Multilevel STATCOM Using Fuzzy Logic Controller in a Transmission Line for Voltage Control

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Abstract: ***This paper deals with the voltage stability analysis and voltage control with multilevel voltage source converter based static synchronous compensator (STATCOM). The main objective of this paper is to maintain the voltage stability by compensating the reactive power in the power system. Hence, a new efficient control method is proposed to reduce the voltage fluctuations like sag and swell conditions and also isolate current and voltage harmonics in the transmission lines. In this transmission system the multilevel stat-com this can be used at the point of common coupling (PCC) to compensate voltage fluctuations. By applying 110kV transmission line with and without stat-com the performance can also compared. In this paper FUZZY LOGIC CONTROLLER method is used for reducing the total harmonic distortion (THD) there by it improves the power quality***

Keywords: Fuzzy Logic Controller (FLC), Power Quality, Point of Common Coupling (PCC), STATCOM, STATCOM Controller, Total Harmonic Distortion (THD), Voltage Sag and Swell.

1. Introduction

Now a days, the Electrical energy plays an important role is the present society and has prodigious importance to a nation's welfare and development. The power plants account for almost all of the energy generated. The electrical power systems if not all of the world are widely interconnected, connection utilities inside its own territories, which extend to inter-utility interconnections and then to interregional and international connection. This is performed for economic reasons, to reduce the cost of the electricity and to improve the reliability of power supply. In the present power grid the long switching periods and discrete operation of the device. It causes difficulty in handling the frequent changing the loads smoothly and damp out the transient oscillations fastly[1]. In recently the power grid, the conventional transmission systems are unable to manage the control devices for variable power flows and interconnection in complicated areas. So these problems to improve the security and stability of the problems. The power electronic technology has expanse to worldwide, these power electronic devices are Flexible AC Transmission System (FACTS)[2]. This FACTS device becomes the technology of choice in voltage control, real and reactive power flow control, transient and steady state stabilization. By these performance analysis the efficiency of the existing generator units and reduce the overall generation and fuel consumption, minimize the operation cost.

2. Flexible AC Transmission System (Facts)

The antiquity of FACTS controllers can be traced back to 1970s. when Hingorani presented the idea of power electronic application in the power system compensation[3]. Now a day's power demand increasing day by day, by these power transfers and controlling load flow of the transmission system is necessary. By this can be achieved more load centers, which can be change frequently, therefore addition of new transmission lines is very costly to take increased load on the system. In the case of FACTS devices are most economical to meet the increased loads on the same transmission lines. The FACTS devices are becoming environmental friendly, it does not produce any type of waste hazards. So, these are pollution free then help to deliver the electrical power more economically with better use of existing transmission lines, while reducing the cost of new transmission line and generating more power. The FACTS technology has expo strong potential and its devices are used in transmission lines to control and utilize the flexibility and system performance, the FACTS controller are classified according to their connections like Shunt and Series connected controllers, These FACTS are mainly,

- Static Var Compensators (SVC)
- Static Synchronous Compensators (STATCOM)
- Unified Power Flow Controller (UPFC)

In the electrical transmission systems by using the FACTS devices have advantages in utilization of existing transmission system to increase the reliability and more increased transient and dynamic stability of the system and also increased more quality of supply for large industries.

3. STATCOM

The STATCOM (Static Synchronous Compensator) is a self-commutated switching power converter supplies from an applicable electrical energy and operated to produce a set of adjustable multiphase voltage, which may be coupled to an AC power system for the purpose of exchanging its own real and reactive power.

