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Implementation of Fuzzy Logic Controller Based D-STATCOM For Power Quality Enhancement in Distribution Systems

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ABSTRACT

The project aims to optimize power quality in distribution systems using a Fuzzy Logic Controller-based Distribution Static Compensator (DSTATCOM) with a combined Proportional Resonant (PR) and Comb Filter Controller. The D-STATCOM is a power electronic device that can control and compensate reactive power, voltage sag/swell, and harmonic distortion in the distribution system. The proposed Fuzzy Logic Controller-based DSTATCOM with a combined PR and Comb Filter Controller offers improved performance in terms of power factor correction, voltage regulation, and harmonic mitigation. The project proposes to design and simulate the system using MATLAB/Simulink, and the results obtained show the effectiveness of the proposed system in improving power quality in distribution systems.

Keywords: D-STATCOM, Fuzzy Logic Controller, Power Quality, PI controller, Voltage Source Inverter.

I. INTRODUCTION

Currently, non-renewable energy resources are the primary source for power generation. However, their excessive use can deplete fossil fuels and pose environmental threats, potentially leading to power quality issues in distribution systems. To address this, renewable energy resources are being considered as an alternative source for power generation in distribution systems [1]. FACTS devices have been employed for various applications, such as stabilizing voltage, utilizing energy, mitigating harmonic contents, and compensating PQ-related issues, as stated in [2]-[3]. Other applications, such as compensating reactive power, regulating voltage, and reducing power loss, are described in [4]-[5]. In addition, for grid protection, the role of power electronic (PE) converters has gained popularity alongside renewable energy resources [6]. In the 1980s, the introduction of FACTS devices aimed to improve the efficiency of power systems-related resources [7]. These devices consider factors that impact harmonics emitted by power converters. However, it's important to note that system operators may impose more stringent restrictions. Passive filters are often utilized to minimize harmonic emissions [8]. Converter control and modulation can also affect harmonic creation, and one approach to address this is through selective harmonics compensation algorithms. These methods are particularly relevant when using weak grid converters as the voltage is more susceptible to harmonics and other disturbances [9]. Efficient control of reactive power flow within the network is essential for optimal power system operation. FACTS-based components, such as D-STATCOM (Distribution Static VAR Compensator), SVC (Static VAR Compensator), and UPQC (Unified Power Quality Conditioner), compensate for reactive power flow and can control voltage, line impedance, and phase angle between the sending and receiving ends [10]. The integration of FACTS devices with power electronic converters is becoming increasingly important for power system analysis and control. As proposed in [11], planning, operation, and calculation can lead to solutions for power flow in the network. Previous studies have focused on the effects of D-STATCOM modelling on PQ problems [12], which can mitigate voltage fluctuations, control voltage at the distribution side, and reduce loadrelated issues. According to [13], D-STATCOM can be defined as a coupling transformer, DC-AC converter, and Energy Storage System (ESS) that is implemented in distribution systems. In contrast, STATCOM manages only fundamental reactive power and provides voltage support at the transmission level. A flexible device like DSTATCOM can also be utilized to correct imbalances or distortions in the source current or supply voltage [14]. Repetitive controllers (RC) have been suggested as a means of reducing voltage and current harmonics [16]. The PI controller topology was employed to address voltage and current issues, and it effectively improves system performance whether used in a single or hybrid structure. The topology and PR controller can be applied in [17]. This study proposes the use of a Fuzzy Logic controller-based DSTATCOM to improve PQ in power distribution systems. The paper includes an introduction and literature review of existing methods in section I, a system description in section II, an explanation of the proposed controller's performance in section III, simulation results in section IV, and a conclusion in section V.

