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A Fuzzy Based Two Level STATCOM for High-Power Applications

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Abstract- *This paper presents a special gating pattern swapping technique for cascaded multilevel inverter, which is used for STATCOM. By using this technique besides minimizing the harmonic level, the inverter unit fundamental output voltages are, equalized. Therefore, all the inverter units in each phase leg can equally share the exchanged active and reactive power with the utility grid. This greatly helps the dc-link voltages balancing control. PI or Fuzzy Control is employed for improving performance. The dc-link voltages of the inverters are regulated at different levels to obtain four-level operation. In this paper two level fuzzy based STATCOM by using MATLAB/SIMULATION software. The simulation study is carried out in MATLAB/SIMULINK to predict the performance of the proposed scheme under balanced and unbalanced supply-voltage conditions.*

Index Term s —DC-link voltage balance, multilevel inverter, Power quality (PQ), static compensator (STATCOM), Fuzzy controller.

I. INTRODUCTION

The rapid growth in electrical energy use, combined with demand for low cost energy, has gradually led to the development of generation sites remotely located from the load center. The generation of bulk power at remote locations necessitates the use of transmission line to connect generation sites to load centers. With long distance ac power transmission and load growth, active control of reactive power is indispensable to stabilize the power system and to maintain the supply voltage. The static synchronous compensator (STATCOM) using voltage source inverters has been accepted as a competitive alternative to the conventional Static VAr compensator (SVC) using thyristor-controlled reactors STATCOM functions as a synchronous voltage source. It can provide reactive power compensation without the dependence on the ac system voltage. By controlling the reactive power, a STATCOM can stabilize the power system, increase the maximum active power flow and regulate the line voltages. Faster response makes STATCOM suitable for continuous power flow control and power system stability improvement. The interaction between the AC system voltage and the inverter-composed voltage provides the control of the STATCOM var output [7] [8]. When these two voltages are synchronized and have the same amplitude, the active and reactive power outputs are zero.

In conventional cascaded multilevel inverter use fundamental switching frequency [2] to generate step waveform at low harmonic distortion and keep the switching loss as low as possible. But the inverter units' duty cycles are different from each other. Due to unequal duty cycle the inverter units cannot equally share the exchanged power with the utility grid [3]. In STATCOM to balance [5] the dc-link voltages, additional auxiliary inverters were used to exchange the energy among various capacitors. But the disadvantage is high cost and complexity in hardware design. In [2], to eliminate unequal duty cycles, the required dc capacitance of each inverter unit is calculated according to the corresponding duty cycle. But in practical application modular design is very difficult. By using proposed method inverter units' fundamental output voltage are equalized. Consequently, all the inverter units can equally share the exchanged power with the utility grid, and the dc-link voltage balancing control can be simplified. A special gating pattern is used for maintain the dc capacitor charge balance and equalize the current stress of the switching device.

In this paper, a static var compensation scheme is proposed for a cascaded two-level inverter-based multilevel inverter. The topology uses standard two-level inverters to achieve multilevel operation. The dc-link voltages of the inverters are regulated at asymmetrical levels to obtain four-level operation. To verify the efficacy of the proposed control strategy, the simulation study is carried out for balanced and unbalanced supply-voltage conditions.

II. CASCADED TWO-LEVEL INVERTER-BASED MULTILEVEL STATCOM.

Fig. 2 shows the circuit topology of the cascaded two-level inverter-based multilevel STATCOM using standard two-level inverters. The inverters are connected on the low-voltage (LV) side of the transformer and the high-voltage (HV) side is connected to the grid. The dc-link voltages of the inverters are maintained constant and modulation indices are controlled to achieve the required objective. The proposed control scheme is derived from the ac side of the equivalent circuit which is shown in Fig.3. In the figure, $v_a^{'}$, $v_b^{'}$ and $v_c^{'}$ are the source voltages referred to LV side of the transformer r_a, r_b, and r_c are the resistances which represent the losses in the transformer and two inverters, and are leakage inductances of transformer windings, and are the output voltages of inverters 1 and 2, respectively. Are the leakage resistances of dc-link capacitors and, respectively. Assuming and applying

