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Fuzzy Five-level Cascaded Multilevel Inverter Based D-STACTOM for Compensation of Reactive Power & Harmonics

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Abstract : *This paper presents an investigation of five-Level Cascaded H-bridge (CHB) inverter as Active Power Filter in Power System (PS) for compensation of reactive power and harmonics. The advantages of CHB inverter are low harmonic distortion, reduced number of switches and suppression of switching losses. The D-STACTOM helps to improve the power factor and eliminate the Total Harmonics Distortion (THD) drawn from a Non-Liner Diode Rectifier Load (NLDRL). The D-Q reference frame theory is used to generate them reference compensating currents for D-STACTOM while Fuzzy controller(FC) is used for capacitor dc voltage regulation. A CHB Inverter is considered for shunt compensation of a 11 kV distribution system. Finally a level shifted PWM (LSPWM) & Phase shifted PWM (PSPWM) technique adopted to investigate the performance of CHB Inverter. The results are obtained through Mat lab/ Simulink*
Keywords: *D-STACTOM, Five-level cascade inverter, level shifted pulse width modulation (LSPWM), fuzzy controller (FC), total harmonic distortion (THD), and harmonics*.

I. Introduction

Modern power systems are of complex networks, where hundreds of generating stations and thousands of load centers are interconnected through long power transmission and distribution networks. Even though the power generation is fairly reliable, the quality of power is not always so reliable. Power distribution system should provide with an uninterrupted few of energy at smooth sinusoidal voltage at the contracted magnitude level and frequency to their customers. PS especially distribution systems, have numerous non linear loads, which significantly a fact the quality of power. Apart from non linear loads, events like capacitor switching, motor starting and unusual faults could also infect power quality (PQ) problems. PQ problem is defined as any manifested problem in voltage/current or leading to frequency deviations that result in failure or mal operation of customer equipment. Voltage sags and swells are among the many PQ problems the industrial processes have to face. Voltage sags are more severe. During the past few decades, power industries have proved that the adverse impacts on the PQ can be mitigated or avoided by conventional means, and that techniques using fast controlled force commutated power electronics (PE) are even more effective. PQ compensators can be categorized into two main types. One is shunt connected compensation device that effectively eliminates harmonics.

The other is the series connected device, which has an edge over the shunt type for correcting the distorted system side voltages and voltage sags caused by power transmission system faults.

The STATCOM used in distribution systems is called DSTACOM (Distribution-STACOM) and its configuration is the same, but with small modifications. It can exchange both active and reactive power with the distribution system by varying the amplitude and phase angle of the converter voltage with respect to the line terminal voltage. A multilevel inverter can reduce the device voltage and the output harmonics by increasing the number of output voltage levels. There are several types of multilevel inverters: cascaded R-bridge (CRB), neutral point clamped, flying capacitor [2-6]. In particular, among these topologies, CRB inverters are being widely used because of their modularity and simplicity. Various modulation methods can be applied to CRB inverters. CRB inverters can also increase the number of output voltage levels easily by increasing the number of R-bridges.

This paper presents various issues in design of Fuzzy controller and level shifted carrier (LSCPWM) & Phase shifted PWM technique are used to obtain switching logic for D-STACTOM. The performance of these controllers is demonstrated with linear resistive-inductive (R-L) loads through simulation results using Power System toolboxes (PST) of Simulink /MATLAB

II. Multilevel Based D-STATCOM

A. Principal of D-STACTOM

A D-STATCOM (Distribution Static Compensator), which is schematically depicted in Fig.1, consists of a two-level Voltage Source Converter (VSC), a dc energy storage device, a coupling transformer connected in shunt to the distribution network through a coupling transformer. The VSC converts the dc voltage across the storage device into a set of three-phase ac output voltages. These voltages are in phase and coupled with the ac system through the reactance of the coupling transformer. Suitable adjustment of the phase and magnitude of the D-STATCOM output voltages allows effective control of active and reactive power exchanges between the DSTATCOM and the ac system. Such configuration allows the device to absorb or generate controllable active and reactive power.