3.1. Working Principle of STATCOM

STATCOM is a primary shunt device of the FACTS family, which uses power electronics to control power flow and improve transient stability on power grids. The STATCOM Regulates voltage at its terminals by controlling the amount of reactive power injected into or absorbed from the power system. For purely reactive power flow the three phase voltages of the STATCOM must be maintained in phase with the system voltages. The variation of reactive power is performed by means of a VSC connected through a coupling transformer. The VSC uses forced commutated power electronics devices (GTO's or IGBT's) to synthesize the voltage from a dc voltage source. The operating principle of STATCOM is explained in Fig 1. It can be seen that if $V_2>V_1$ then the reactive current I_q flows from the converter to the ac system through the coupling transformer by injecting reactive power to the ac system. On the other hand, if $V_2<V_1$ then current I_q flows from ac system to the converter by absorbing reactive power from the system. Finally, if $V_2=V_1$ that shows in equation (1) there is no exchange of reactive power. The amount of reactive power exchange is given by:

$$Q = \frac{V_1(V_1 - V_2)}{X_s} \qquad \textbf{(1)}$$

Where,
V_1 : Magnitude of system Voltage.
V_2 : Magnitude of STATCOM output voltage.
X_s : Equivalent impedance between STATCOM and the system[4].

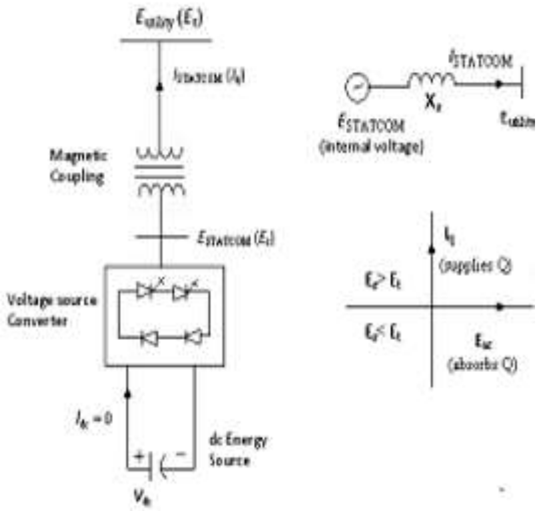

Figure 1: Schematic Configuration of STATCOM

3.2. Cascade Multi-Level STATCOM

A cascade multi-level converter circuit is shown in Fig.2. It is a three phase VSC which comprises of three single phase and each phase consists of H-Bridges connected in series. The three phases in the converter are star connected. Each single phase H-Bridge converter has two arms consisting of two pairs of GTO and diode connected in anti-parallel. Each H-bridge has its own capacitor, acting as a voltage source. Individual capacitors of same capacitance are selected to meet the economic and harmonic criteria as shown in Fig.3. The peak output voltage of STATCOM in N times to that of the capacitor voltage, where N is the number of H-Bridges in each phase. Each H-bridge generates three voltage levels +Vde, 0 and Vde and the total output voltage of each phase is the combination of individual H-bridge voltage as shown in Fig.4. A STATCOM with N converter per phase can synthesize 2N+1 voltage level[5].

