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Power Quality Improvement in Distribution System by Cascaded Multilevel Inverter Based Statcom

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Abstract: In this paper, a simple static var compensating scheme using a cascaded two-level inverter-based multilevel inverter is proposed. The topology consists of two standard two-level inverters connected in cascade through open-end windings of a three-phase transformer. The dc-link voltages of the inverters are regulated at different levels to obtain four-level operation. PI Control is employed for improving performance. Fuzzy control is employed to the system for deduction of THD. The dc-link voltages of the inverters are regulated at different levels to obtain four-level operation. The simulation study is carried out in MATLAB/SIMULINK to predict the performance of the proposed scheme.
Keywords: Cascaded Converter, DC-Link Voltage Balance, Multilevel Inverter, Power Quality (PQ), STATCOM.

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 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. When these two voltages are synchronized and have the same amplitude, the active and reactive power outputs are zero.

Multilevel inverters are used in high power applications for var compensation. Several topologies with various control strategies are available in literature. In conventional cascaded multilevel inverter use fundamental switching frequency to generate step waveform at low harmonic distortion and keep the switching loss as low as possible. In STATCOM to balance 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. By using proposed method inverter units" fundamental output voltage are equalized. Consequently, all the inverter units can equally share the exchanged power with the transmission line, and the dc-link voltage balancing control can be simplified. A special gating pattern is used for maintaining 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. This 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 [10] [16]. To verify the efficacy of the proposed control strategy, the simulation study is carried out in MATLAB/SIMULINK.

II. CASCADED TWO-LEVEL INVERTER-BASEDMULTILEVEL STATCOM

Fig.1 shows the circuit topology of the cascaded two-level inverter-based multilevel STATCOM with conventional two-level inverters. A three phase transformer of suitable rating is connected in between the two two-level inverters. The secondary of the transformer is connected in between source and load. The inverters are connected on the low-voltage (LV) side of the transformer and the high-voltage (HV) side is connected to the line. The dc-link voltages of the inverters are maintained as constant.

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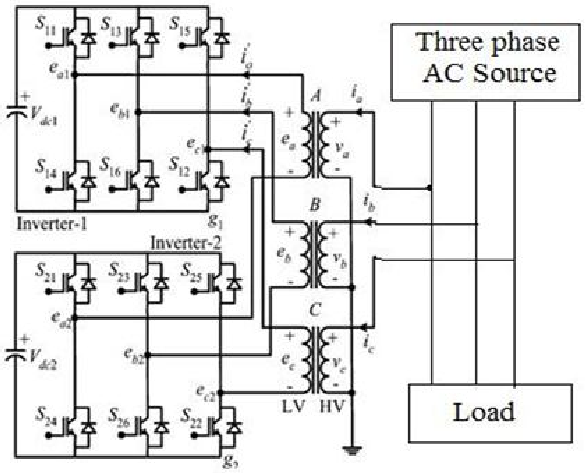

Fig.1.Cascaded two-level inverter-based multilevel STATCOM.

The proposed control strategy is derived from the ac side of the equivalent circuit which is shown in Fig. 2. In this 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 in the inverters, La, Lb and Lc are leakage inductances of transformer windings, and ea1, eb1, ec1 and ea2, eb2, ec2 are the output voltages of inverters 1 and 2, respectively and r1, r2 are the leakage resistances of dc-link capacitors C1 and C2, respectively.

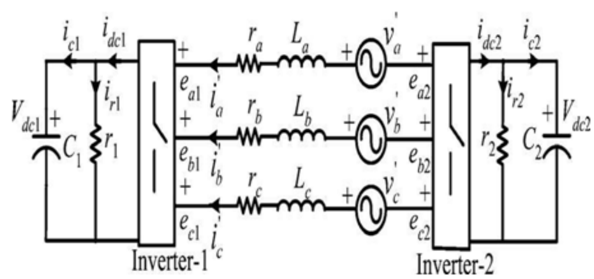

Fig.2.Equivalent circuit of the cascaded two-level Inverter-based multilevel STATCOM.

