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Hybrid Multilevel H-Bridge Converter Based STATCOM

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Abstract - ***A cascaded H-bridge converter with equal dc voltage has been widely used for static synchronous compensator (STATCOM) application. The hybrid multilevel STATCOM is characterized by per-phase series connection of a high-voltage H-bridge converter operating at fundamental frequency and a low-voltage H-bridge converter operating at 5 kHz without any other circuit for dc voltage control The delta-type cascaded hybrid single-phase H-bridge topology is preferred because of modularity and simplicity. By using the dc voltage control system, we can control the variations in load voltage and load current, when non-linear loads are connected. Compared with other hybrid multilevel approaches, this control strategy along with the STATCOM system has the advantages of fast-speed response to load change, accurate unbalanced load compensation, specific unequal dc voltage regulation, as well as certain but unequal switching frequencies. MATLAB/SIMULINK modeling of the system has been done and a satisfactory result is obtained.***

Key Words: *Cascaded H-bridge, hybrid modulation, hybrid multilevel, STATCOM*

1. INTRODUCTION

STATIC SYNCHRONOUS COMPENSATOR (STATCOM) is an important flexible ac transmission systems (FACTS) controller in power system. Because of natural modular and high-quality output spectrum a cascaded H-bridge converter with equal dc voltage is widely used for STATCOM application [1]–[7], [25]. The cascaded single-phase H-bridge converter saves a large amount of clamped diodes and flying capacitors compared with diode-clamped converter and flying capacitor converter, [8]. In high-power application further improvement of power efficiency and waveform quality is expected of cascade H-bridge topology [9]. Either by increasing switching frequency or number of cascaded modules, a low distorted ac voltage waveform can be achieve but which may results in high power loss or high cost to the STATCOM system. A good tradeoff between waveform quality and switching loss can be obtained by hybrid multilevel technology [9]. Increased voltage levels of output waveform, improved ac current quality, reduced switching frequency resulting in low switching loss and also enhanced converter efficiency are the main advantages of hybrid multilevel converters.

"Hybrid multilevel" concept is proposed in literature [10], which paid great attentions to this field. Many hybrid multilevel approaches has been discussed in literature [11]-[22], [26], [27]. Compared with traditional ones this topology effectively produces higher voltage levels with same number of switches but faces a problem of dc voltage control. All dc-link voltages are controlled by controlled purely by control algorithm in [27].

Hybrid multilevel topology based on cascaded single-phase H-bridge converter with unequal dc voltage is discussed in [17]-[22]. A high voltage converter fed by dc supplies and a low voltage converter fed by dc capacitor in the literature [19]-[21]. In [19] high voltage inverter is performed by a diode clamped H-bridge with multi output boost rectifier. The clamped diode and rectifier makes the whole system costly. In literature [21] fundamental frequency modulation is adopted for cascaded hybrid H-bridge converters. Selective harmonic elimination method is used for hybrid modulation in literature [21] and for capacitor voltage control selecting switching redundant states is applied. But the output voltage waveform quality is not good which prevents this method for STATCOM application.

This paper focused on STATCOM application based on hybrid multilevel converters and proposes a new dc voltage control strategy for hybrid multilevel converters. Because of modularity and simplicity delta-type cascaded hybrid single –phase H-bridge topology is preferred. Clustered balancing control is achieved by the injection of zero sequence current to delta loop and individual voltage control by trimming fundamental component of quasi-square wave voltage of high voltage converters. Fast speed response to load change, accurate unbalanced load compensation, less on-line calculation, no auxiliary circuit for dc links, specific unequal dc link voltage regulation as well as certain but unequal switching frequencies are the advantages of this control strategy along with STATCOM system compared with other hybrid multilevel approaches.