II. SYSTEM DESCRIPTION

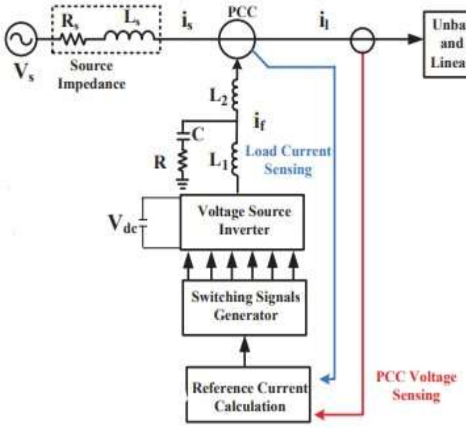


Figure 1: D-STATCOM Structure

Figure 1 above shows the schematic representation of a D-STATCOM in shunt connection to the grid, which is the primary source for non-linear and unbalanced loads in a 3-phase AC grid. Non-linearity in loads can cause power quality issues in the grid, and FACTS devices can be used to compensate for these issues, including harmonics. In this study, a DSTATCOM is implemented in parallel with the grid, using a DC source that passes through an inverter circuit to produce AC power. The inverter is controlled using a new topology called FLC, which regulates the voltage at the DC link and injects the necessary compensating current into the three-phase grid to reduce harmonics in the system. The theory of instantaneous symmetrical components can be used to express the selection of power factor angle as follows:

$$\angle\{a v_{sb} + v_{sa} + a^2 v_{sc}\} = \angle\{a i_{sb} + i_{sa} a^2 i_{sc}\} + \varphi^{+} \quad (1)$$

By rewriting the above equation can be obtained as follows:

$$i_{sa}(v_{sb} - v_{sc} - 3\gamma(v_{sa} - v_0)) +$$
$$i_{sb}(v_{sc} - v_{sa} - 3\gamma(v_{sb} - v_0)) +$$
$$i_{sc}(v_{sa} - v_{sb} - 3\gamma(v_{sb} - v_o)) = 0 \quad (2)$$

Where, $\gamma = tan\,\varphi +$, angle$\varphi + = 0$, hence$\gamma = 0$, is used for UPF operation.

P$_{lavg}$, The source supplies the load's average active power, while the compensator supplies the load's oscillating component. Therefore,

$$i_{sa}v_{sa} + i_{sb}v_{sb} + i_{sc}v_{sc} = p_{lavg} \quad (3)$$

If the inverter is functioning perfectly, the source solely supplies the average power of the load.

However, because the switches are not ideal, the source must compensate for the losses (Ploss) in the VSI.

$$\begin{bmatrix} i^*_{sa} \\ i^*_{sb} \\ i^*_{sc} \end{bmatrix} = M^{-1} \begin{bmatrix} 0 \\ 0 \\ P_{lavg} + P_{loss} \end{bmatrix}$$

(4)

Where,

$$= \begin{vmatrix} 1 & 1 & 1 \\ x_1 & x_2 & x_3 \\ v_{sa} & v_{sb} & v_{sc} \end{vmatrix} \quad (5)$$

Where, x$_1$, x$_2$ and x$_3$ are stated as

$$x_1 = -v_{sc} - 3\gamma(v_{sa} - v_o) + v_{sb}$$
$$x_2 = -v_{sa} - 3\gamma(v_{sb} - v_0) + v_{sc}$$
$$x_3 = -v_{sb} - 3\gamma(v_{sc} - v_o) + v_{sa}$$

Hence, the reference currents can be given as

$$\begin{bmatrix} i^*_{fa} \\ i^*_{fb} \\ i^*_{fc} \end{bmatrix} = \begin{bmatrix} i_{la} - i^*_{sa} \\ i_{lb} - i^*_{sb} \\ i_{lc} - i^*_{sc} \end{bmatrix}$$

(6)

$$\begin{bmatrix} i^*_{sa} \\ i^*_{sb} \\ i^*_{sc} \end{bmatrix} = M^{-1} \begin{bmatrix} 0 \\ 0 \\ P_{lavg} + P_{loss} \end{bmatrix} \quad (7)$$

The current generation process is illustrated in detail in Fig. 2(a) through the use of equations. Figure 2(b) shows the generation of pulses for the D-STATCOM in a single phase, while the analysis was applied to all three phases.

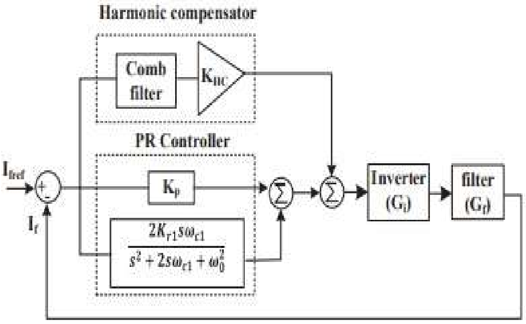


Figure 2 (b): schematic representation for comb filter along with PR-controller A) PR controller:

The PR controller consists of a proportional term and a resonant term with a high gain, which is similar to the frequency. The controller PR provides the following frequency response:

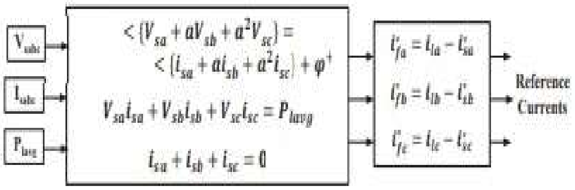


Figure 2 (a): Equation format for producing reference currents

$$G_{pr}(s) = k_p + k_r \frac{s}{s^2+\omega_0^2}$$

(8)

$$G_{pr}(s) = k_p + k_r \frac{2\omega_c s}{s^2+2\omega_c s+\omega_0^2}$$

(9)

Where ωc denotes the cutoff frequency, gain constants are denoted by K$_r$ and K$_p$. Resonant frequency is denoted by ω$_0$.

B) COMB Filter:

The addition of the delayed signal to the input signal is the process involved in implementing a comb filter to obtain the desired output. The feedback form and feedforward form are the two types of comb filters, both of which incorporate the delayed signal. The equations below express these two types.

$$\boldsymbol{H(\omega) = (1 + \alpha e^{-ST})} \qquad (10)$$

$$\boldsymbol{H(\omega)} = (\underline{\qquad\qquad} 1 - \alpha e^{1} \, {-ST})$$

(11)

Similarly, the controller proposed in Fig. 2(b) comprises of a proportional resonant controller and a harmonic compensator (HC) based on a comb filter with a gain of KHC. The reference currents are generated using the stationary reference (abc) frame of the instantaneous symmetrical component theory. The actual currents are compared with the reference currents to derive the odd-order harmonics of the current. The fundamental harmonic components error is then processed by the PR controller with the comb filter. The

$$(s) = K_p + \frac{2K_r s\omega_c}{2 \qquad\qquad 2} + \sum \qquad {}_{c \quad 0}$$

$${}_{ci \quad 0}$$

(12)

Equations 13 and 14 illustrate the transfer function of the PR controller combined with feedforward (Gpr1)

$$\boldsymbol{Gpr} \qquad s+2\omega\, s+\omega \qquad i{=}5{,}7{,}11{,}13\; s\underline{\qquad\qquad} 2+2\omega^{ri} + {}^{ci}\omega 2$$

and feedback (Gpr2) controllers. These controllers include a harmonics compensator for the 5th, 7th, 11th, and 13th harmonic components, in addition to the basic PR controller. The delay length is represented by τ, and the scaling factor applied to the delayed signal is denoted by ω. For each dominant harmonic, the comb filter acts as a resonant filter. The transfer function of the LCL filter and inverter are given by Equations 15 and 16.

$$\boldsymbol{Gpr1(s) = Kp1} + s2{+}2K2\omega r1c1s\omega s{+}c1\omega 20 + \boldsymbol{(1 + \alpha e{-}ST)}$$

(13)

$$\boldsymbol{2K \quad s\omega \qquad\qquad 1}$$

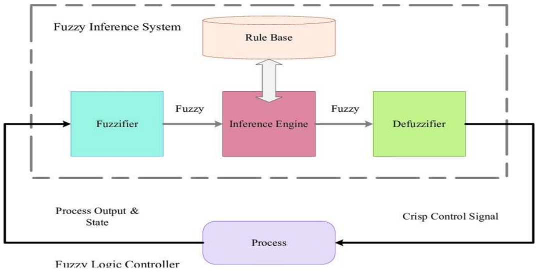


Figure 3: Block Diagram of FLC

comb filter is set to produce a resonant peak at a frequency that is (2n+1) times the fundamental frequency, allowing it to compensate for all dominant harmonics. The output of the comb filter can be adjusted to enhance harmonic compensation and maintain system stability, with the tuning range kept between 10 dB and 300. Equation 12 below demonstrates the resonant component for each individual harmonic, described by implementing the PR-controller with its transfer function.

$$\boldsymbol{2K \quad s\omega}$$

comprised of three main stages: the input stage (Fuzzification), the inference stage (rule-based), and the output stage (defuzzification). The process of FLC operation is demonstrated step-by-step in Figure 3.

The membership functions of the Fuzzy Logic Controller are shown in the accompanying figure. The controller takes two inputs, namely the voltage error as shown in figure (4) and the rate of change of voltage error as shown in figure (5), and generates an output which is the power loss as shown in figure (6).