Applying KVL on the ac side, we have equations as follows:

$$-v_a + r_a i_a' + L_a \frac{di_a'}{dt} + (e_{a1} - e_{a2}) \qquad (1)$$

$$-v_b + r_b i_b' + L_b \frac{di_b'}{dt} + (e_{b1} - e_{b2}) \qquad (2)$$

$$-v_c + r_c i_c' + L_c \frac{di_c'}{dt} + (e_{c1} - e_{c2}) \qquad (3)$$

Assuming $r_a = r_b = r_c = r$, $L_a = L_b = L_c = L$ the above equations can be written as

$$\begin{bmatrix} \frac{di_a'}{dt} \\ \frac{di_b'}{dt} \\ \frac{di_c'}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{r}{L} & 0 & 0 \\ 0 & -\frac{r}{L} & 0 \\ 0 & 0 & -\frac{r}{L} \end{bmatrix} \begin{bmatrix} i_a' \\ i_b' \\ i_c' \end{bmatrix} + \frac{1}{L} \begin{bmatrix} v_a' - (e_{a1} - e_{a2}) \\ v_b' - (e_{b1} - e_{b2}) \\ v_c' - (e_{c1} - e_{c2}) \end{bmatrix} \quad (4)$$

The above equation represents the mathematical model of the cascaded two-level inverter-based multilevel STATCOM in the stationary reference frame and it is transformed to the synchronously rotating reference frame[8]. By this conversion both active and reactive currents are decoupled and can be controlled independently[8]. v_q , source voltage of q-component, is made zero so that d-component of source voltage, v_d is aligned with synchronous rotating reference frame. The system model equation in synchronous

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rotating reference frame is as follows:

$$\begin{bmatrix} \frac{di'_d}{dt} \\ \frac{di'_q}{dt} \end{bmatrix} = \begin{bmatrix} \frac{-r}{L} & \omega \\ -\omega & \frac{-r}{L} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \frac{1}{L} \begin{bmatrix} v_d - e_d \\ -e_q \end{bmatrix} \qquad (5)$$

Where v_d is d- axis voltage component of ac source and $v_q = 0$, e_d, e_q are d, q- axis components of STATCOM output voltage and i_d, i_q are d, q- axis components of STATCOM output current respectively. The STATCOM d-q voltage components are controlled, for required active and reactive currents. The d-q axes reference voltage components of the converter e_d* and e_q* are controlled as

$$e_d^* = -X_1 + \omega L i_q + v_d \qquad (6)$$

$$e_q^* = -X_2 - \omega L i_d + v_q \qquad (7)$$

The control parameters x1 and x2 are controlled as follows:

$$X_1 = (k_{p1} + \frac{k_{i1}}{s})(i_d^* - i_d) \qquad (8)$$

$$X_2 = (k_{p2} + \frac{k_{i2}}{s})(i_q^* - i_q) \qquad (9)$$

The d-axis reference current i_d^* is obtained as

$$i_d^* = (k_{p3} + \frac{k_{i3}}{s})[(V_{dc1}^* - V_{dc2}^*) - (V_{dc1} - V_{dc2}) \qquad (10)$$

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

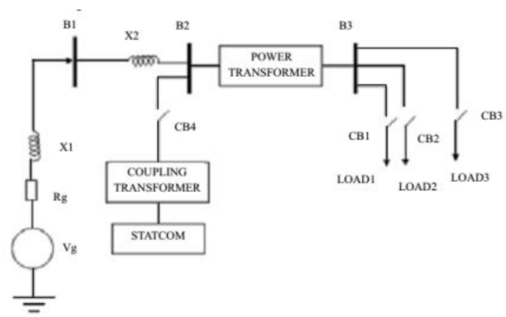

Fig.3. Single Line Diagram Representing STATCOM

A 100Mvar STATCOM device is connected to the 230-kV (L-L)grid network. Fig.3 shows the single line diagram representing the STATCOM and the host sample grid network [12]. The feeding network is represented by a the ver in 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. 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. At the time of starting, STATCOM is inactive. It neither absorbs nor provides reactive power to the network. The following load sequence is tested and results are taken.

A. Control strategy

The control block diagram for system configuration is shown in Fig.4. The unit signals cosωt and sinωt are generated from the phase-locked loop (PLL) using supply voltages (v_a, v_b, v_c). The converter currents (i'_a, i'_b, i'_c) are transformed to the synchronous rotating reference frame by using the unit signals. The switching frequency ripple in the converter current components are eliminated by using a low pass filter (LPF). From $(V_{dc1}^* + V_{dc2}^*)$ and i_q^* loops, the controller generates d-q axes reference voltages, e_d^* and e_q^* to maintain total dc link voltage and to supply required reactive current. Power sharing between the inverters is ensured by V_{dc2}^* loop. However, this will not ensure that individual dclink voltages of the inverters are controlled at their respective reference values. So, additional control is required to regulate individual dc-link voltages of the inverters.

