q current references of each phase are given to hysteresis current controller

D. Hysteresis Current Controller

In conventional hysteresis band (HB) current control, the switching signal is sent to the IGBT at the same arm (T1 andT4). The output of the HBC is directly connected to the transistor T1 and inverted signal is connected to the T4, therefore the transistor in the same leg is not simultaneously ON or OFF. IGBT are self-commutated. Hysteresis Current Controller compares the actual and reference current and generates pulses for the inverter
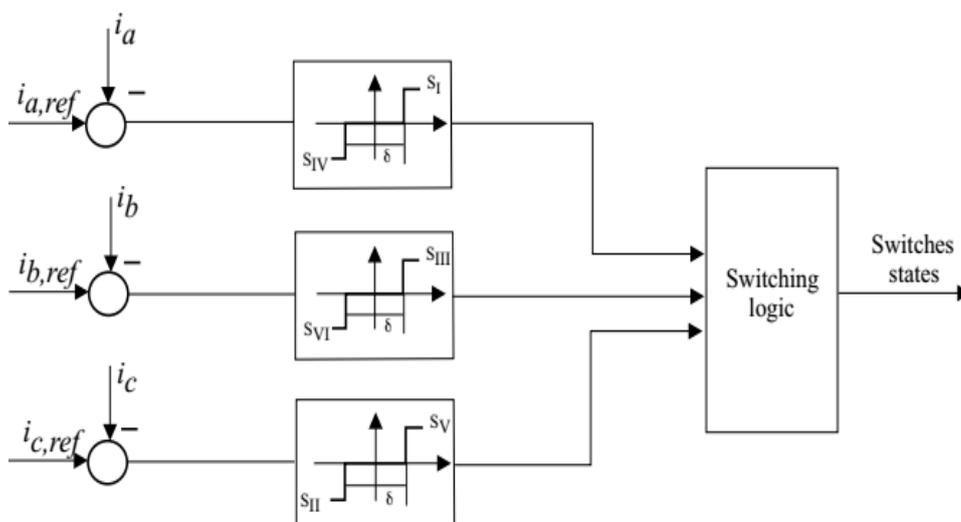

Figure 5: Structure of hysteresis control

If $i \leq (i^* - HB)$, then T_1 is ON

If $i \geq (i^* + HB)$, then T_4 is ON

Where T_1 is the switch in the upper commutation group for phase A in VSI, instantaneous power flows from DC to AC and T_4 is the switch in the lower commutation group for phase A, instantaneous power flows form AC to DC.

RESULTS & DISCUSSION

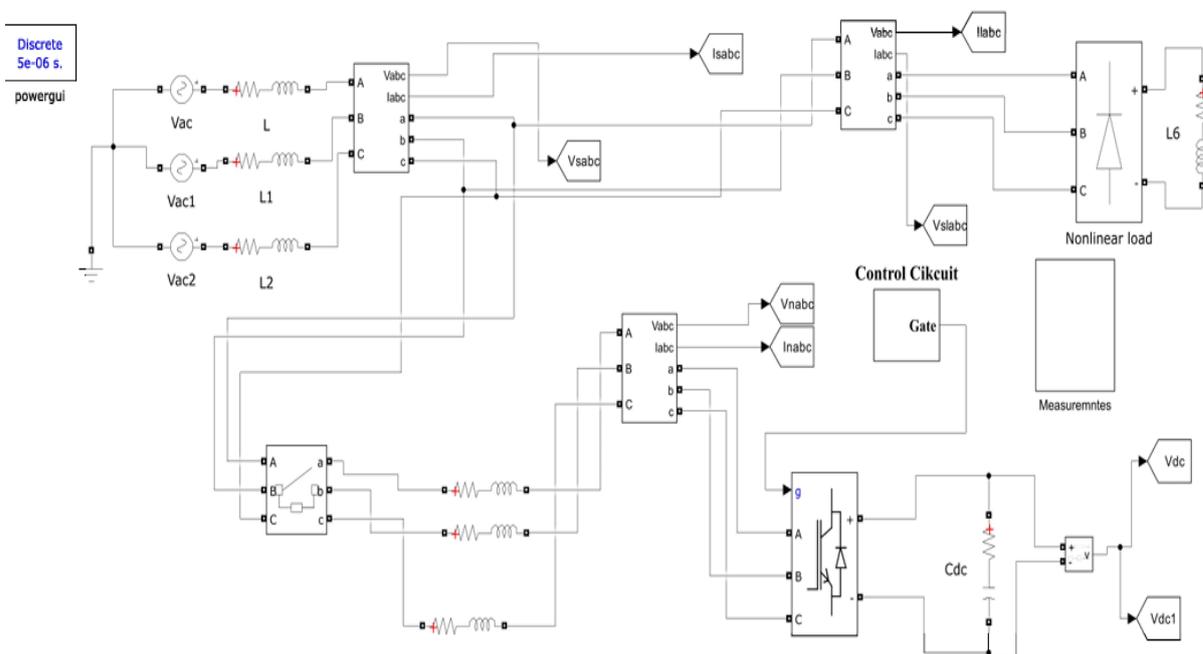The Simulink Diagram of the proposed system is shown below:

Figure 6 :Simulink diagram of proposed system

Shows the Simulink diagram of proposed system ,which consists of D-STATCOM connected to grid at point of common coupling . PCC is the one where non-linear load is connected to grid. The D STATCOM is connected to PCC with a circuit breaker to realize the behaviour of injection of D-STATCOM when grid is feeding a non-linear load.

(a)
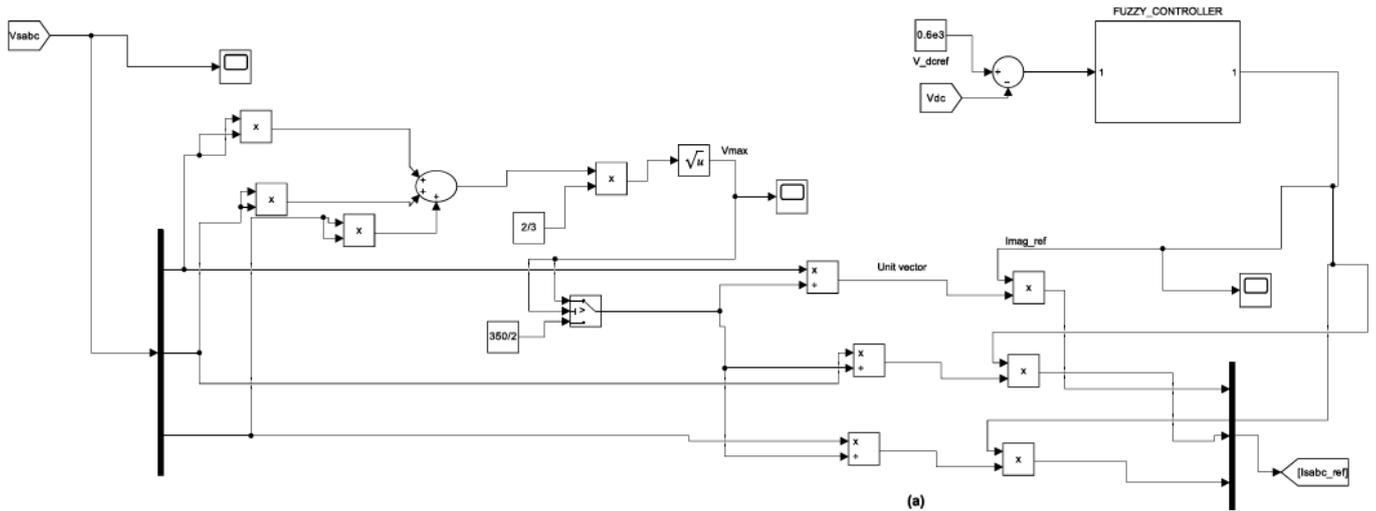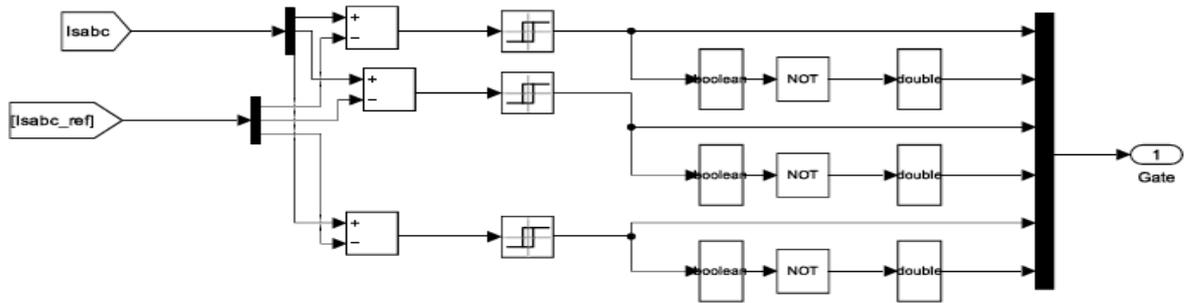
Figure 7: Simulink diagram of fuzzy logic based control strategy to generate current references(a), Simulink diagram of hysteresis current control(b)
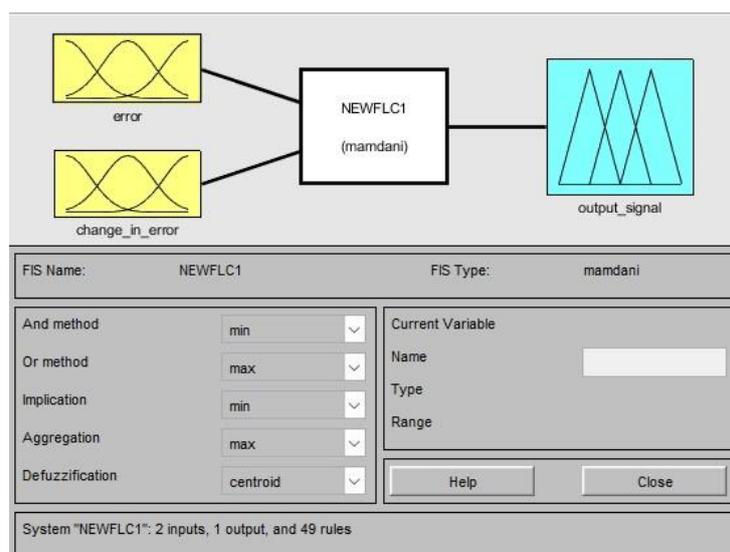