KVL on the ac side, the dynamic model can be derived using as

$$\begin{bmatrix} \frac{di_a^{'}}{dt} \\ \frac{di_b^{'}}{dt} \\ \frac{di_c^{'}}{dt} \end{bmatrix} = \begin{bmatrix} \frac{-r}{L} & 0 & 0 \\ 0 & \frac{-r}{L} & 0 \\ 0 & 0 & \frac{-r}{L} \end{bmatrix} \begin{bmatrix} i_a^{'} \\ i_b^{'} \\ i_c^{'} \end{bmatrix} + \frac{1}{L} \begin{bmatrix} v_a^{'} - (e_{a1} - e_{a2}) \\ v_b^{'} - (e_{b1} - e_{b2}) \\ v_c^{'} - (e_{c1} - e_{c2}) \end{bmatrix} \quad (1)$$

Equation (1) represents the mathematical model of the cascaded two-level inverter-based multilevel STATCOM in the stationary reference frame. This model is transformed to the synchronously rotating reference frame. The d-q axes reference voltage components of the converter and are controlled as

$$e_d^* = -x_1 + \omega L i_q^{'} + v_d^{'} \quad (2)$$

$$e_q^* = -x_2 - \omega L i_d^{'} + v_q^{'} \quad (3)$$

Where $v_d^{'}$ is the -axis voltage component of the ac source and $i_d^{'}$, $i_q^{'}$ are - axes current components of the cascaded inverter, respectively. The synchronously rotating frame is aligned with source voltage vector so that the -component of the source voltage $v_q^{'}$ is made zero. The control parameters and are controlled as follows:

$$x_1 = \left(k_{p1} + \frac{k_{i1}}{s}\right)\left(i_d^* - i_d^{'}\right) \quad (4)$$

The -axis reference current is i_d^* obtained as

$$i_d^* = \left(k_{p3} + \frac{k_{i3}}{s}\right)\left[\left(V_{dc1}^* + V_{dc2}^*\right) - \left(V_{dc1} + V_{dc2}\right)\right] \quad (5)$$

Wherev_{dc1}^*, v_{dc2}^* and are the reference and actual dc-link voltages of inverters 1 and 2, respectively. The q-axis reference current i_q^* is obtained either from an outer voltage regulation loop when the converter is used in transmission-line voltage support [5] or from the load in case of load compensation.

A 100Mvar STATCOM device is connected to the 230-kV (L-L) grid network. Fig.2 shows the single line diagram representing the STATCOM and the host sample grid network. The feeding network is represented by a thevenin equivalent at (bus B1) where the voltage source is represented by a kV with 10,000 MVA short circuit power level with a followed by the transmission line connected to bus B2. The STATCOM device comprises the voltage source converter-cascade model connected to the host electric grid. 7-level is chosen here for STATCOM. It is connected to the network through the coupling transformer. The dc link voltage is provided by the capacitor C, which is charged from the ac network. The decoupled current control system ensures full dynamic regulation of the bus voltage and the dc link voltage.

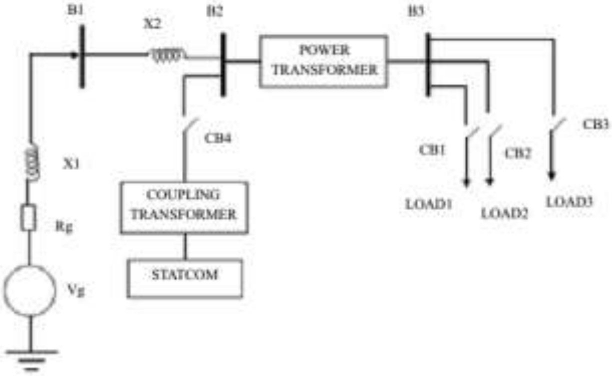

Fig.1.Single Line Diagram Representing STATCOM.

At the time of starting the source voltage is such that the STATCOM is inactive. It neither absorbs nor provides reactive power to the network. The following load sequence is tested and results are taken.