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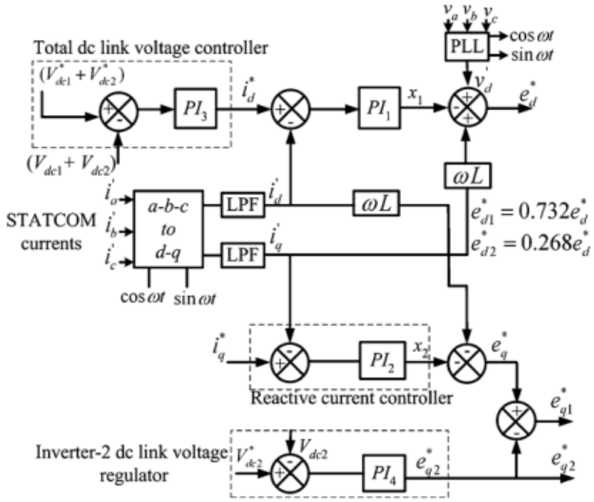

Fig.4.Control block diagram.

B. *DC link balance controller*

The resulting voltage of the cascaded converter can be given as e_I with an angleδ, where $e_I = \sqrt{e_d^2 + e_q^2}$ and $\delta = \tan^{-1}\left(\frac{e_q}{e_d}\right)$. The active power transfer between the source and inverter depends on δ and is usually small in the inverters. Hence, δ is assumed to be proportional to e_q. Therefore, to control the dc-link voltage of inverter-2, the q-axis reference voltage component of inverter-2 e^*_{q2} is derived as

$e^*_{q2} = (k_{p4} + \frac{k_{i4}}{s})\,[(V^*_{dc2} - V_{dc2})$ (11)

The q-axis reference voltage component of inverter-1 e^*_{q1} can be obtained as

$$e^*_{q1} = e^*_q - e^*_{q2} \qquad (12)$$

The dc-link voltage of inverter-2, V_{dc2} is controlled as 0.366 times the dc-link voltage of inverter-1, V_{dc1} [9]. Hence it results in four level operation in the output voltage and improves the harmonic spectrum. Dc-link voltages of inverter-1 and inverter-2 can be expressed in terms of total dc-link voltage, V_{dc} as

V_{dc1}= 0.732 V_{dc} (13)

V_{dc2} = 0.268 V_{dc} (14)

The reference d-axis voltage component, e^*_d is divided in between the two inverters in proportion to their respective dc link voltages so that two inverters operate almost at same modulation index.

e^*_{d1} = 0.732 e^*_d (15)

e^*_{d2} = 0.268 e^*_d (16)

For a gven power input, if $V_{dc2} < V^*_{dc2}$, δ_2 = tan−1 ($\tan^{-1}\left(\frac{e_{q2}}{e_{d2}}\right)$.) increases and δ_1 =tan−1 ($\tan^{-1}\left(\frac{e_{q1}}{e_{d1}}\right)$) decreases. Hence, power transfer to inverter-2 increases, while it decreases for inverter-1. So, the power transfer to inverter-2 is directly controlled, while for inverter-1, it is controlled indirectly. Therefore, during disturbances, the dc-link voltage of inverter-2 is restored to its reference quickly compared to that of dc-link voltage of inverter-1. Using $e^*_{d1}$and e^*_{q1}, the reference voltages are generated in stationary reference frame for inverter-1 and by using e^*_{d2} and $e^*_{q2}$for inverter-2. The reference voltages generated for inverter-1 are in phase opposition to that of inverter-2. By considering reference voltages, gate signals are generated using the sinusoidal pulse-width modulation technique.