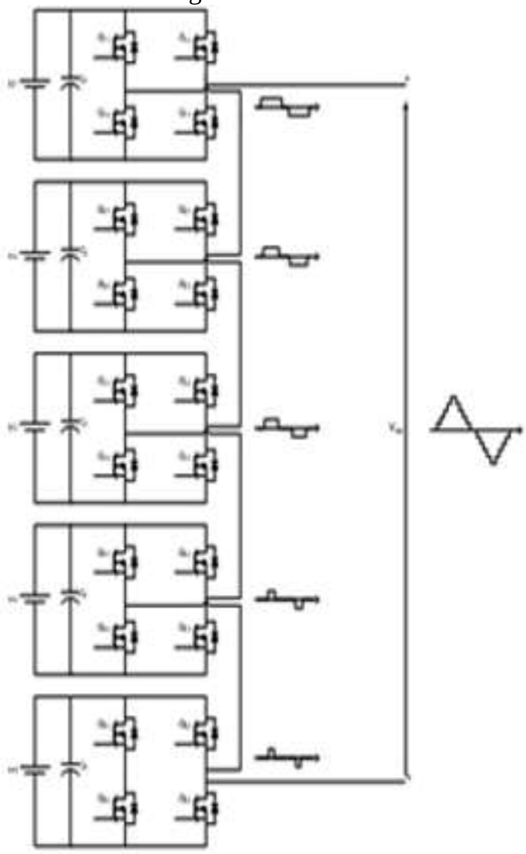

Figure 2: Single phase 9-level H-bridge inverter and switching strategies

The output voltage waveform of the cascaded N-level STATCOM depends on the switching pattern, which is controlled by the switching angles of the converters. These switching angles can be independently selected, but appropriate switching angles are required to achieve good quality of the output voltage waveform. By employing SHEM, lower order harmonics can be eliminated in the output waveform, shown in equation (2). The amplitude of the odd harmonic order of the output voltage with 2N+1 level can be represented using Fourier's series method as,

$$V_n = \frac{4V_{dc}}{n\prod} \sum_{k=1}^{N} \cos(n\theta) \qquad (2)$$

Where,
V_n is the amplitude of voltage harmonic of n^{th} order
V_{dc} is the DC voltage acreoss the capacitor
N is the number of the bridges in each phase
N is the odd harmonic order
Θ is the switching angle of the single phase bridge

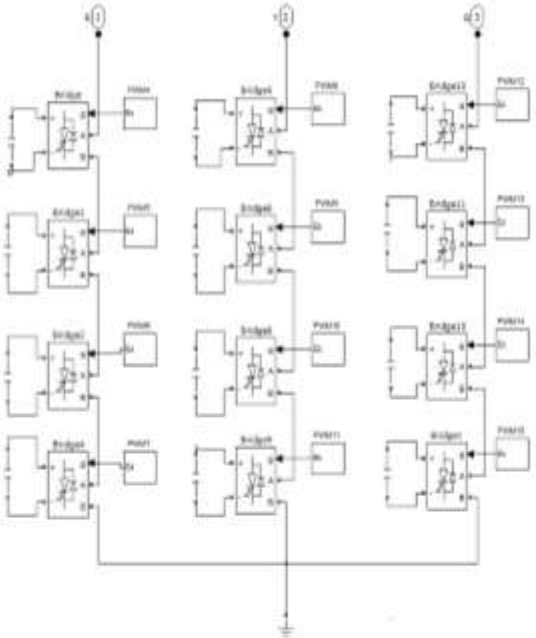

Figure 3: MATLAB implementation of 9-levels

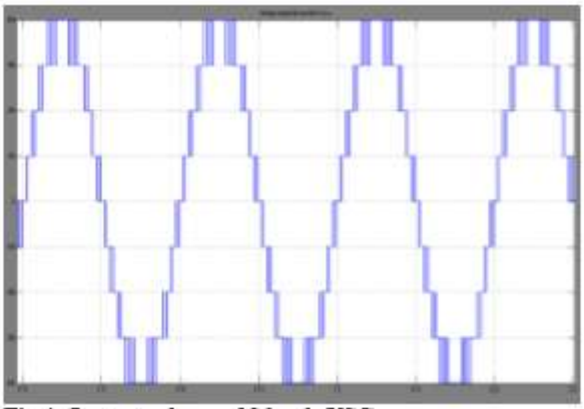

Figure 4: Output voltage of 9-levels VSC

3.3. STATCOM Controller

The main objective for control of STATCOM is to enhance the power transmission by injecting or absorbing reactive power to or from the grid. The basic control strategy used for the proposed STATCOM controller is direct control. In this approach reactive output current can be controlled directly by the internal voltage control mechanism of the converter (e.g, PWM) in which the internal dc voltage is kept constant. The STATCOM is controlled to deliver either inductive or capacitive currents to the power system by varying its output voltages V2a, V2b and V2c. In the design of the STATCOM controller, the three-phase quantities (voltage and current) are first transformed into direct and quadrature components in a synchronously rotating reference frame, then a current regulator is employed for the current control.