2. System Configuration

Three phase STATCOM rated at 100V and 3KVA based on hybrid cascade single H-bridge cell configuration is shown in Fig.1. Cascaded number of N=2 is assigned which results in 6 converter cells in total. In each phase cluster upper single phase H-bridge cell is controlled as high voltage converter with dc link voltage of 110V and lower single phase H-bridge cell is controlled as low voltage converter with dc link voltage of 65V.

Each cell is equipped with an isolating electrolytic capacitor. An ac inductor is also used in each cluster to support the difference between sinusoidal source voltage and ac pulse width modulation voltage of cluster and also used to filtering out switch ripples caused by high frequency modulation. High voltage converter and low voltage converter are assigned with switching frequencies of 50Hz and 5kHz respectively. Constant dc voltages are achieved purely by control algorithm.

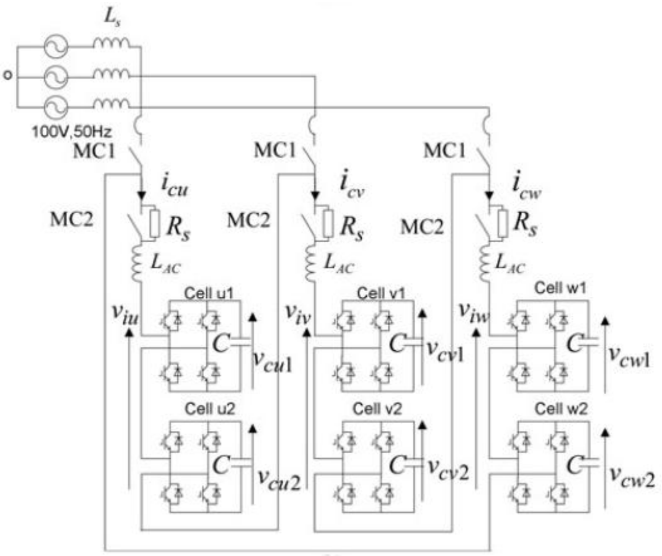

Fig -1: 100V 3KVA downscaled STATCOM

3. Hybrid modulation

Hybrid modulation is shown in Fig.2 which includes two parts: fundamental modulation and pulse width modulation. Fundamental modulation is defined as: when the sinusoidal voltage command is greater than a positive threshold value of V*cmp* high voltage converter outputs positive voltage; when the sinusoidal voltage command is lower than the negative threshold value of -V*cmp* high voltage converter outputs negative voltage and if sinusoidal command is in range between –V*cmp* and V*cmp* high voltage converter outputs zero. Remaining part of sinusoidal command and quasi square waveform voltage is command voltage for low voltage converter. It is modulated by single-polar PWM modulation technology with the carrier frequency of 5 kHz. Based on this modulation strategy, an ac waveform with higher voltage levels is produced. It brings the advantages of improving output quality, keeping high equivalent switching frequency, and reducing power loss.

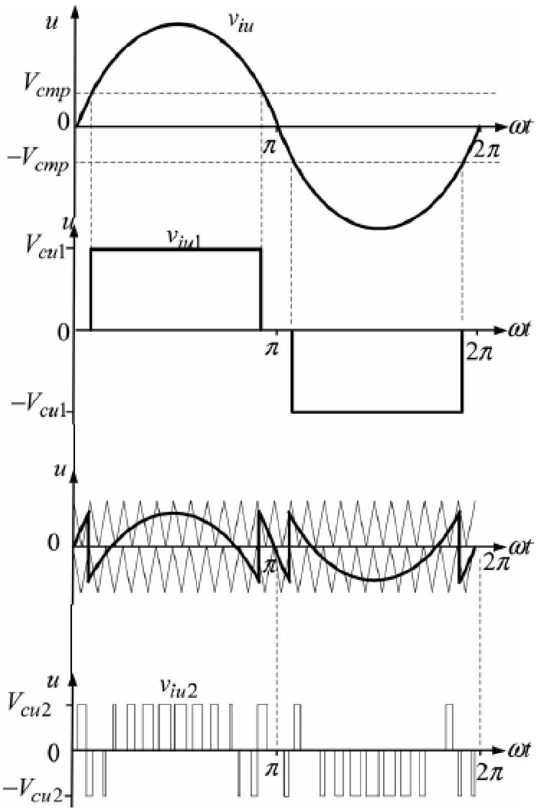

Fig -2: Diagram for hybrid modulation

4. CONTROL STRATEGY

The overall control system consist of :