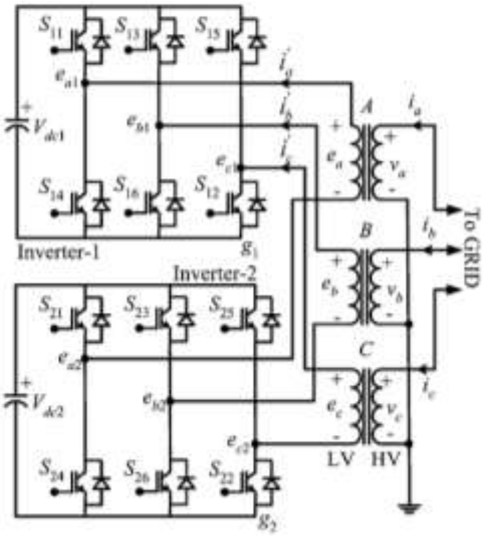

Fig.2. Cascaded two-level inverter-based multilevel STATCOM

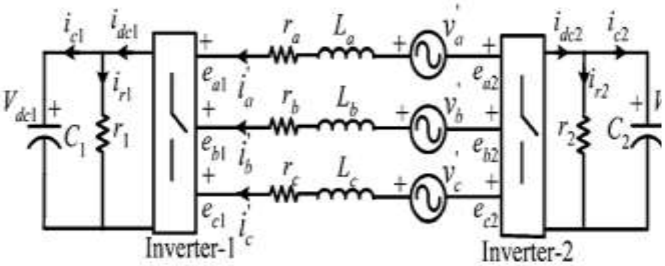

Fig.3.Equivalent circuit of the cascaded two-level inverter-based multilevel STATCOM.

A. Control strategy

The control block diagram is shown in Fig.4. The unit signals and are generated from the phase-locked loop (PLL) using three-phase supply voltages. The converter currents (i_a' , i_b' , i_c') are transformed to the synchronous rotating reference frame using the unit signals. The switching frequency ripple in the converter current components is eliminated using a low-pass filter (LPF). From ($v_{dc1}^* + v_{dc2}^*$) and i_q^* loops, the controller generates – axes reference voltages, e_d^* and e_q^* for the cascaded inverter. With these reference voltages, the inverter supplies the desired reactive current i_q^* and draws required active current (i_q') to regulate total dc-link voltage $v_{dc1}^* +$ v_{dc2}^* However, this will not ensure that individual dc-link voltages are controlled at their respective reference values. Hence, additional control is required to regulate individual dc-link voltages of the inverters.

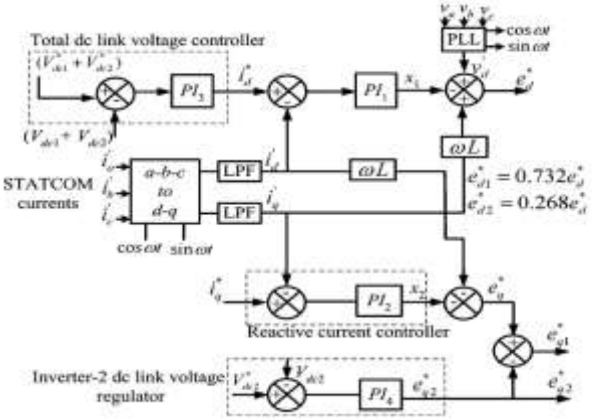

Fig.4.Control block diagram.

B. DC link balance controller

The resulting voltage of the cascaded converter can be given as $e_I \angle \delta$, where $e_I = \sqrt{e_d^2 + e_q^2}$ and $\delta = \tan^{-1}((e_q)/(e_d))$.The active power transfer between the source and inverter depends on δ and is usually small in the inverters supplying var to the grid [1]. Hence, δ can be assumed to be proportional to e_q. Therefore, the q-axis reference voltage component of inverter-2 e_{q2}^* is derived to control the dc-link voltage of inverter-2 as

$$e_{q2}^* = \left(k_{p4} + \frac{k_{i4}}{s}\right)(V_{dc2}^* - V_{dc2}) \tag{6}$$

The q-axis reference voltage component of inverter-1 e_{q1}^* is obtained as

$$e_{q1}^* = e_q^* - e_{q2}^* \tag{7}$$

The dc-link voltage of inverter-2 is controlled at 0.366 times the dc-link voltage of inverter-1 [9]. It results in four-level operation in the output voltage and improves the harmonic spectrum.

C. Unbalanced conditions

Network voltages are unbalanced due to asymmetric faults or unbalanced loads. As a result, negative-sequence voltage appears in the supply voltage. This causes a double supply frequency component in the dc-link voltage of the inverter. This double frequency component injects the third harmonic component in the ac side. Moreover, due to negative-sequence voltage, large negative-sequence current flows through the inverter which may cause the STATCOM to trip. Therefore, during unbalance, the inverter voltages are controlled in such a way that either negative-sequence current flowing into the inverter is eliminated or reduces the unbalance in the grid voltage. In the latter case, STATCOM needs to supply large currents since the interfacing impedance is small. This may lead to tripping of the converter.