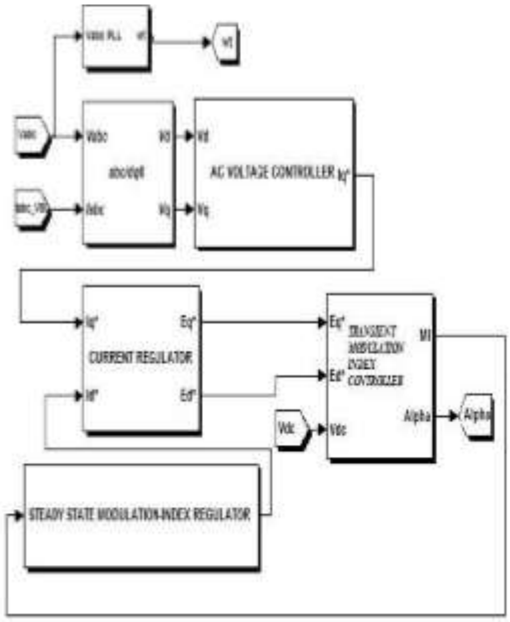

Figure 5: STATCOM Controller

In addition an ac voltage controller is designed to regulate the PCC bus voltage through a PI controller. The ac voltage controller generates the desired reactive current reference for the current regulator. In the design of the STATCOM controller, it is essential to have good dynamic response in the transient period and to ensure minimal harmonics at steady state. As shown in Fig.5. a transient modulation index controller and a steady state modulation index regulator are proposed to achieve the goals of good transient response and minimal steady-state harmonics respectively. Details for the design of transient modulation index controller, steady-state modulation index regulator, phase locked loop (PLL), abc to dq0 transformation, AC voltage controller, Current regulator, PWM generator are described below:

PLL: The PLL provides synchronizing signal which is the phase angle of the bus. In the case of a sudden change in the power system, such as load rejection, it takes about half a cycle of voltage (10ms for 50 Hz) for the PLL to be synchronized with the new voltage phase angle, plus the signal processing delay. During this time the STATCOM operates at the previous phase angle, while the bus voltage phase has changed. Depending on the amount of phase angle change and whether it is increased or decreased, an uncontrolled real power, and reactive power exchange would occur between the STATCOM and the transmission line during this inherent PLL delay. Therefore depending on the amount of the phase angle change and whether it is increased or decreased, the dc capacitor would be charged or discharged at load switching instants.

abc to dq0 Transformation: This block performs the abc to dq0 transformation on a set of three phase signals. It computes the direct axis V_{do} quadrature axis V_{qo} and zero sequence V_0 quantities in a two axis rotating reference frame according to the Park's Transformation shown below,

$$V_d = \frac{2}{3}\left[V_a \sin(wt) + V_b \sin(wt - \frac{2\pi}{3}) + V_c \sin(wt + \frac{2\pi}{3})\right] \quad (3)$$

$$V_d = \frac{2}{3}\left[V_a \cos(wt) + V_b \cos(wt - \frac{2\pi}{3}) + V_c \cos(wt + \frac{2\pi}{3})\right] \quad (4)$$

$$V_0 = \frac{2}{3}\left[V_a + V_b + V_c\right] \quad (5)$$

Where (0= rotating speed (rad/sec) of the frame)

AC Voltage Controller and Current Regulator: The AC voltage controller converts V_d , Vq into reference reactive current 1, using appropriate PI Controller as shown in Fig.