- Decoupled Current Control
- Command Current Generating Control
- Capacitor Voltage Control
- Cluster balancing control
- Individual Voltage Balancing Control

4.1 Decoupled Current Control

Referring to Fig.1, the total voltage across each cluster can be written as:

$$L_{AC}\frac{di_{cu}}{dt} + R_S.i_{cu} = V_{sab} - V_{iu}$$

$$L_{AC}\frac{dicv}{dt} + R_S.i_{cv} = V_{sab} - V_{iv}$$

$$L_{AC}\frac{dicw}{dt} + R_S.i_{cw} = V_{sab} - V_{iw} \qquad (1)$$

Where R_S is the equivalent series resistance, L_{AC} is the ac series inductance. Applying the d-q transformation on equ.1, then the equations in d-q axis be,

$$L_{AC}\frac{did}{dt} - \omega\, L_{AC}\, .i_q + R_S.i_d = V_{sd} - V_{id}$$

$$L_{AC}\frac{diq}{dt} - \omega\, L_{AC}\, .i_d + R_S.i_q = V_{sd} - V_{iq} \qquad (2)$$

Here, id and iq are the feedback currents in d-axis and q-axis, respectively. The three-phase command voltages v*iu , v* iv , and v*iw can be obtained by applying the inverse d–q transformations to Vid and Viq.

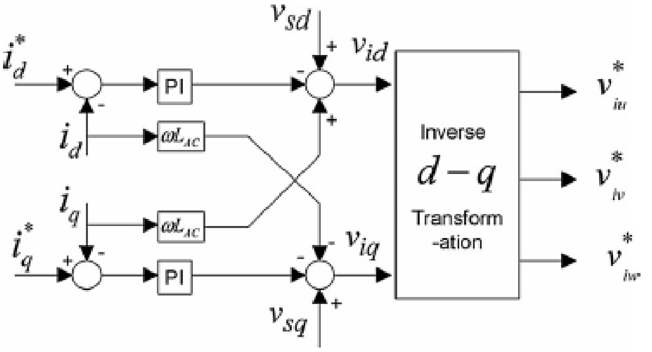

Fig -3: Decoupled current control

4.2 Command Current Generating Control

The command current generating algorithm intended for detecting reactive and negative-sequence load current includes two parts: the reactive current algorithm and the negative-sequence current algorithm. These two parts are all based on d-q transformations and moving average low-pass filter. The main difference between them is that the negative-sequence current algorithm needs to change the position of b-phase current and c-phase current when applying d-q transformations. As shown in Fig.4 the upper algorithm is for reactive current detection and the lower algorithm is for negative-sequence current detection. The three-phase line currents i^*_{la}, i^*_{lb}, i^*_{lc} ought to be transformed into phase current because of the delta configuration of the three clusters.

iuref = -(i*la - i*lb) /3

ivref = -(i*lb - i*lc) /3

iwref = -(i*lc - i*la) /3 (3)

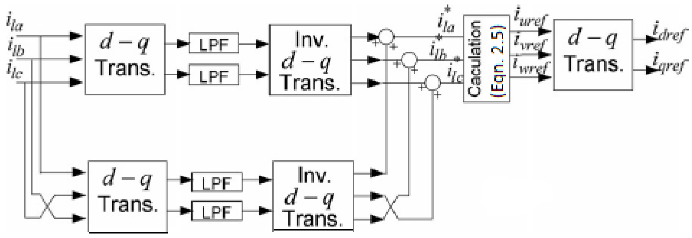

Fig -4: Command current generating algorithm

4.3 Capacitor Voltage Control

The block diagram of capacitor voltage control algorithm, as shown in Fig.4.3. Vdc_ref is the reference value for the sum of all the dc capacitor voltage. Vdc_ref value is constant. Vdc_sum acts as the feedback, which is obtained by summing up all the dc capacitors voltage. That means when there is any disturbances in the transmission line, the value of Vdc_sum varies and there is an output in the comparator, then the PI controller activates. The PI regulator is preferred for overall control. The output of PI regulator is the active component of command current.