The negative-sequence reference voltage components of the inverter e_{dn}^* and e_{qn}^* are controlled similar to positive-sequence components in the negative synchronous rotating frame as

$$e_{dn}^* = -x_3 + (-\omega L)i_{qn}^{'} + v_{dn}^{'} \quad (8)$$

$$e_{qn}^* = -x_4 - (-\omega L)i_{dn}^{'} + v_{qn}^{'} \quad (9)$$

III. CONTROL SCHEME FOR STATCOM

To regulate the system voltage and reactive power compensation PI control is employed. To enhance the transient stability fuzzy control is employed.

A.PI Control for STATCOM

Auxiliary control method is used to regulate the system voltage and to regulate the reactive power current effectively. Fig 5 shows the controller for STATCOM. The output of the PLL is the angle that used to measure the direct axis and quadrature axis component of the ac three-phase voltage and current. The outer regulation loop Comprising the ac voltage regulator provides the reference current (Iqf) for the current regulator that is always in quadrature with the terminal voltage to control the reactive power. The voltage regulator is a PI controller. A supplementary regulator loop is added using the dc capacitor voltage. The dc side capacitor voltage charge is chosen as the rate of the variation of this dc voltage. The current regulator controls the magnitude and phase of the voltage generated by the PWM converter (Vq, Vd) from the Idf and Iqf reference currents produced, respectively, by the dc voltage.

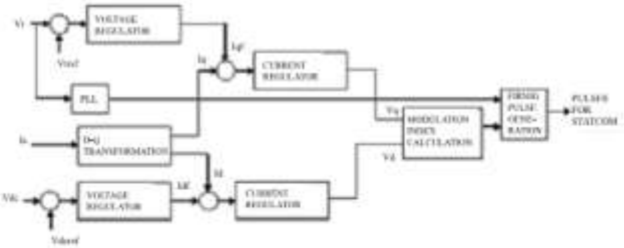

Figure 5. PI Controller for STATCOM.

IV. INTRODUCTION TO FUZZY LOGIC CONTROLLER

A new language was developed to describe the fuzzy properties of reality, which are very difficult and sometime even impossible to be described using conventional methods. Fuzzy set theory has been widely used in the control area with some application to dc-to-dc converter system. A simple fuzzy logic control is built up by a group of rules based on the human knowledge of system behavior. Matlab/Simulink simulation model is built to study the dynamic behavior of dc-to-dc converter and performance of proposed controllers. Furthermore, design of fuzzy logic controller can provide desirable both small signal and large signal dynamic performance at same time, which is not possible with linear control technique. Thus, fuzzy logic controller has been potential ability to improve the robustness of dc-to-dc converters. The basic scheme of a fuzzy logic controller is shown in Fig 5 and consists of four principal components such as: a fuzzy fication interface, which converts input data into suitable linguistic values; a knowledge base, which consists of a data base with the necessary linguistic definitions and the control rule set; a decision-making logic which, simulating a human decision process, infer the fuzzy control action from the knowledge of the control rules and linguistic variable definitions; a de-fuzzification interface which yields non fuzzy control action from an inferred fuzzy control action [10].

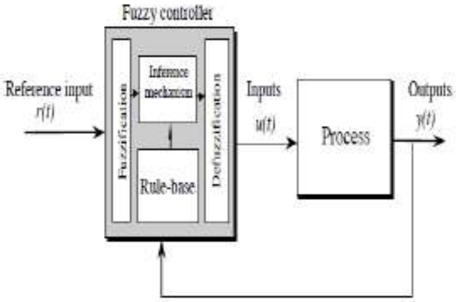

Fig.6. General structure of the fuzzy logic controller on closed-loop system

The fuzzy control systems are based on expert knowledge that converts the human linguistic concepts into an automatic control strategy without any complicated mathematical model [10]. Simulation is performed in buck converter to verify the proposed fuzzy logic controllers.

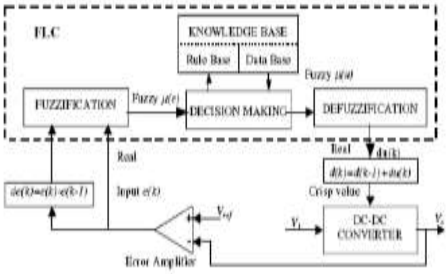

Fig.7. Block diagram of the Fuzzy Logic Controller (FLC) for dc-dc converters

A. Fuzzy Logic Membership Functions:

The dc-dc converter is a nonlinear function of the duty cycle because of the small signal model and its control method was applied to the control of boost converters. Fuzzy controllers do not require an exact mathematical model. Instead, they are designed based on general knowledge of the plant. Fuzzy controllers are designed to adapt to varying operating points. Fuzzy Logic Controller is designed to control the output of boost dc-dc converter using Mamdani style fuzzy inference system. Two input variables, error (e) and change of error (de) are used in this fuzzy logic system. The single output variable (u) is duty cycle of PWM output.