$$i_q^* = G_1(s)[V_{rms} - V^*_{rms}]$$

$$G_1(s) = k_1 + \frac{k_2}{s}$$

Similarly current regulator uses reference reactive current I_q^* and reference direct current I_d^* along with PI controllers to generate reference direct and quadrature voltages. Respectively,

$$E_d^* = -wL_f i_q + V_{dc} - x_1 \quad (6)$$

Where

$$x_1 = G_2(s)[i_d^* - i_d]$$

$$G_2(s) = k_3 + \frac{k_4}{s}$$

Where,

L_f is leakage inductance

V_{dc} is capacitor voltage

Transient Modulation-Index Controller: The efficient way to modulate the reactive power output Q of the STATCOM and to regulate the PCC bus voltage is to control the output voltage of the STATCOM on the transient period. STATCOM output voltage is proportional to the product of modulation index (MI) and V_{dc}. Since it is impossible to change V_{dc} instantaneously it is desirable to adjust the MI in the transient period such that the PCC bus voltage can be regulated efficiently. Thus, a transient modulation-index controller is proposed to adjust the MI rapidly in the transient period.

$$MI = \frac{\sqrt{E_d^* + E_q^*}}{KV_{dc}} \quad \textbf{(7)}$$

$$\alpha = \tan^{-1}\left(\frac{E_q^*}{E_d^*}\right) \quad \textbf{(8)}$$

Staedy-State Modulation Index Regulator: It has also been observed that a lower modulation index would give more harmonic contents at steady state. Thus it is desirable to have the MI fixed at unity in order to ensure minimal harmonic at steady state. To achieve this goal, a steady-state modulation index regulator to drive the modulation index to the pre-set value (MI^*=1 in the work) at steady state through the action of a PI controller. As shown in Fig.5. the real current reference id is generated by the proposed steadt state modulation index regulator as given in equation (12) and (13)

$$i_d^* = G_3(s)[MI^* - MI] \quad (8)$$

$$G_3(s) = k_5 + \frac{k_6}{s} \quad (9)$$

Using the proposed steady state modulation index regulator and transient modulation –index controller, the advantage of minimal harmonics can be retained under steady-state situations. When there is a need to adjust the reactive power output during the transient period, the actual MI is no longer equal to the steady-state reference MI^* which is equal to the pre-set value. As a result the MI deviates from the steady-state, Value MI^* However, this deviation of the modulation index has little effect on steady-state harmonic contents since the transient lasts for only a very short period. With the adjustment of the modulation index by the proposed STATCOM controller during the transient period the STATCOM output voltage $|V_2|$ and reactive power Q can be modulated in a very rapid manner.

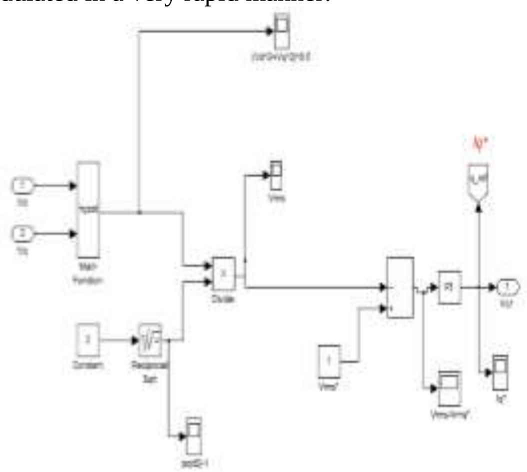

Figure 6: PI Controller

PI Controller: PI Controller generates a gated command to operate the converters and to compensate the error, which has been calculated by comparing defined values against measured values for both reactive and real powers. This is an integral part of the converters which generates a gated command to operate the converters in order to produce the fundamental voltage waveform which compensates the voltage magnitude by synchronizing with the AC system. The internal control also takes preventive measures to limit the maximum voltage and current from the individual power converter to maintain safe operations under any system contingency as shown in Fig.6.