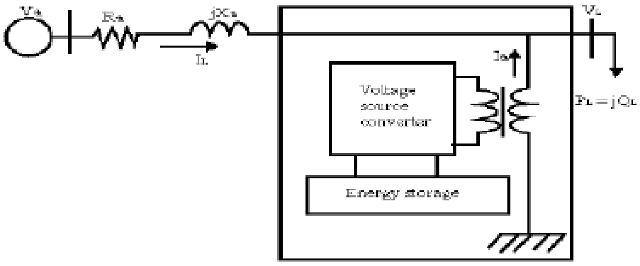

Fig.1 Two Level Voltage Source Converter

The VSC connected in shunt with the ac system provides a multifunctional topology which can be used for up to three quite distinct purposes:

1. Voltage regulation and compensation of reactive power;
2. Correction of power factor
3. Elimination of current harmonics.

B. Control for Reactive Power Compensation

The aim of the control scheme is to maintain constant voltage magnitude at the point where a sensitive load under system disturbances is connected. The control system only measures the root mean square (r.m.s) voltage at the load point, i.e., no reactive power measurements are required. The VSC switching strategy is based on a sinusoidal PWM technique which offers simplicity and good response. Since custom power is a relatively low-power application, PWM methods offer a more flexible option than the fundamental frequency switching methods favored in FACTS applications. Apart from this, high switching frequencies can be used to improve on the efficiency of the converter, without incurring significant switching losses.

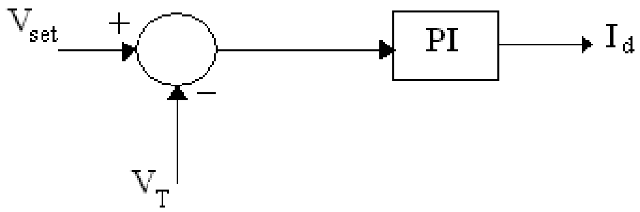

Fig. 2 PI Control Scheme

The controller input is an error signal obtained from the reference voltage and the r.m.s terminal voltage measured. Such error is processed by a PI controller; the output is the angle δ, which is provided to the PWM signal generator. It is important to note that in this case, of indirectly controlled converter, there is active and reactive power exchange with the network simultaneously. The PI controller processes the error signal and generates the required angle to drive the error to zero, i.e. the load r.m.s voltage is brought back to the reference voltage.

C. Control for Harmonics Compensation

The Modified Synchronous Frame method is presented in [7]. It is called the instantaneous current component (i_d-i_q) method. This is similar to the Synchrous Reference Frame theory (SRFT) method. The transformation angle is now obtained with the voltages of the ac network. The major difference is that, due to voltage harmonics and imbalance, the speed of the reference frame is no longer constant. It varies instantaneously depending of the waveform of the 3-phase voltage system.

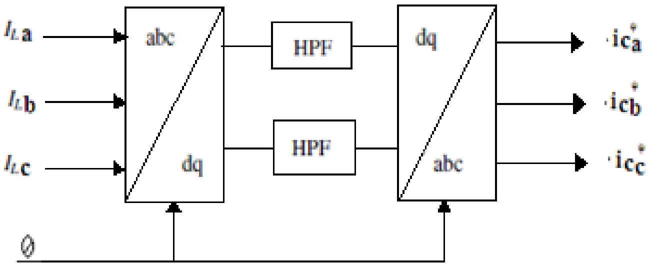

Fig. 3 Block Diagram of SRF method

D. Fuzzy Control

Fuzzy control system gives the switching angles and frequency value. By using this value the harmonic contents present in the system are eliminated. The overall process takes place in proposed method is shown in Fig.4. Feed back controller used here is to calculate voltage error values in the system. This voltage error values is given as the input to fuzzy control system. In the feedback controller, the voltage values are calculated from the voltage waveform for different time values. From the reference waveform voltage values at different time values are taken as reference voltage value. Then for different time values, the voltage values are taken from the harmonics waveform and compared with the reference waveform. The voltage error values are calculated using the equation given below.