Figure 8:Fuzzy logic controller block diagram
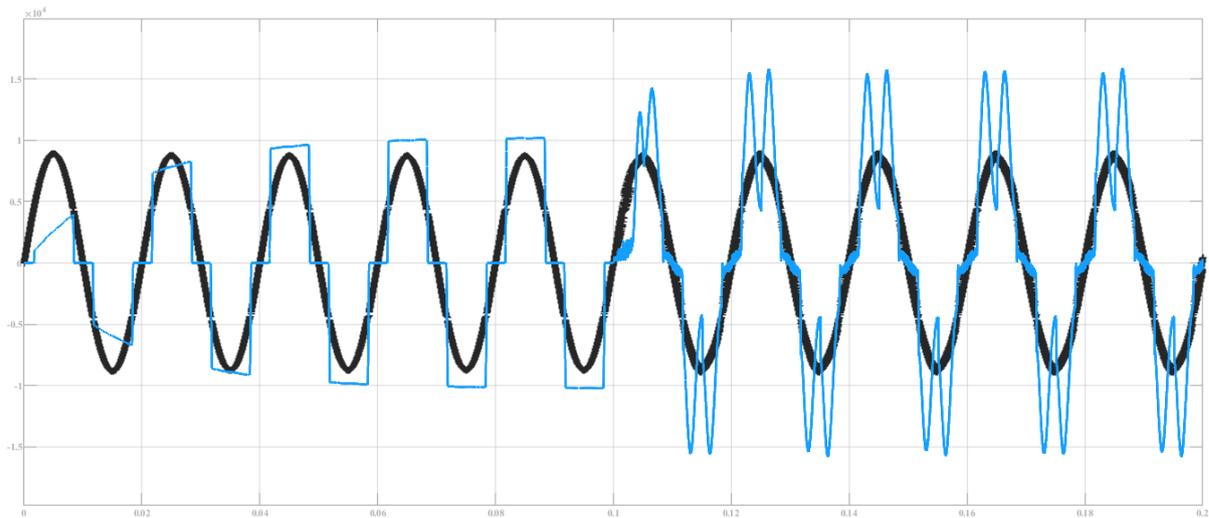
Figure 9: Fuzzy logic controller rule base