C. *Unbalanced conditions*

Network voltages are unbalanced due to unbalanced loads or asymmetric faults. As a result, negative-sequence voltage appears in the supply voltage which causes a double supply frequency component in the dc-link voltage of the inverter. So, this double frequency component injects the third harmonic component in the ac side. However, due to negative-sequence voltage, large negative-sequence current flows through the inverter which may cause STATCOM to trip. Hence, during unbalance, the inverter

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voltages are controlled in such a way that either negative-sequence current flowing into the inverter is eliminated or reduces the unbalance in the line voltage. In the latter case, STATCOM needs to supply large currents as the interfacing impedance is small. This may lead to tripping of the converter in the power system. The negative-sequence reference voltage components of the inverter e^{*}_{dn} and e^{*}_{qn} are controlled similar to positivesequence components in the negative synchronous rotating frame[14]. The reference values of negative-sequence current components $i^{*}_{dn}$and i^{*}_{qn} are set at zero to block negativesequence current, flowing through the inverter.

III. CONTROL SCHEME FOR STATCOM

To regulate the system voltage and reactive power compensation PI control is employed. For deduction of THD 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 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.

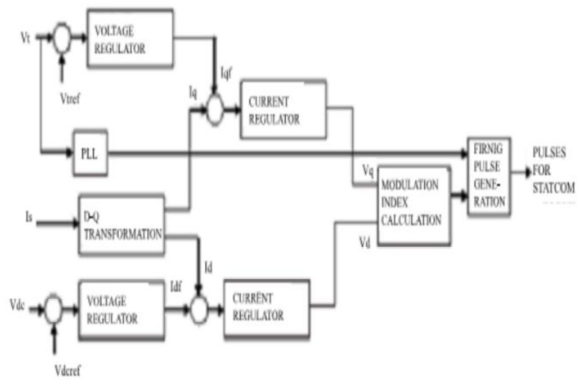

Fig.5.PI Controller for STATCOM

The outer regulation loop comprising the ac voltage regulator provides the reference current (I_{qf}) 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 ($V_{q,}V_{d,}$) from the I_{df} and I_{qf} reference currents produced, respectively, by the dc voltage.

B. Fuzzy Control for STATCOM

A simple fuzzy logic control is built up by a group of rules based on the human knowledge of system behavior. Fuzzy logic controller has potential ability to improve the robustness of converters & controlling the STATCOM currents. Fig.6 shows the membership functions for this controller.

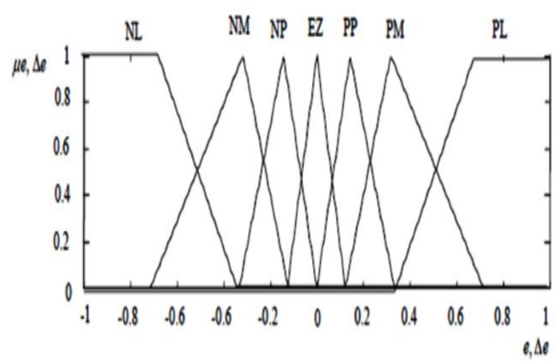

Fig.6.Membership functions for Input, Change in input,Output.

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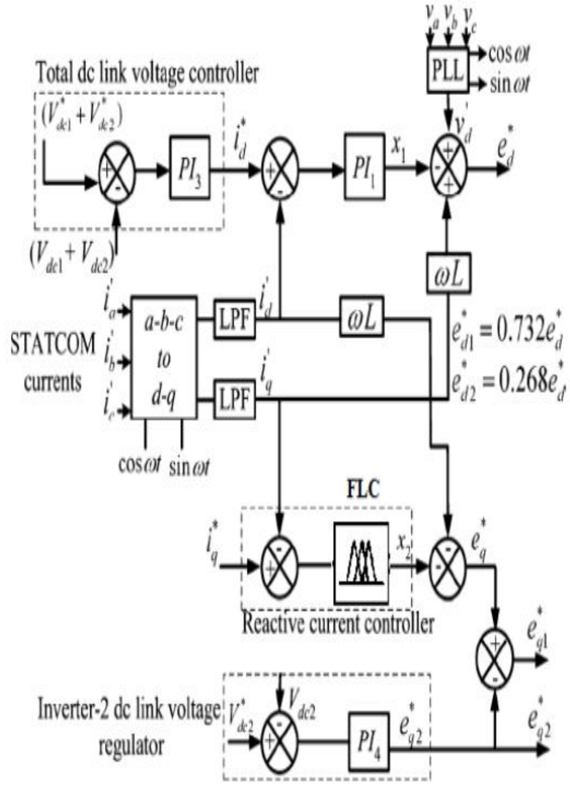

Fig.7.Control block diagram with Fuzzy Controller.