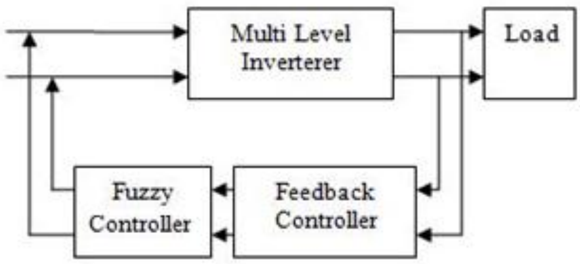

Fig. 4 Fuzzy Controller

$$V_{errer} = V_{ref} - V_h \qquad (1)$$

Where V*ref is* the voltage value of the system without Harmonics.

After calculating the voltage error values, next step is to generate training dataset for training fuzzy system. Generating training dataset is one of the most important Processes because based on the training dataset only the Fuzzy control system will be trained. The training dataset generated for training fuzzy System consists of *n* input variables and s+1 output Variables. Here, stands for number of voltage values taken For generating dataset, is the total number of dataset Generated, is the switching angle and stands for number of Switching angles. The dataset generated for our proposed Method is shown below.

$$D = \begin{bmatrix} V_{t11}\, V_{t12} & \cdots & V_{t1n} \\ \vdots & \cdots. & \vdots \\ V_{tr1}\, V_{tr2} & \cdots & V_{trn} \end{bmatrix} \begin{bmatrix} \theta_{11}\, \theta_{12} & \cdots & \theta_{1n} \\ \vdots & \ddots & \vdots \\ \theta_{r1}\, \theta_{r2} & \cdots & \theta_{rn} \end{bmatrix} \qquad (2)$$

By using the above dataset, fuzzy system is trained. The fuzzy operation is explained briefly in the below Sections.

After completion of training, fuzzy is used for Practical application. After completion of training fuzzy System the next step is to eliminate the harmonic contents in the system. First voltage error values are calculated using the equation 3. By giving voltage error values as input to the Fuzzy system, it gives corresponding frequency and Switching angles as output. By applying this frequency and Switching angle values to the system the harmonic contents present in the system are eliminated. The frequency and switching angle are substituted in the equation given below

.

$$V(t) = V_h \sin(h.2\pi f_f t) \qquad (3)$$

where, f_f is the frequency obtained from fuzzy system.

$$V_h = \frac{4V_{dc}}{h\pi} \sum_{j=1}^{s} \cos(h\theta_j) \qquad (4)$$

where, θ_j is the switching angles obtained from fuzzy system and h is the harmonic order.
By substituting Equation (4) in Equation (3) we get the output dc voltage. The harmonics content eliminated or not is calculated using the below condition.

$$H_{eli} = \begin{cases} V_{ref}(t) = V(t); \textit{harmonics}\text{ eliminated} \\ V_{ref}(t) \neq V(t); \textit{harmonics}\text{ present} \end{cases} \qquad (5)$$

E. Cascaded H-Bridge Multilevel Inverter

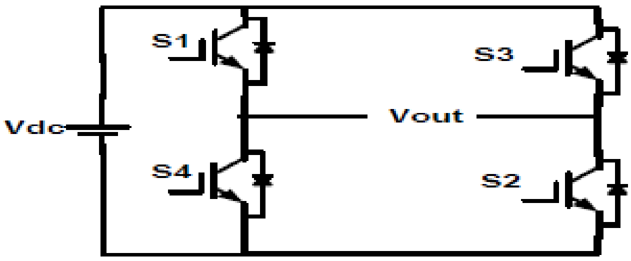

Fig. 5 Single Cascade H-Bridge Inverter

Fig.5 shows the circuit model of a single CHB inverter configuration. By using single H-Bridge we can get 3 voltage levels. The number of output voltage levels of CHB is given by 2n+1 and voltage step of each level is given by Vdc/2n, where n is number of H-bridges connected in cascaded. The switching table is given in Table 1