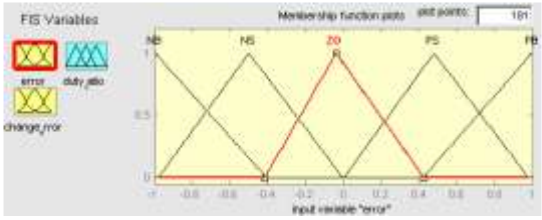

Fig. 8.The Membership Function plots of error

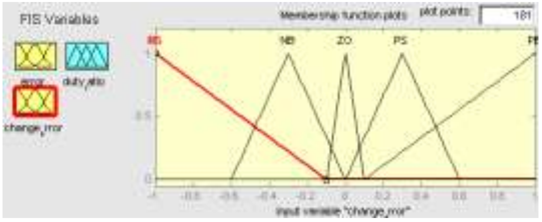

Fig.9. The Membership Function plots of change error

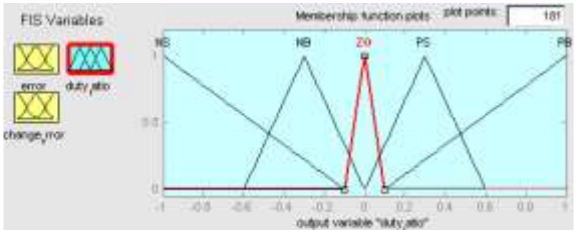

Fig.10. The Membership Function plots of duty ratio

B. Fuzzy Logic Rules:

The objective of this dissertation is to control the output voltage of the boost converter. The error and change of error of the output voltage will be the inputs of fuzzy logic controller. These 2 inputs are divided into five groups; NB: Negative Big, NS: Negative Small, ZO: Zero Area, PS: Positive small and PB: Positive Big and its parameter [10]. These fuzzy control rules for error and change of error can be referred in the table that is shown in Table II as per below:

Table II
Table rules for error and change of error

(de) \ (e)	NB	NS	ZO	PS	PB
NB	NB	NB	NB	NS	ZO
NS	NB	NB	NS	ZO	PS
ZO	NB	NS	ZO	PS	PB
PS	NS	ZO	PS	PB	PB
PB	ZO	PS	PB	PB	PB

V.MATLAB/SIMULINK RESULTS

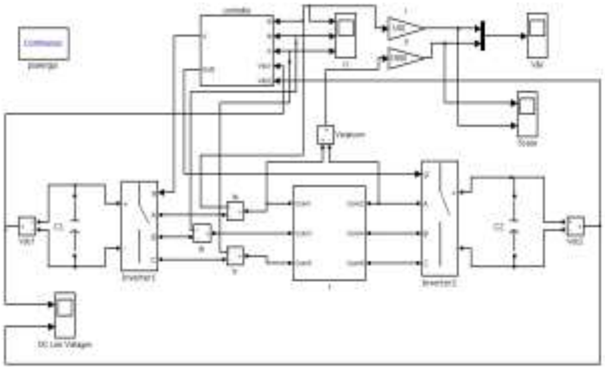

Fig.11. Matlab/Simulink model of Cascaded two-level inverter-based multilevel STATCOM

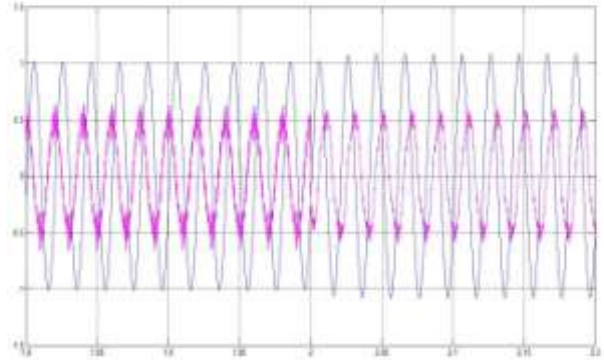

Fig. 12. Reactive power control: Source voltage and inverter current.