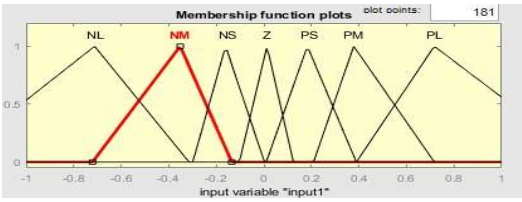


Figure 4: Voltage error

$$\boldsymbol{Gpr2(s) = Kp1} + {}_{s^2+2\omega^{r1}c1s+^{c1}\omega20} + {}_{(1-\alpha e-ST)} \qquad (14)$$

$$\boldsymbol{G_f} = {}_{Iv^{i}i^{(}(^{s}s^{)})} = {}_{Ls(^{1}s^{+}3L^{sCR}pC+^{+}S^{s}2^{2}CR^{LgC}+s)} \qquad (15)$$

$$\boldsymbol{G_i = e^{-sTd} =} {}_{1+^{1}sT_{d}}$$

(16)

It is possible to compute the transfer function from the overall system.

III. PROPOSED CONTROLLER (FLC)

The present study proposes the use of a Fuzzy Logic Controller (FLC) to regulate the operation of DSTATCOM. Unlike conventional PI controllers, the FLC is a new and innovative controller that results in improved system response and stability. The FLC is designed based on a set of logical rules, without the need for a mathematical approach, making it simple to construct and implement. The controller is

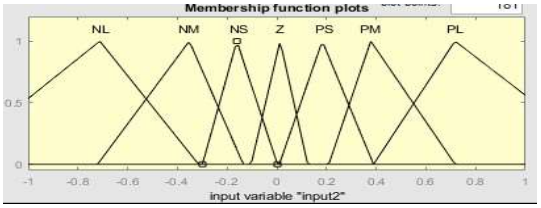


Figure 5: Voltage change in error

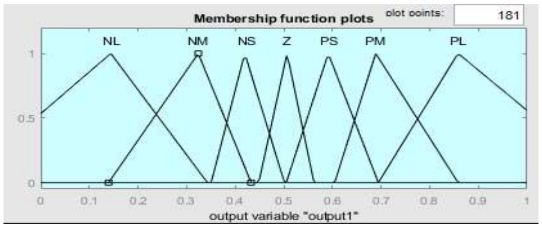


Figure 6: Power loss error The main focus of this proposed work is on the control of the DC link voltage, which plays a crucial role in ensuring the smooth operation of the DSTATCOM. To achieve this, the Fuzzy Logic Controller (FLC) is utilized to control the voltage at the DC link. The table below illustrates the rules that have been implemented in the proposed system. Table 1: Rules of FLC

E/CE	NB	NS	ZE	PS	PM
NB	NM	NS	NS	PS	PM
NS	NM	NS	ZE	PS	PM
ZE	NM	NS	ZE	PS	PM
PS	NM	NS	ZE	PS	PM
PB	NM	NS	PS	PS	PM

The table above displays the Fuzzy Logic Controller's rules, which comprise a total of 25 rules that are formed by a combination of five input and output membership functions. The membership functions are categorized as negative big, negative medium, and small, which are represented by NB, NM, and NS, respectively. Similarly, positive big, medium, and small are denoted by PB, PM, and PS, whereas ZE denotes zero error.

IV. SIMULATION RESULTS

The MATLAB/Simulink Software can be utilized to assess the proposed technique. The system under consideration is a 3-phase grid system with a 75.35 kVA 3φ-load rating. The primary objective is to compensate for harmonics and provide reactive power to the load using a D-STATCOM controlled by a fuzzy logic controller. The study considers five cases in total. Table-2 outlines the parameters taken into account during the implementation of the study, while Table-3 examines the controller parameters assumed while evaluating the results.

Case i: without compensation

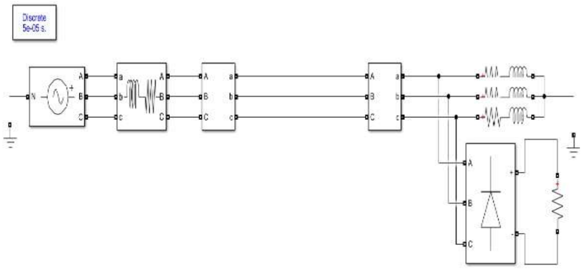


Figure 7: Simulink Diagram of distribution system without compensation

The simulation diagram for the distribution system without any compensation is presented in Figure 7 above. A three-phase distribution grid is connected to an unbalanced and non-linear load, which results in power quality issues in the distribution system and load. The outcome of the simulation is demonstrated below.