4. Fuzzy Logic Controller

The Fuzzy Logic is mathematical tool for dealing with uncertainty and it provides an inference structure that enables appropriate human reasoning capabilities. The utility of fuzzy system lies in their ability to model uncertain or ambiguous data. In the power system the fuzzy is used traditionally the operations analytical approaches have been used overall the years. Fuzzy has rule based operation therefore it can process any number of reasonable input and output. Fuzzy logic reduces the time needed to develop the complex system[7]. A fuzzy logic controller is based on the set of rules called as fuzzy rules among the linguistic variables as shown in Fig.7. These rules are expressed in the form of conditional statements. Fuzzy logic uses fuzzy set theory, in which a variable is member of one or more sets, with a specified degree of membership. Fuzzy logic allow us to emulate the human reasoning process in computers, quantify imprecise information, make decision based on vague and in complete data, yet by applying a “defuzzification” process, arrive at definite conclusions. The FLC mainly consists of three blocks

- Fuzzification
- Inference
- Defuzzification

Rules:

- If input is NEGATIVE then output is POSITIVE
- If input is ZERO then output is ZERO
- If input is POSITIVE then output is NEGATIVE

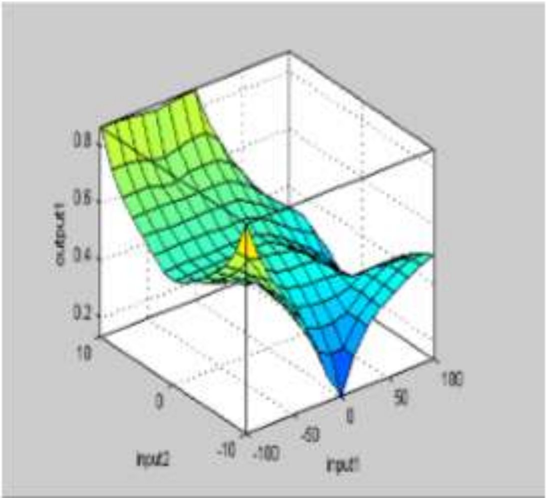

Fig.7. Surface of the Fuzzy logic controller

	N	Z	P
N	P	Z	P
Z	N	Z	P
P	Z	N	N

Table I: Fuzzy Rules for Total Harmonic Distortion

In this method using 3×3 matrices and it will produce nine rules as shown below,

- IF input 1 is N and input 2 is N THEN output is P
- IF input 1 is N and input 2 is Z THEN output is Z
- IF input 1 is N and input 2 is P THEN output is P

IF input 1 is Z and input 2 is N THEN output is N

- IF input 1 is Z and input 2 is Z THEN output is Z
- IF input 1 is Z and input 2 is P THEN output is P
- IF input 1 is P and input 2 is N THEN output is Z
- IF input 1 is P and input2 is Z THEN output is N
- IF input 1 is P and input 2 is P THEN output is N

5. Simulation & Results Analysis

This paper deals with the implementation of a 9-level voltage source converter based static synchronous compensator (STATCOM). The main objective of this project is to maintain the voltage stability by compensating the reactive power in the power system. Hence, a new efficient strategy is proposed in order to reduce the voltage fluctuations like sag and swell conditions and also to isolate current and voltage harmonics in the transmission system.

5.1 Without STATCOM

In this project the three phase fault, the system is installed without STATCOM the system becomes unstable. The voltage and current are having fluctuations like sag and swells and loads are unbalance in the transmission system. When the voltage and current magnitude also not stable in the power system.

5.2 With STATCOM

The system is installed with PI based STATCOM. The system is stable and voltage and current waveforms are in Fig.8 to Fig.10 as shown below.