Rule Base: The elements of this rule base table are determined based on the theory that in the transient state, large errors need coarse control, which requires coarse input/output variables; in the steady state, small errors need fine control, which requires fine input/output variables. Based on this the elements of the rule table are obtained as shown in Table 1, with I_q^* and I_q as inputs. A novel intelligent control scheme is used to regulate the STATCOM current to regulate the reactive power effectively. Fig.7 shows the fuzzy controller for STATCOM. The outer regulation loop comprising the ac current regulator provides the reference current (I_q) for the current regulator that is always in quadrature with the terminal voltage to control the reactive power. The current regulator acts as a Fuzzy controller. The current controller controls the magnitude and phase of the voltage generated by the STATCOM with in phase to current (V_q, V_d) from the I_{df} and I_{qf} reference currents produced. These reference & actual currents are compared & fed to fuzzy controller to regulate the THD values.

Table1. Rules

Δe \ e	NL	NM	NS	EZ	PS	PM	PL
NL	NL	NL	NL	NL	NM	NS	EZ
NM	NL	NL	NL	NM	NS	EZ	PS
NS	NL	NL	NM	NS	EZ	PS	PM
EZ	NL	NM	NS	EZ	PS	PM	PL
PS	NM	NS	EZ	PS	PM	PL	PL
PM	NS	EZ	PS	PM	PL	PL	PL
PL	NL	NM	NS	EZ	PS	PM	PL

IV. MATLAB/SIMULINK RESULTS

The system configuration shown in Fig.2 is considered for simulation. The simulation study is carried out by using MATLAB/ SIMULINK. The system parameters are shown in Table II.

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Table II. Simulation System Parameters

Rated power	10 MVA
Ac supply frequency, f	50 Hz
Inverter-1 dc link voltage, V_{dc1}	659 V
Inverter-2 dc link voltage, V_{dc2}	241V
Transformer leakage reactance, X_l	13%
Transformer resistance, R	3%
DC link capacitances, C_1, C_2	50 mF
Switching frequency	1200

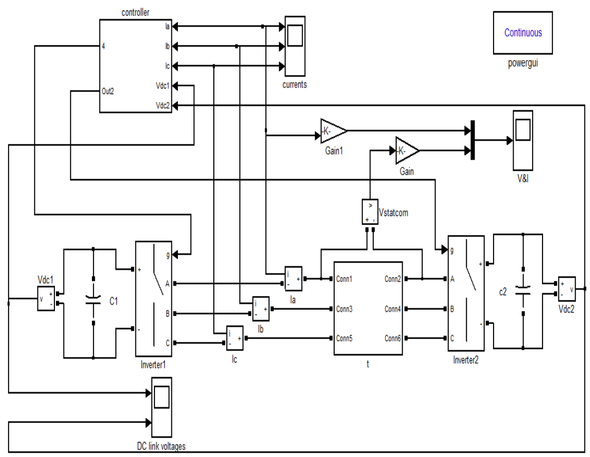

Fig.8.Matlab/Simulink model of Cascaded two-level inverter-based multilevel STATCOM.

A. *Case 1: Reactive Power Control*

In this case, reactive power is directly injected into the line by setting the reference reactive current component i_q^* at a particular value. Initially, q-axis reference current i_q^* is set at 0.5 p.u, at t = 2.0 s, i_q^* is changed to - 0.5 p.u. Fig.9 shows the source voltage and converter current of the A phase. Fig.10 shows the dc-link voltages of two inverters. From the figure, it can be observed that the dc-link voltages of the inverters are regulated at their respective reference values when the STATCOM mode is changed from capacitive to inductive. However, the dc-link voltage of inverter 2 attains its reference value faster compared to that of inverter 1.

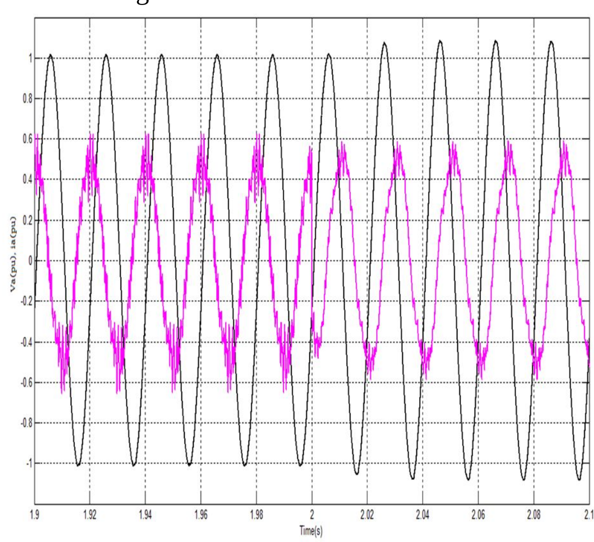

Fig.9.Reactive power control: Source voltage and inverter current.