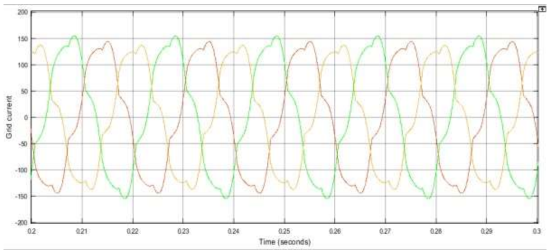


Figure 8: Grid current under without compensation

The figure above illustrates the current waveform of the grid with an amplitude of 150A, but it is not in the sinusoidal form. The waveform contains significant harmonic content.

Case ii: with compensation

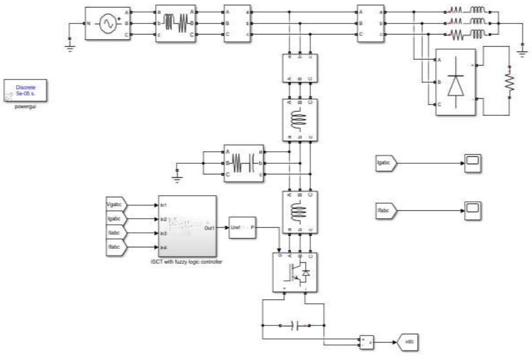


Figure 9: Simulation Diagram of distribution system with compensation

The simulation diagram above illustrates the proposed system after integrating D-STATCOM. The power supply from the grid is connected to the loads, and a D-STATCOM is placed in parallel with the grid, which includes a DC source, inverter, and filter. Different controllers are used to provide pulses to the inverter, including PR, PR+FF, PR+FB, and Fuzzy Logic controllers. The results obtained by utilizing these controllers are presented below. A. Using PR Controller:

To address power quality issues in the distribution system caused by non-linear loads, a D-STATCOM is connected in parallel with the grid. The D-STATCOM is controlled by a PR controller to regulate the supply from the grid to the non-linear and unbalanced loads. The resulting waveforms of the grid current and filter current, obtained by using the PR controller, are shown in the figures below.

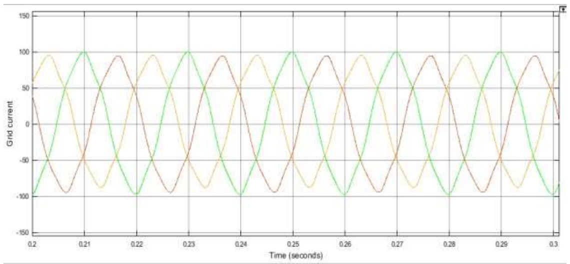


Figure 10: Grid current obtained after compensation by using PR Controller

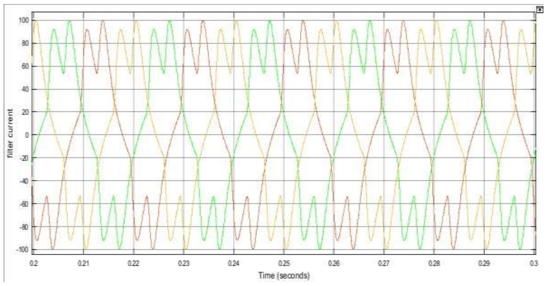
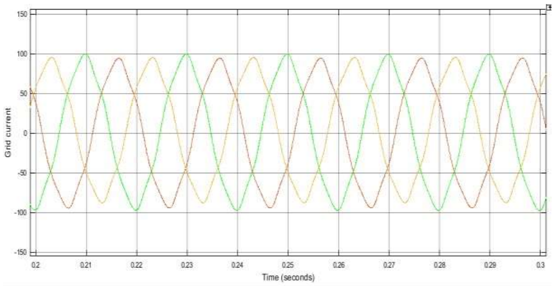


Figure 11: Filter current obtained after compensation by using PR controller B. Using PR+FF Controller:

The non-linear and unbalanced loads are supplied power from the grid. To address the power quality issues arising from these loads, a D-STATCOM is connected in parallel with the grid. This DSTATCOM is controlled by a PR+FF controller. The figures below illustrate the results obtained using the PR+FF controller, which show the performance



of the grid current and filter current.