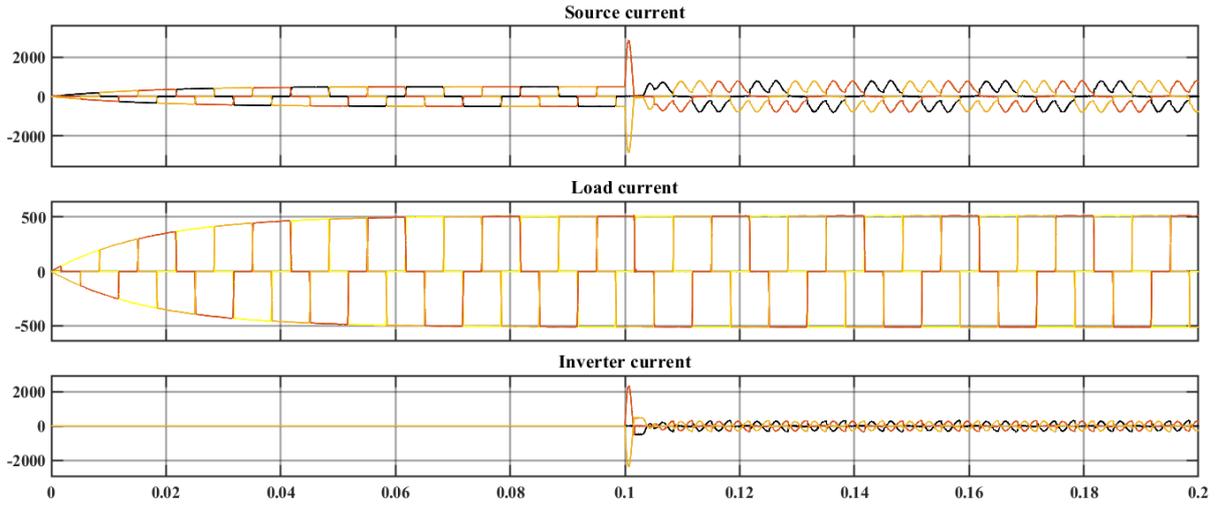Figure 10:Source Power factor Correction : Source Voltage and current waveforms
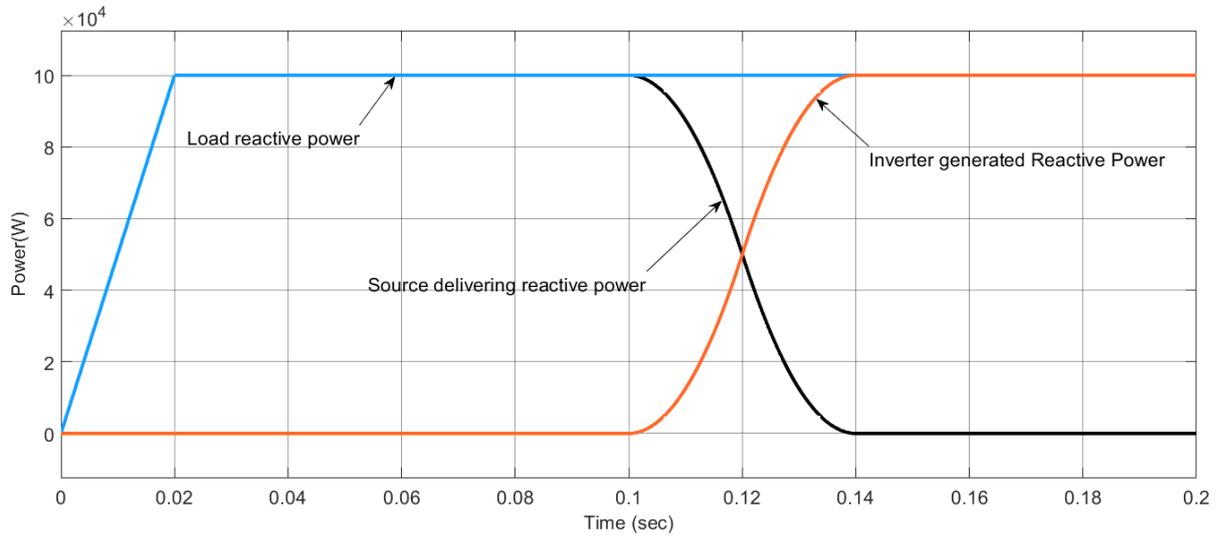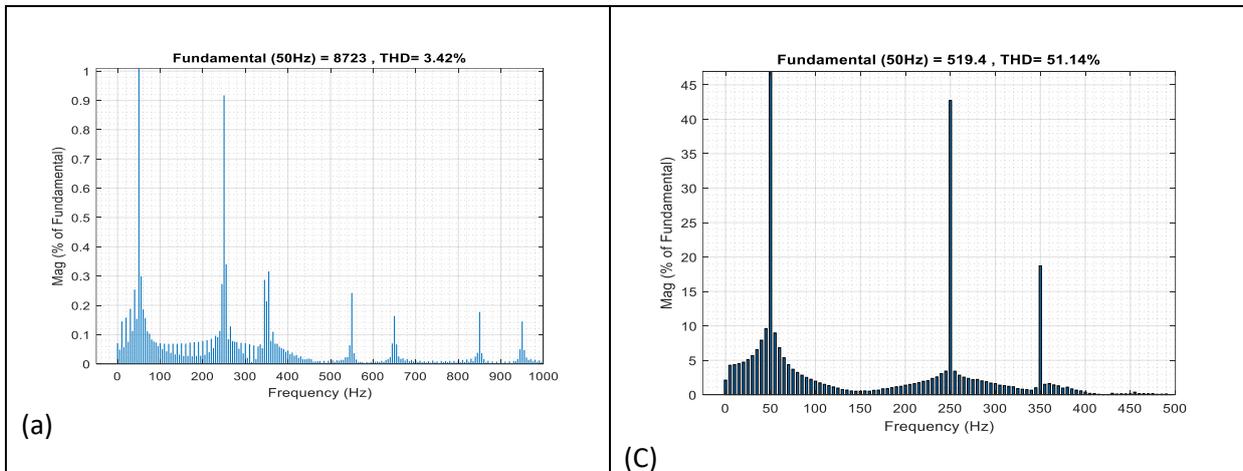
Figure 11: Source, load and inverter current waveforms