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Volume 5 Issue V, May 2017
ISSN: 2321-9653

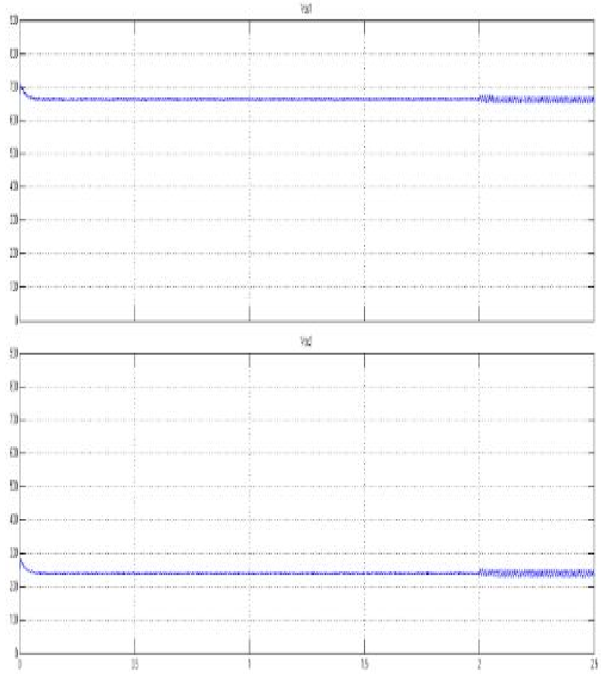

Fig.10.Reactive power control: DC-link voltages of two inverters.

B. *Case 2: Load Compensation*

In this case, reactive power is directly injected into the line by setting the reference reactive current component i_q^* at a particular value. Initially, q-axis reference current i_q^* is set at 0.5 p.u, at t = 2.0 s, i_q^* is changed to - 0.5 p.u. Fig.9 shows the source voltage and converter current of the A phase. Fig.10 shows the dc-link voltages of two inverters. From the figure, it can be observed that the dc-link voltages of the inverters are regulated at their respective reference values when the STATCOM mode is changed from capacitive to inductive. However, the dc-link voltage of inverter 2 attains its reference value faster compared to that of inverter 1.

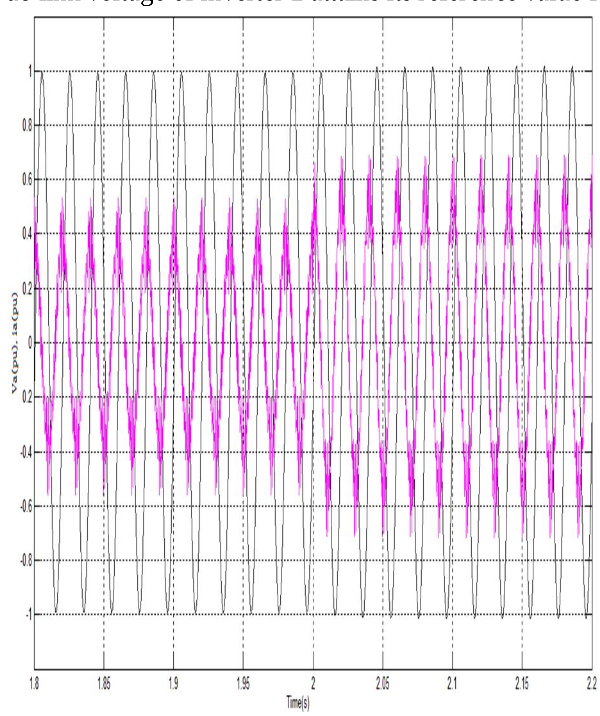

Fig.11.Load compensation: Source voltage and inverter current.