Figure 12: Grid current obtained after compensation by using PR+FF Controller

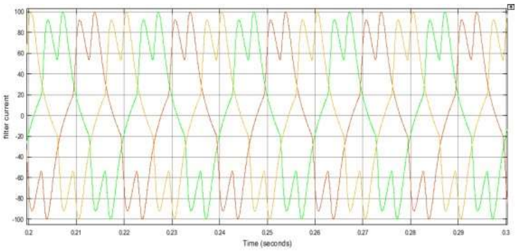


Figure 13: Filter current obtained after compensation by using PR+FF Controller

C. Using PR+FB Controller:

The non-linear and unbalanced loads are supplied with power from the grid. In order to address the power quality issues that arise in the distribution system as a result of these loads, a D-STATCOM is connected in parallel to the grid. The D-STATCOM is controlled by a PR+FB controller. The figures below show the results obtained by using the PR+FB controller, including the performance results of grid current and filter current.

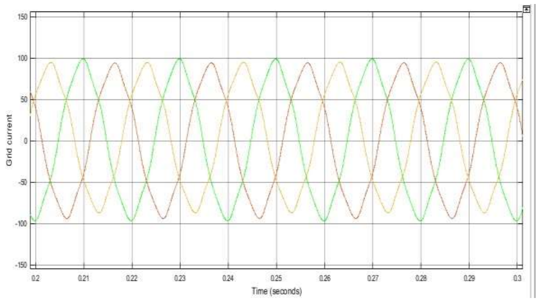


Figure 14: Grid current obtained after compensation by using PR+FB Controller

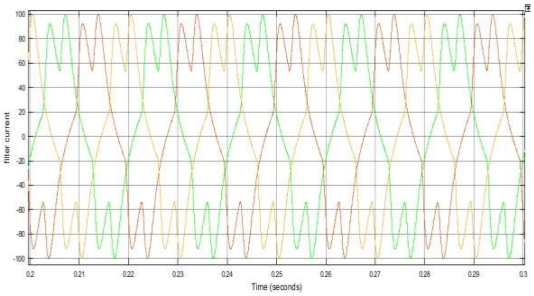


Figure 15: Filter current obtained after compensation by using PR+FB Controller

1) Sudden change of load.

The distribution system was tested under a sudden change in load, as the load in any power system is not constant and varies from time to time. Therefore, the proposed system must exhibit good performance under varying loads. In this case, the proposed system was tested using the PR+FB controller topology for D-STATCOM. The obtained results are presented below.

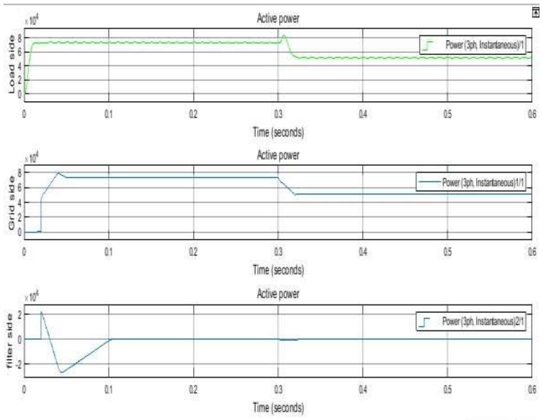


Figure 16: Active power attained under sudden change of load by using PR+FB Controller

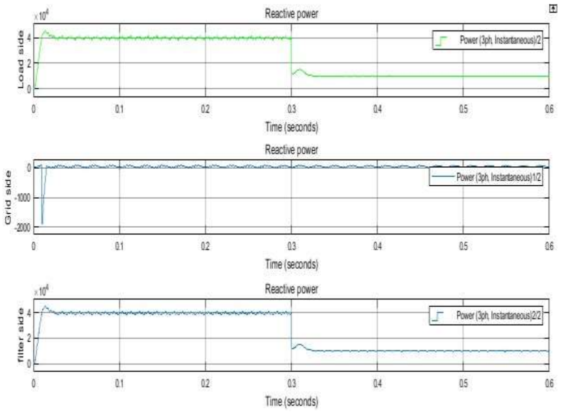


Figure 17: Reactive power attained under sudden change of load by using PR+FB Controller