Table 1 switching mechanism for single CHB inverter

Switches Turn On	Voltage Levels
S1,S2	Vdc
S3,S4	-Vdc
S4,D2	0

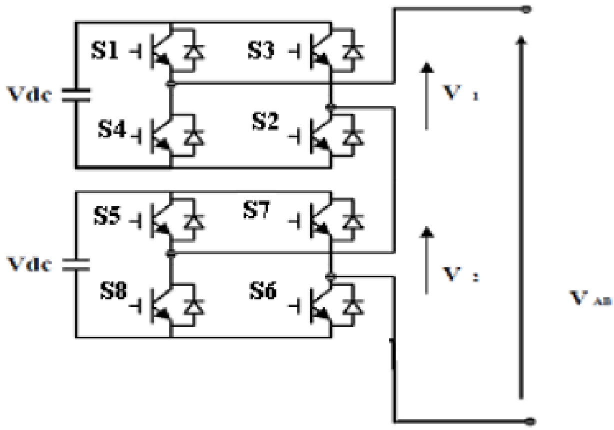

Table 2 Switching mechanism for 5-level CHB inverter

Switches Turn On	**Voltage Levels**
S1,S2	Vdc
S1,S2,S5,S6	2Vdc
S4,D2,S8,D6	0
S3,S4	-Vdc
S3,S4,S7,S8	-2Vdc

F. PWM Techniques for CHB Inverter

The most popular PWM techniques for CHB inverter are
1. Phase Shifted Carrier PWM (PSCPWM),

2. Level Shifted Carrier PWM (LSCPWM).

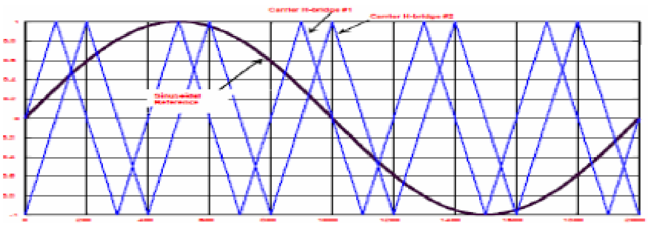

Fig.7 Phase shifted carrier pulse width modulation.

In general, a multilevel inverter with *m* voltage levels requires (m – 1) triangular carriers. In the phase shifted multicarrier modulation, all the triangular carriers have the same frequency and the same peak-to-peak amplitude, but there is a phase shift between any two adjacent carrier waves, given by (). The modulating signal is usually a three-phase sinusoidal wave with adjustable amplitude and frequency. The gate signals are generated by comparing the modulating wave with the carrier waves. It means for the five level inverter, four are triangular carriers are needed with a 90° phase displacement between any two adjacent carriers. In this case the phase displacement of V_{cr1} = 0°, V_{cr2} = 90°, V_{cr1-} = 180° *and* V_{cr2-} = 270°.

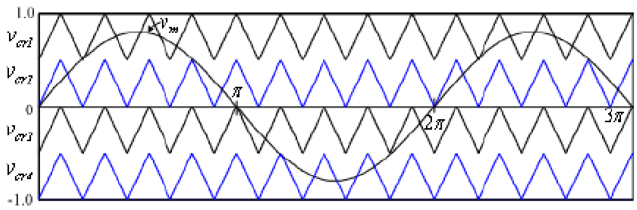

Fig.8 Level shifted carrier pulse width modulation.

An m-level Cascaded H-bridge inverter using level shifted modulation requires (*m–1*) triangular carriers, all having the same frequency and amplitude. The frequency modulation index is given by $m_f = f_{cr} / f_m$, which remains the same as that for the phase-shifted modulation scheme. For PID modulation, the multilevel converter with multilevel requires (m_1) triangular carriers with same amplitude and frequency. The frequency modulation index „m_f‟ which can be expressed as:

$$m_f = f_{cr} / f_m \qquad (6)$$

where „f_m‟ is modulating frequency and „f_{cr}‟ are carrier waves frequency. The amplitude modulation index „m_a‟ is defined by

$$m_a = V_m / V_{cr}\,(m-1) \text{ for } 0 \le ma \le 1 \qquad (7)$$

Where Vm is the peak value of the modulating wave and V_{cr} is the peak value of the each carrier wave [1]. The amplitude modulation index, m_a is 1 and the frequency modulation index, m_f is 6. The triggering circuit is designed based on the three phase sinusoidal modulation waves, V_a, V_b, and V_c. Three of the sine wave sources have been obtained with same amplitude and frequency but displaced 120° out of the phase with each others. For carriers wave sources block parameters, the time values of each carrier waves are set to [0 1/600 1/300] while the outputs values are set according to the disposition of carrier waves. After comparing, the output signals of comparator are transmitted to the IGBTs.