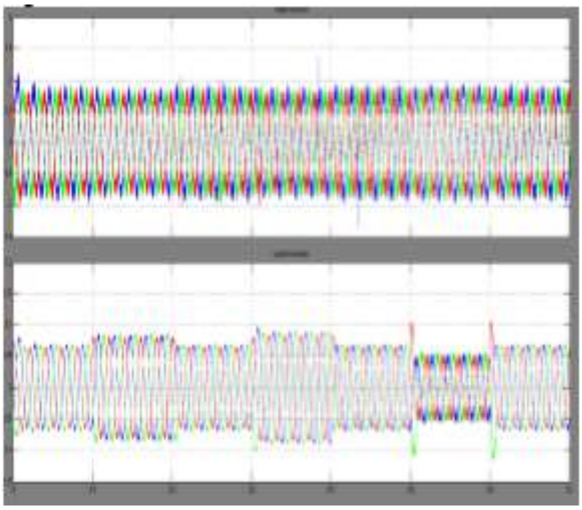

Figure 8: Output voltage and current of the power system

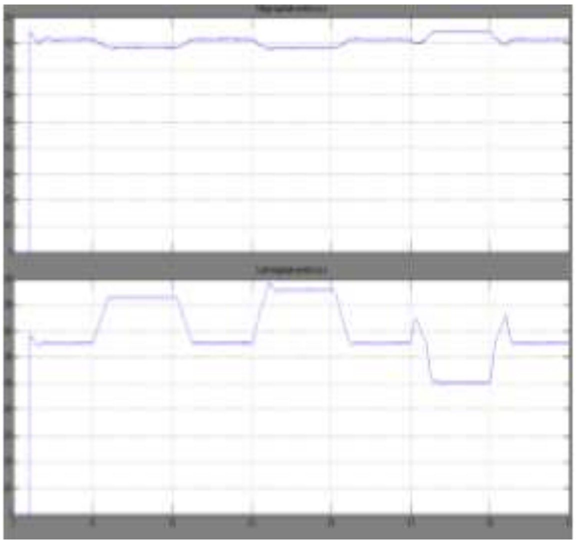

Figure 9: Voltage and Current magnitude

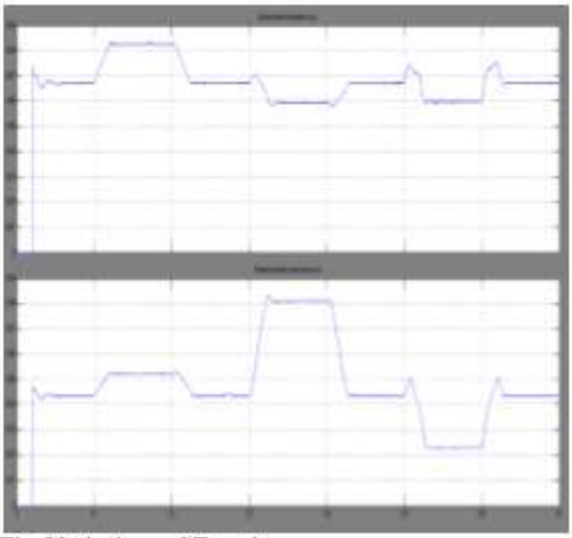

Figure 10: Active and Reactive power

5.3. System Installed with Fuzzy Based STATCOM controller

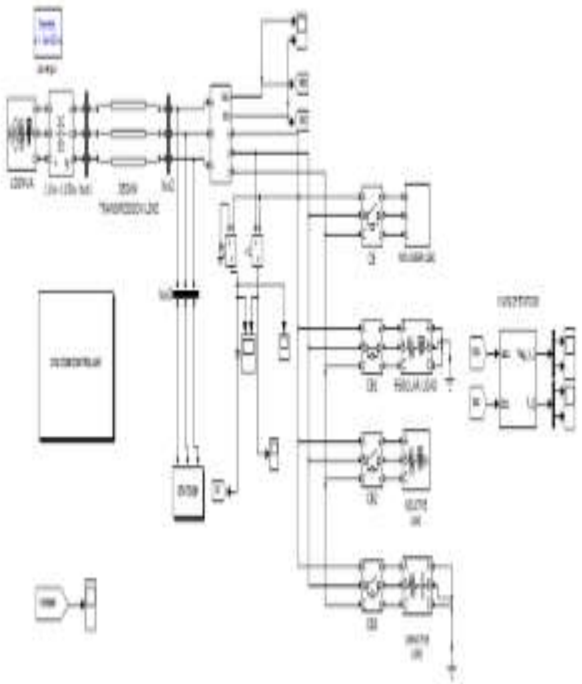

Figure 11: Simulation of fuzzy based STATCOM controller

The above Fig.11 shows a simulation of fuzzy based STATCOM. In this input source is 100MVA, the main components are step-up transformer and bus bars. In these buses 1 and 2, 350KM distance transmission line, in this line point of common coupling the STATCOM device is connected and also bus 3 is connected to different types of loads. These loads are connected by circuit breakers.

Comparison between FFT analysis of PI and FLC controllers:

Comparison between FFT analysis of PI and FLC controllers as shown in Fig.12 to Fig.13

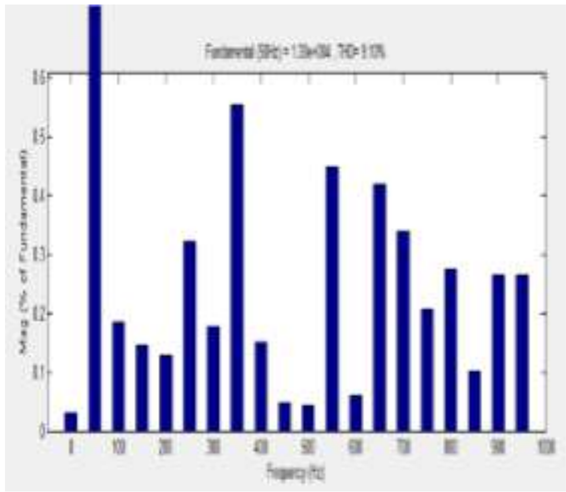

Figure 12: FFT analysis of source current waveform with PI based STATCOM