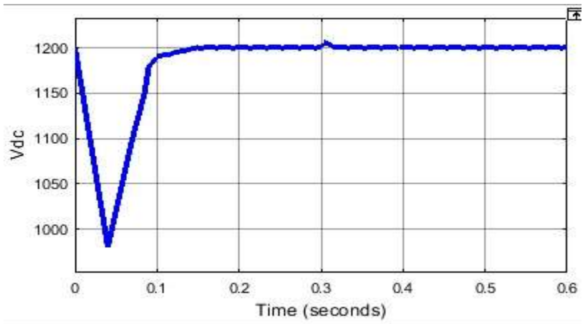


Figure 18: DC Link Voltage (Vdc) obtained under sudden change of load using PR+FB controller

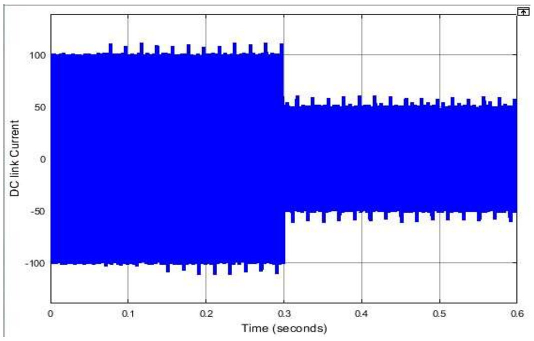


Figure 19: DC Link Current (Idc) obtained under sudden change of load using PR+FB controller

D. Using FLC:

An FLC topology was utilized to address power quality issues in the proposed system caused by nonlinear and unbalanced loads in the distribution system. Several conventional control topologies were implemented for D-STATCOM in previous cases to improve power quality. However, the FLC DSTATCOM demonstrated superior performance compared to conventional control topologies.

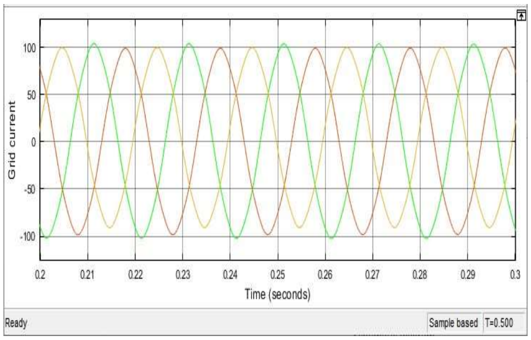


Figure 20: Grid current obtained with compensation using Fuzzy Logic Controller

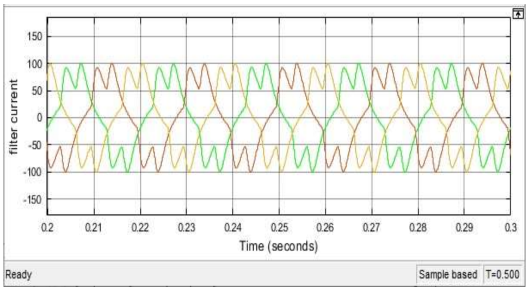


Figure 21: Filter current obtained with compensation using Fuzzy Logic Controller

1) Sudden changing of Load:

When implementing the Fuzzy Logic Controller, the distribution system experienced dynamic changes in load, resulting in some changes in the system. The simulation diagram, shown below, depicts the sudden changes in load.

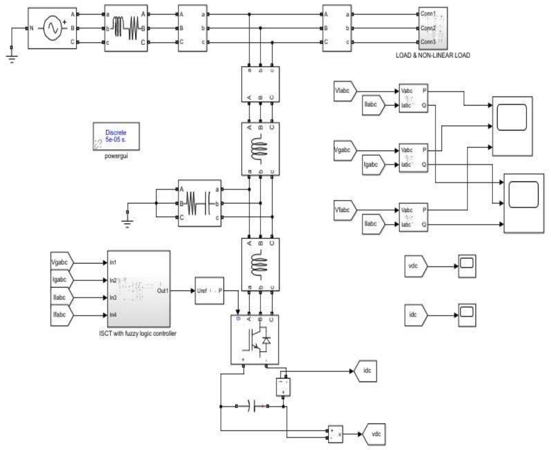


Figure: 22 Simulation diagram of Fuzzy based D-STATCOM with varying load

The simulation results of active power, reactive power at the grid side, load side, and filter side, as well as the DC link voltage and current at the DC side, are shown in the figures below. These figures demonstrate the performance of the proposed system using the Fuzzy Logic Controller.