III. Mat Lab/Simulink Modeling And Simulation Results

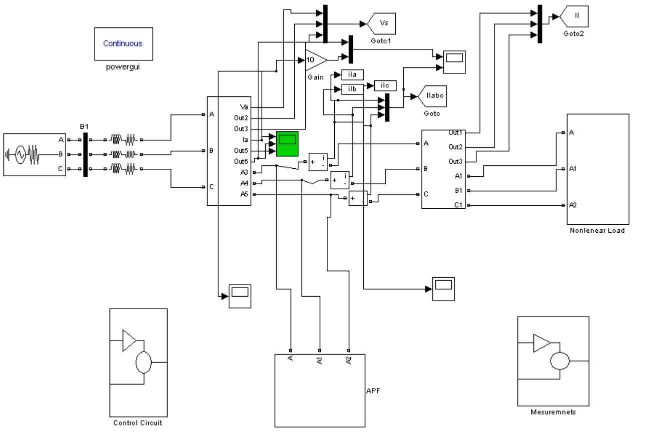

Fig. 9 Mat lab/Simulink power circuit model of D-STACTOM

Case-1 level shifted carrier PWM technique results

Fig. 10 shows the phase-A voltage of five level output of phase shifted carrier PWM inverter.

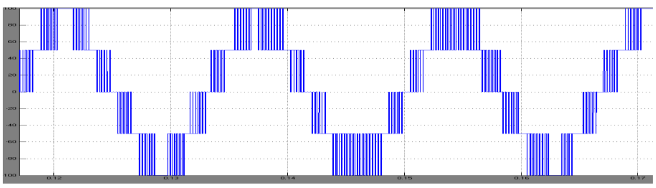

Fig. 10 Five level LSCPWM output

Fig.11 shows the three phase source voltages, three phase source currents and load currents respectively without DSTATCOM. It is clear that without DSTATCOM load current and source currents are same.

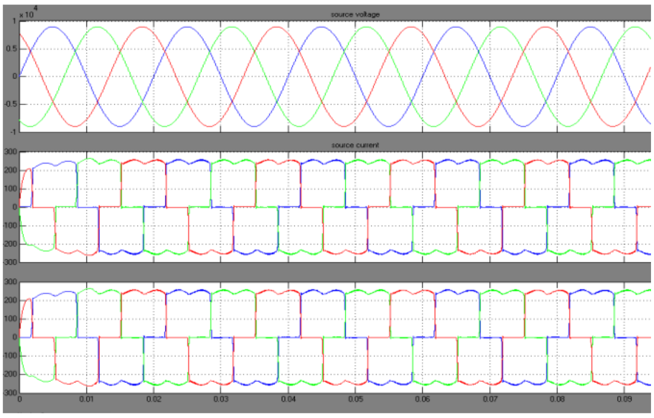

Fig. 11 Source voltage, current and load current without D-STACTOM

Fig. 12 shows the three phase source voltages, three phase source currents and load currents respectively with DSTATCOM. It is clear that with DSTATCOM even though load current is non sinusoidal source currents are sinusoidal

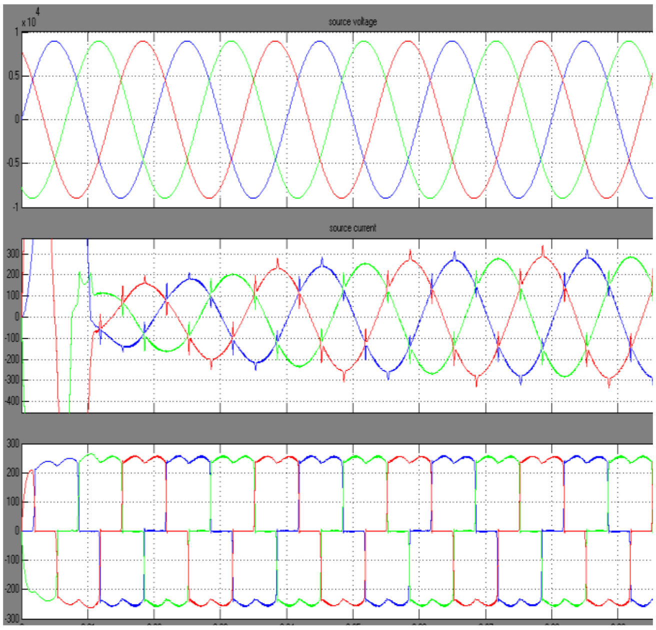

Fig. 13 Source voltage, current and load current with D-STACTOM

Fig. 14 shows the DC bus voltage. The DC bus voltage is regulated to 11kv by using PI regulator.