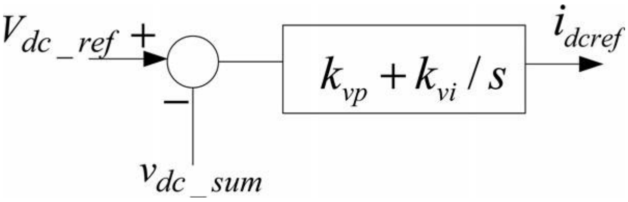

Fig -5: Capacitor voltage control

4.4 Injection of Zero-Sequence Current for Clustered Balancing Control

The command zero-sequence current Io and phase angle φ_o could be written as

$$i_0 = I_0 \sin(\omega t + \varphi_o) \qquad (4)$$

where Io and φ_o are the magnitude and original phase angle, respectively. The average power redistributed by zero-sequence current is expressed as

$$\overline{P_{oab}} = \frac{1}{Ts}\int_t^{t+Ts} V_{sab}\,.\, i_0\,.dt = \frac{Vs.\ io}{2}\cos(\varphi_o)$$
$$\overline{P_{obc}} = \frac{1}{Ts}\int_t^{t+Ts} V_{sbc}\,.\, i_0\,.dt = \frac{Vs.\ io}{2}\cos(\varphi_o + \frac{2\pi}{3})$$
$$\overline{P_{oca}} = \frac{1}{Ts}\int_t^{t+Ts} V_{sca}\,.\, i_0\,.dt = \frac{Vs.\ io}{2}\cos(\varphi_o - \frac{2\pi}{3}) \qquad (5)$$

where Vs is the magnitude of line-to-line grid voltage and Ts is a line period. V_{sab}, V_{sbc}, V_{sca} are the three-phase line-to-line voltages. The sum of the three equations in (5) is equal to zero, which indicates that zero-sequence current just causes there distribution of active power among three clusters without any influence on total active power. The redistributed power could be used for canceling that is caused by unbalanced compensating current, as well as for providing proper amount of power for balancing of dc voltages among three clusters. Therefore, the average power could be expressed as

$$\overline{P_{oab}} = \overline{P_{nab}} + \Delta\,\mathrm{Pab}$$

$$\overline{P_{obc}} = \overline{P_{nbc}} + \Delta\,\mathrm{Pbc}$$

$$\overline{P_{oca}} = \overline{P_{nca}} + \Delta\,\mathrm{Pca} \qquad (6)$$

where terms of $\overline{P_{nab}}$, $\overline{P_{nbc}}$, $\overline{P_{nca}}$ are used for power cancellation and terms of Δpab, Δpbc, and Δpca are used for balancing of dc voltages among clusters.

The amount of active power redistributed by zero sequence current is calculated by closed-loop-based regulator. Once the required power is determined, the command zero sequence current can be obtained by solving equation (5). The magnitude Io and original phase angle φ₀ are derived by,

$$i_0 = \frac{2}{Vs} \cdot \sqrt{((\overline{Poab})^2 + \frac{1}{3} \cdot (\overline{Poab} + 2.\overline{Pobc})^2}$$

$$\varphi_0 = \tan^{-1}[-\frac{1}{\sqrt{3}}(1 + 2.\frac{\overline{Pobc}}{\overline{Poab}})] \qquad (7)$$

4.5 Clustered Balancing Control

Two PI regulators with constant parameters are adopted for calculating the amount of power for redistribution. The reference zero-sequence current is synthesized based on the equations (4) and (7).