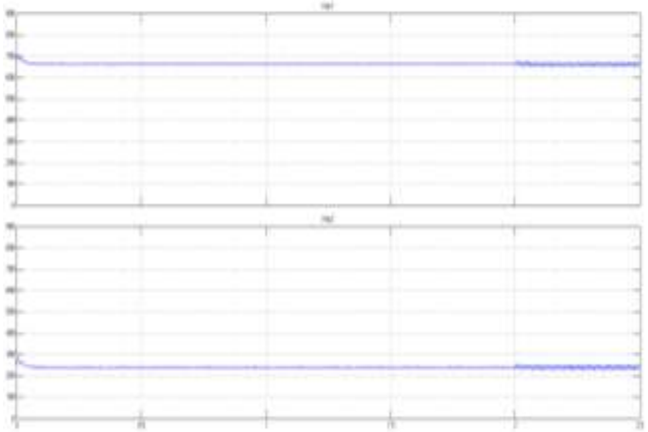

Fig.13. Reactive power control: DC-link voltages of two inverters

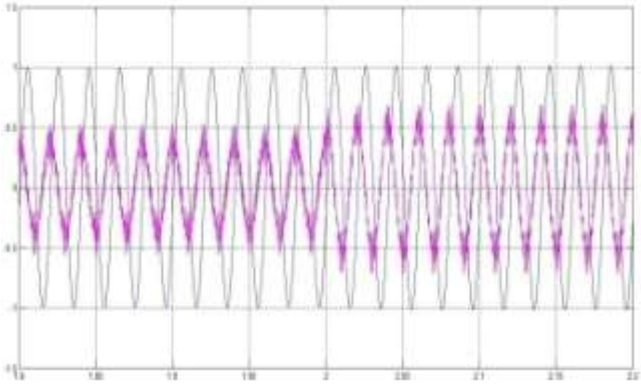

Fig.14. Load compensation: Source voltage and inverter current.

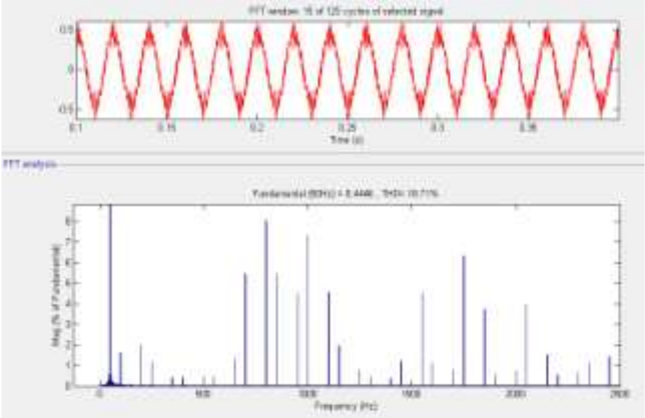

Figure:15. Harmonic spectrum of current

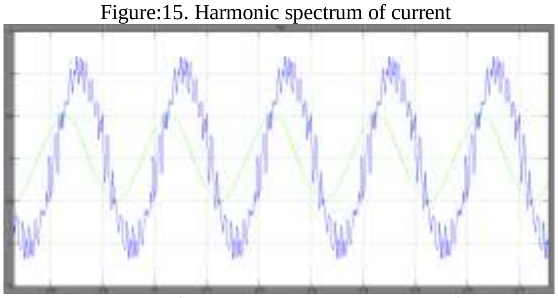

Fig.16.Simulation result for voltage and current by using fuzzy controller

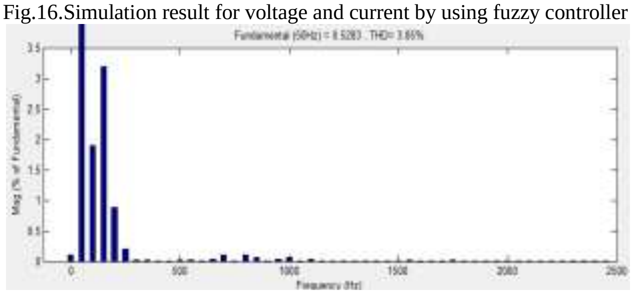

Fig.17.harmonic spectrum for source current by using fuzzy controller

V.CONCLUSION

DC-link voltage balance is one of the major issues in cascaded inverter-based STATCOMs. In this paper, a simple var compensating scheme is proposed for a cascaded two-level inverter-based multilevel inverter. The scheme ensures regulation of dc-link voltages of inverters at asymmetrical levels and reactive power compensation. The performance of the scheme is validated by simulation and experimentations under balanced and unbalanced voltage conditions. Further, the cause for instability when there is a change in reference current is investigated. From the FFT analysis we conclude that Fuzzy based STATCOM has better value compared to PI based, this value is under IEEE standards.

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