Figure 12:Reactive power generated by inverter, delivered by load and drawn by the load
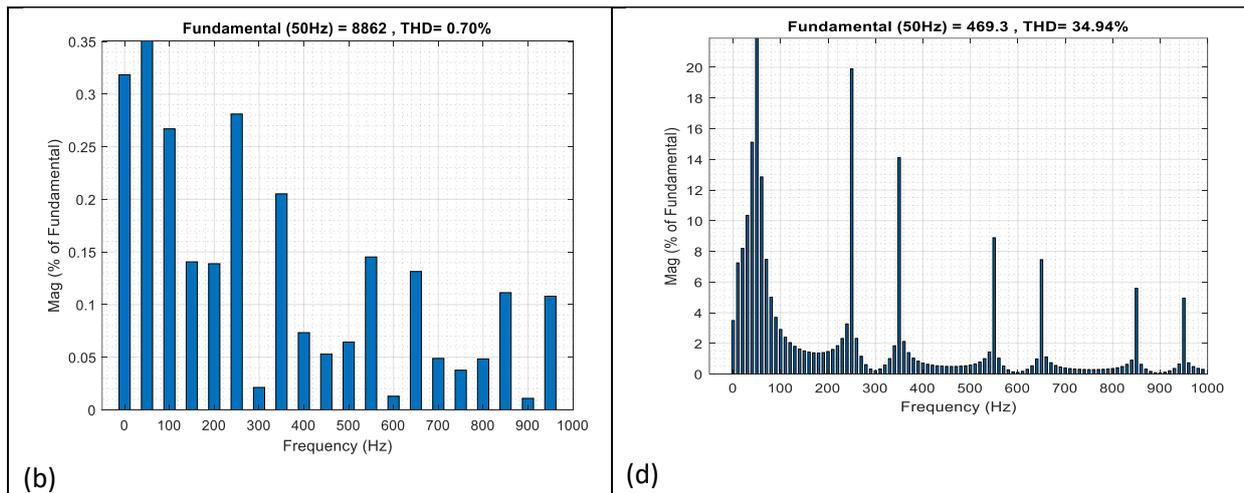
Figure 13: THD analysis : Load Voltage THD with non-linear load at PCC (a), source voltage THD with compensation(b),current THD with conventional control(c) and with fuzzy based control (d)