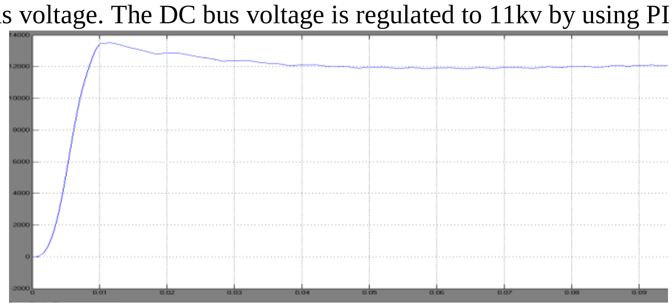

Fig. 14 DC Bus Voltage

Fig. 15 shows the harmonic spectrum of Phase –A Source current without DSTATCOM.

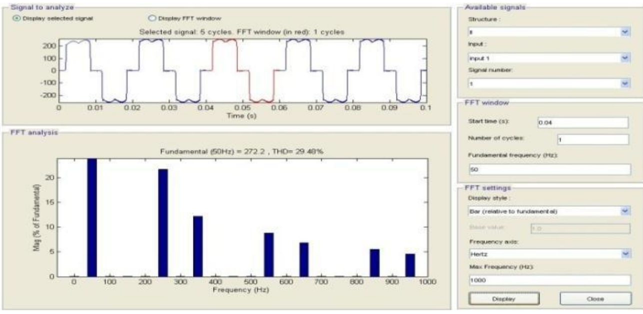

Fig. 15 Harmonic spectrum of Phase-A Source current without D-STACTOM

Fig. 16 shows the harmonic spectrum of Phase –A Source current with DSTATCOM. The THD of source current without DSTACOM is 29.93%.

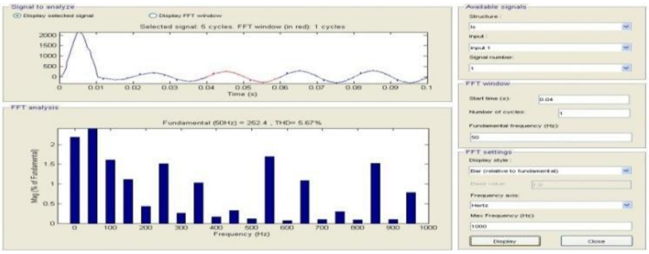

Fig. 16 Harmonic spectrum of Phase-A Source current with D-STACTOM

Case-2 Level shifted carrier PWM technique results

Fig.17 shows the three phase source voltages, three phase source currents and load currents respectively with DSTATCOM. It is clear that with DSTATCOM even though load current is non sinusoidal source currents are sinusoidal.

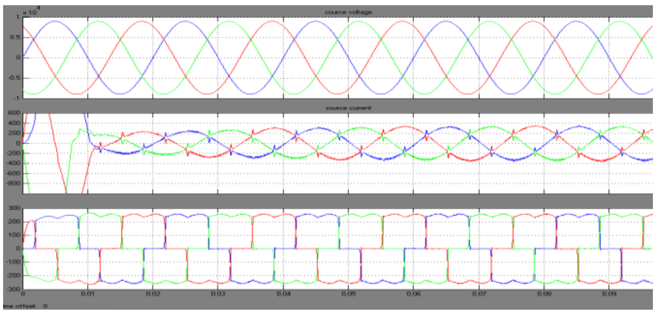

Fig. 17 Source voltage, current and load current with D-STACTOM

Fig.18 shows the DC bus voltage with respect to time. The DC bus voltage is regulated to 11kv by using PI regulator.