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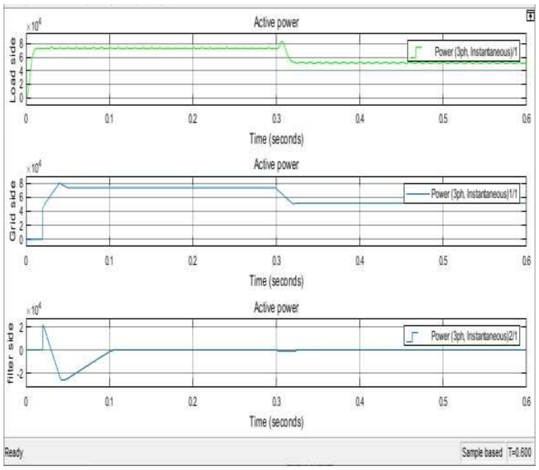

Figure 23: Active power obtained using FLC during a sudden change in load

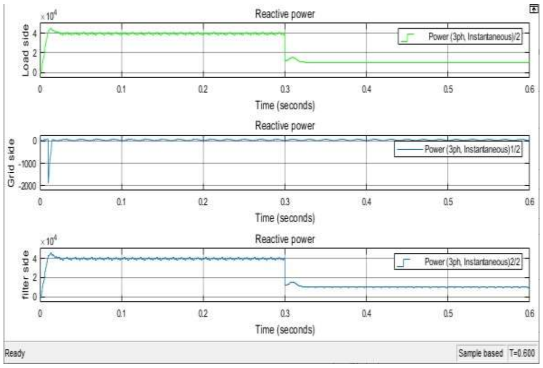

Figure 24: Reactive Power attained by FLC under a sudden change in load

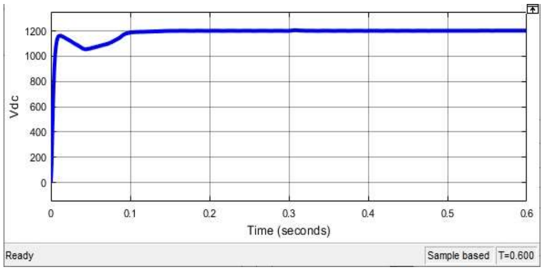

Figure 25: FLC is used to obtain DC Link Voltage under a sudden change in load.

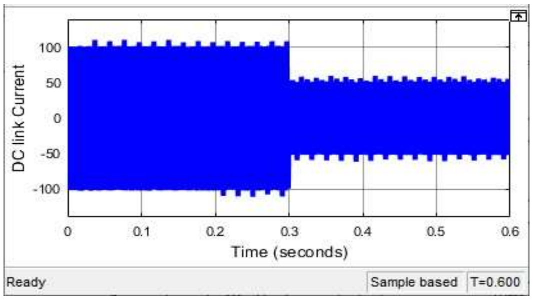

Figure 26: DC Link Current obtained using FLC under a sudden change in load

The implementation of the proposed fuzzy logic controller for D-STATCOM has demonstrated a significant improvement in power quality in distribution systems, as it provides more precise results than both uncompensated and various conventionally compensated methods. The FLC DSTATCOM achieves less than 2% THD for 3-phase grid currents, which is better than conventional methods. The table above clearly illustrates the superior accuracy of the FLC D-STATCOM compared to all conventional methods.

Table 2: THD comparison table

Parameter	**Without compensation**	**With Compensation**			
		PR	**PR +FF**	**PR +FB**	**PR+FB+FLC**
THD of Grid current at Phase-A(Ia)	11.49 %	4.20 %	4.22 %	4.04 %	1.37 %
THD of Grid current at Phase-B(Ib)	12.19 %	4.43 %	4.44 %	4.26 %	1.42 %
THD of Grid current at Phase-C(Ic)	12.83 %	4.64 %	4.65 %	4.45 %	1.50 %

V. CONCLUSION

The proposed Fuzzy Logic Controller-based DSTATCOM with a combined PR and Comb Filter Controller is an effective solution for optimizing power quality in distribution systems. The system is capable of compensating reactive power, voltage sag/swell, and harmonic distortion, thereby improving power factor correction, voltage regulation, and harmonic mitigation. The results obtained from the simulation Using MATLAB/Simulink demonstrate the effectiveness of the proposed system in improving power quality in distribution systems. The proposed system can be implemented in practical distribution systems to improve power quality and ensure reliable operation. Overall, this project provides a promising solution to the challenge of power quality optimization in distribution systems.

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