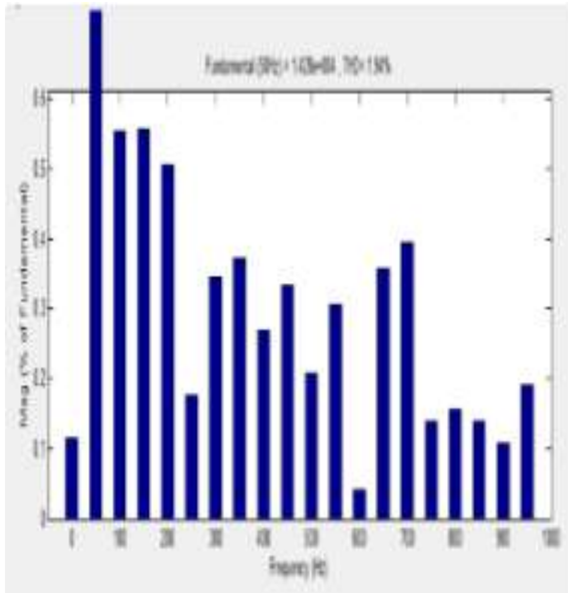

Figure 13: FFT analysis of source current waveform with FLC based STATCOM

6. Conclusion

This paper presents a STATCOM model, developed with all the necessary components and controllers in order to demonstrate its effectiveness in maintaining simple and fast voltage regulation at any point in the transmission line. In the system the multilevel voltage source converter device to achieve the compensation, overcome on all disturbances and deliver pure voltage, current, active and reactive power to destination areas (loads). The proposed FLC based STATCOM have improved the power quality of source current significantly by reducing the Total harmonic Distortion (THD). The PI controller and Fuzzy logic controller are compared. It is clearly presented that STATCOM with FLC gives better performance than STATCOM with conventional PI controller. Therefore, it is concluded that STATCOM acts as voltage regulator, load balancer and also harmonic eliminator.

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