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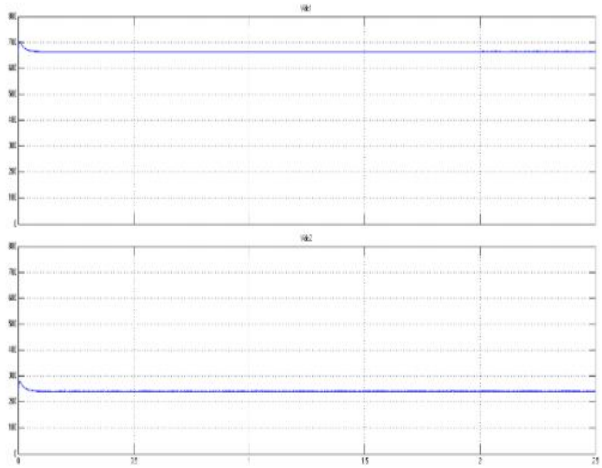

Fig.12. Reactive power .control: DC-link voltages of two inverters

As in Fig.9 and Fig.11 current waveforms consist lot of distortions, by using fuzzy controllers instead of PI controllers in the control strategy distortion factor reduces. Thus, power quality can be increased by reducing the total harmonic distortion factor (THD). The respective waveforms of load compensation are shown in Fig.13.

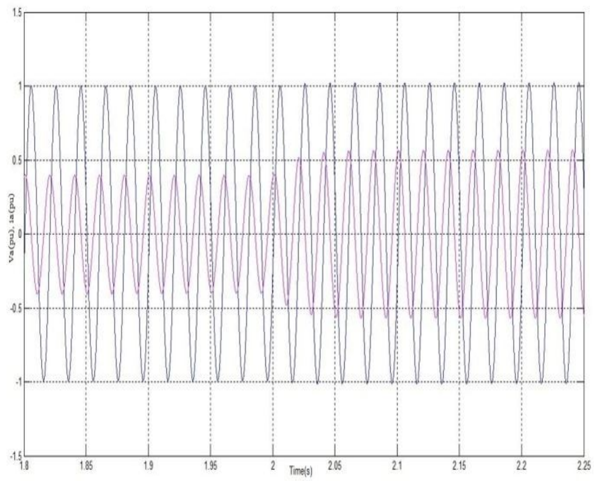

Fig.13. Load compensation: Source voltage and inverter current waveform with fuzzy

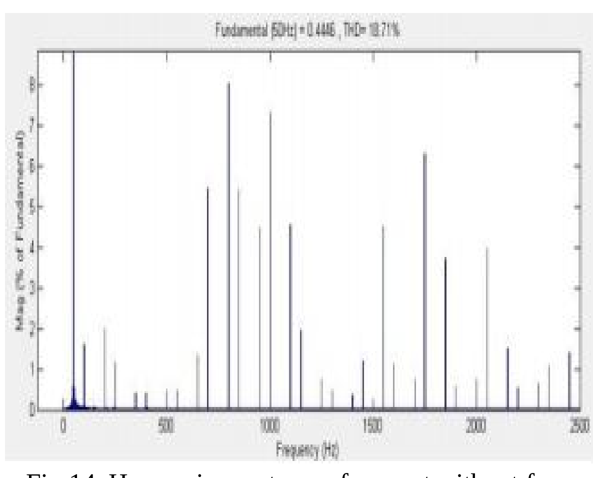

Fig.14. Harmonic spectrum of current without fuzzy

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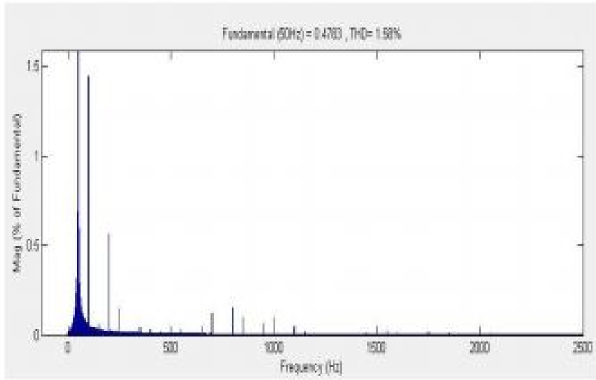

Fig.15. Harmonic spectrum of current with fuzzy

V. CONCLUSION

DC-link voltage unbalance is one of the major limitation in cascaded inverter-based STATCOM. In this paper, a simple static var compensating scheme is proposed for a cascaded two-level inverter-based multilevel inverter. This scheme ensures regulation of dc-link voltages of inverters and reactive power compensation. The performance of the scheme is validated by simulation under different conditions. The operation of the control system developed for the STATCOM in MATLAB/SIMULINK for maintaining the power quality is simulated. Further, the cause of distortions in the injected reactive current is investigated, so Fuzzy ruled based control strategy is used. By using this Fuzzy control technique distortion factor is decreased in the reactive current waveform. Hence we can stabilize the transmission systems by improving power quality (PQ) in distribution systems and decreasing total harmonic distortion factor.