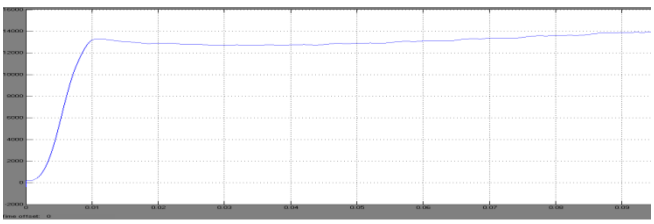

Fig. 18 DC Bus Voltage

Fig.19 shows the harmonic spectrum of Phase –A Source current without DSTATCOM..

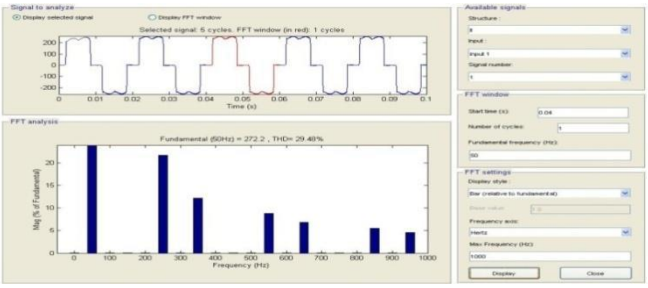

Fig. 19 Harmonic spectrum of Phase-A Source current without D-STACTOM

Fig.20 shows the harmonic spectrum of Phase –A Source current with DSTATCOM. The THD of source current with DSTACOM is 6.19%.

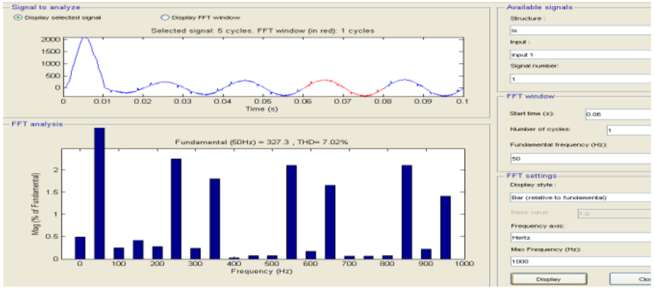

Fig. 20 Harmonic spectrum of Phase-A Source current without D-STACTOM

Case 3: Level shifted carrier PWM technique with Fuzzy controller results

Fig. 21 shows the phase-A voltage of five level output of level shifted carrier PWM inverter.

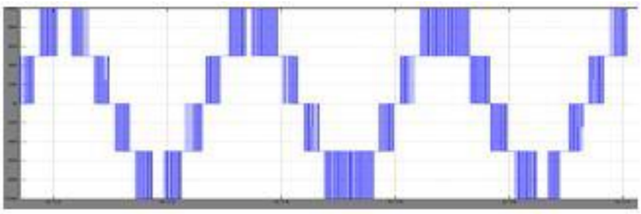

Fig. 21 Five level LSCPWM output

Fig.22. shows the three phase source voltages, three phase

source currents and load currents respectively without D-STATCOM. It is clear that without D-STATCOM load current and source currents are same.

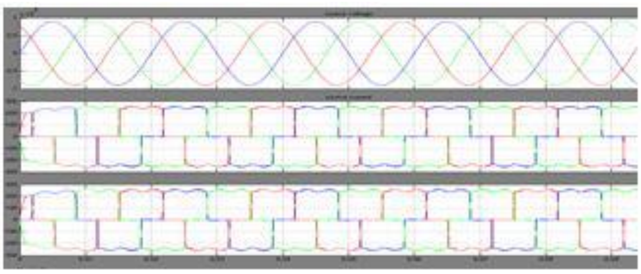

Fig. 22 Source voltage, current and load current without D-STACTOM

Fig.23 shows the three phase source voltages, three phase

source currents and load currents respectively with D-STATCOM. It is clear that with D-STATCOM even though load current is non sinusoidal source currents are sinusoidal.