IV.   CONCLUSION

The model is designed and analysed its performance on the basis of reactive power compensation and power quality improvement. In this model, PI and Fuzzy controller are used. The proposed concept is simulated using matlab/Simulink and performance is observed doing THD analysis. From that we can observe that fuzzy controlling technique is having much better performance than PI controller. From the above results ,it is evident that the proposed Fuzzy logic based control strategy for reactive power compensation in improving the power quality ,maintaining unity power factor and improved system voltage THD and current THDs compared with the conventional PI controller based control strategy.

References

[1].   B. Singh, K. Al-Haddad, and A. Chandra, "A review of active filters for power quality improvement," IEEE Trans. Ind. Electron., vol. 46, no. 5, pp. 960–971, Oct. 1999.

[2].   H. Hingorani, "Introducing custom power," IEEE Spectrum, vol. 32, no. 6, pp. 41–48, Jun. 1995.

[3].   A. Ghosh and G. Ledwich, Power Quality Enhancement Using Custom Power Devices, Springer, 2002.

[4].   R. Gupta, A. Ghosh, and A. Joshi, "Performance comparison of VSC-based shunt and series compensators used for load voltage control," IEEE Trans. Power Del., vol. 26, no. 1, pp. 268–278, Jan. 2011.

[5].   M. Aredes, J. Hafner, and K. Heumann, "Three-phase four-wire shunt active filter control strategies," IEEE Trans. Power Electron., vol. 12, no. 2, pp. 311–318, Mar. 1997.

[6].   C. Sankaran, Power Quality, CRC Press, 2002.

[7]. S. Mishra, A. Joshi, and A. Ghosh, "A new algorithm for control of active power filters," IEEE Trans. Power Del., vol. 18, no. 1, pp. 212–218, Jan. 2003.

[8]. D. Driankov, H. Hellendoorn, and M. Reinfrank, An Introduction to Fuzzy Control, Springer, 1996.

[9]. Z. L. Gaing, "A particle swarm optimization approach for optimum design of PID controller in AVR system," IEEE Trans. Energy Convers., vol. 19, no. 2, pp. 384–391, Jun. 2004.

[10]. R. Kennedy and S. Das, "A comparative analysis of PI and fuzzy logic controllers for D-STATCOM," Int. J. Emerging Elect. Power Syst., vol. 11, no. 3, pp. 1–10, 2010.

[11]. A. M. Shiddiq Yunus, T. Senjyu, and T. Funabashi, "Fuzzy logic-based control of D-STATCOM for voltage sag mitigation," Int. J. Elect. Power Energy Syst., vol. 43, no. 1, pp. 568–574, Dec. 2012.

[12]. N. Kumar and B. Singh, "Design and analysis of fuzzy logic-based D-STATCOM for power quality improvement," Int. J. Emerging Elect. Power Syst., vol. 15, no. 2, pp. 139–150, 2014.

[13]. M. K. Pal, "Voltage stability conditions considering load characteristics," in IEEE Transactions on Power Systems, vol. 7, no. 1, pp. 243-249, Feb. 1992, doi: 10.1109/59.141710.

[14]. Vandana S Pai, Jo Joy. "Reactive Power Compensation and Harmonic Mitigation in a Grid connected system using STATCOM", IJAREEIE, Volume 3, Special Issue5, (2014).

[15]. Pranati Katyal, Rajesh Katyal, K.Premkumar, "PV, Wind powered Electric Vehicle Charging Station with Fuzzy and Perturb & Observe MPPT Control", Journal of Next Generation Technology (ISSN: 2583-021X), 4(3), pp. 1-14. Dec 2024.