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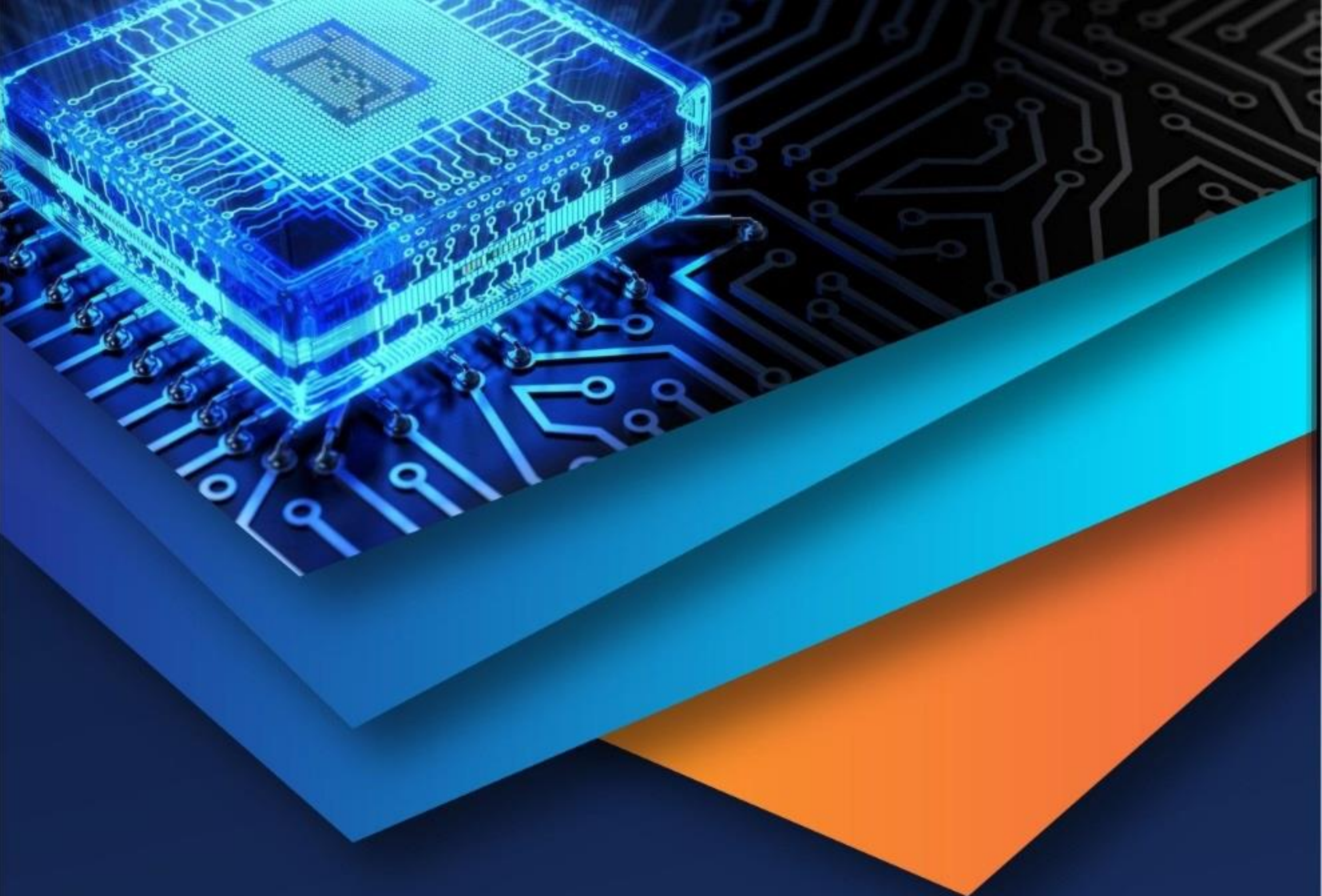

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