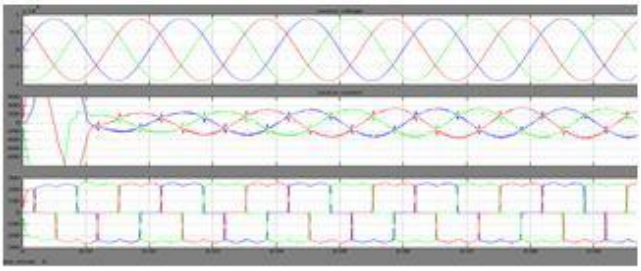

Fig. 23 Source voltage, current and load current with D-STACTOM

Fig.24. shows the DC bus voltage with respect to time. The DC bus voltage is regulated to 11kv by using Fuzzy controller.

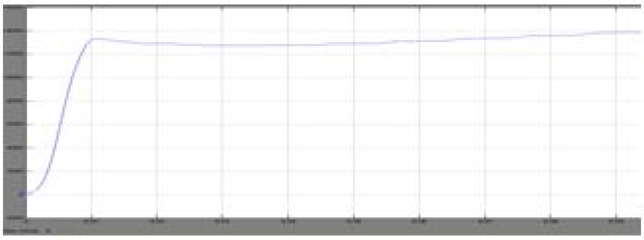

Fig. 24 DC Bus Voltage

Fig.25 shows the phase-A source voltage and current, even though the load is non linear RL load the source power factor is unity.

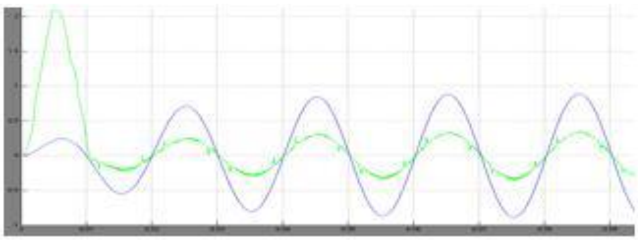

Fig.26. shows the harmonic spectrum of Phase –A Source current without D-STATCOM.

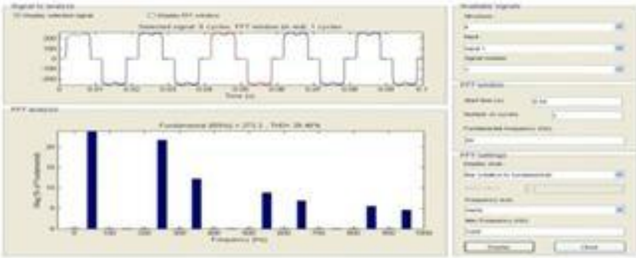

Fig. 26 Harmonic spectrum of Phase-A Source current without D-STACTOM

Fig.27. shows the harmonic spectrum of Phase –A Source current with D-STATCOM. The THD of source current with D-STATCOM is 5.05%.

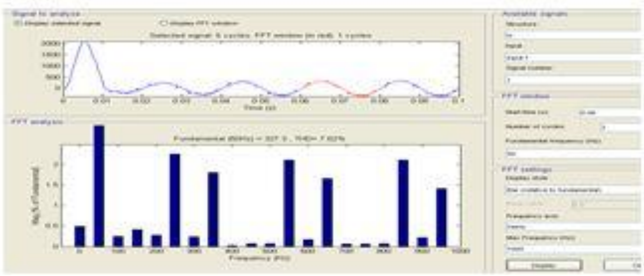

Fig. 27 Harmonic spectrum of Phase-A Source current with D-STACTOM

Table 3 Comparison between the level shifted PWM scheme without,with dstatcom & with Fuzzy Controller

comparisons	Without dstatcom	Dstatcom (pi controller)	Dstatcom (fuzzy controller)
THD of Source Current	**29.93%**	**6.19%**	**5.05%**

IV. Conclusion

A DSTATCOM with five levels CHB inverter is investigated. Mathematical model for single H-Bridge inverter is developed which can be extended to multi H-Bridge. The source voltage, load voltage, source current, load current, power factor simulation results under non-linear loads are investigated for LSCPWM and are tabulated. Finally with the help of Mat lab/Simulink based model simulation we conclude that dststcom fuzzy controller is better than the pi controller techniques and the results are presented.

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