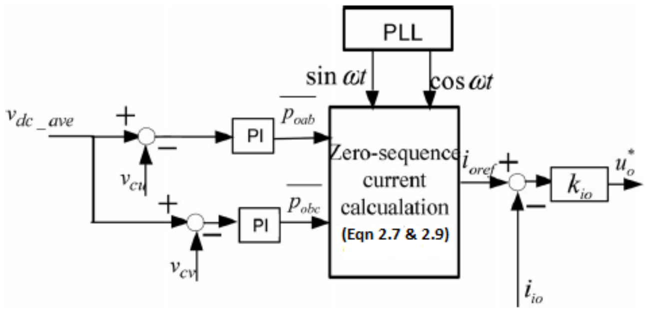

Fig -6: Clustered balancing control

4.6 Individual Voltage Control

The difference between the reference voltage and the capacitor voltage of high voltage converter is given to the comparator. In the comparator, this value is compared with the Vcmp, then the comparator output is taken as gate signals for lower voltage H-bridge. These comparator output is also used as the modulating signals for PWM modulation and it compares with triangular wave, then these modulated signal is given to the high voltage converter.

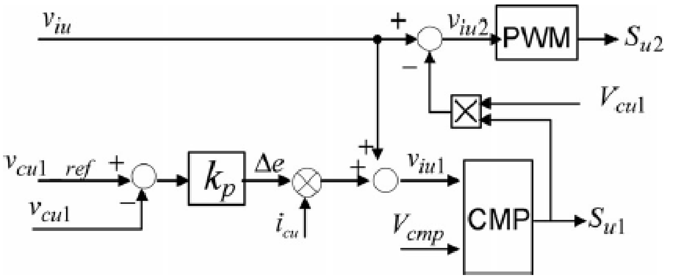

Fig -7: Individual voltage control

5. MATLAB MODELLING AND SIMULATION RESULTS

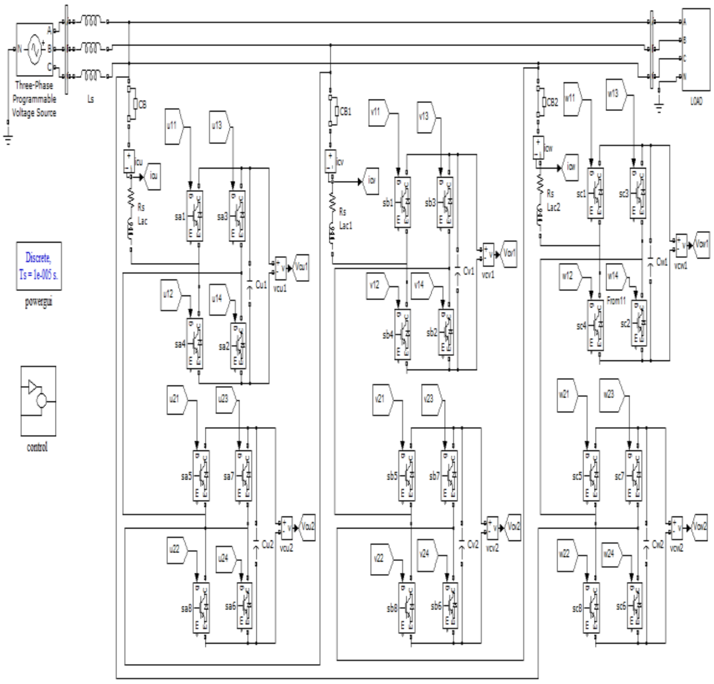

Fig -8: Matlab/Simulink model of Hybrid Multilevel H-bridge converter based STATCOM

Fig.8 shows the Matlab/Simulink model of Hybrid multilevel H-bridge converter based STATCOM. Fig.9. shows the Matlab/Simulink block of total control scheme.

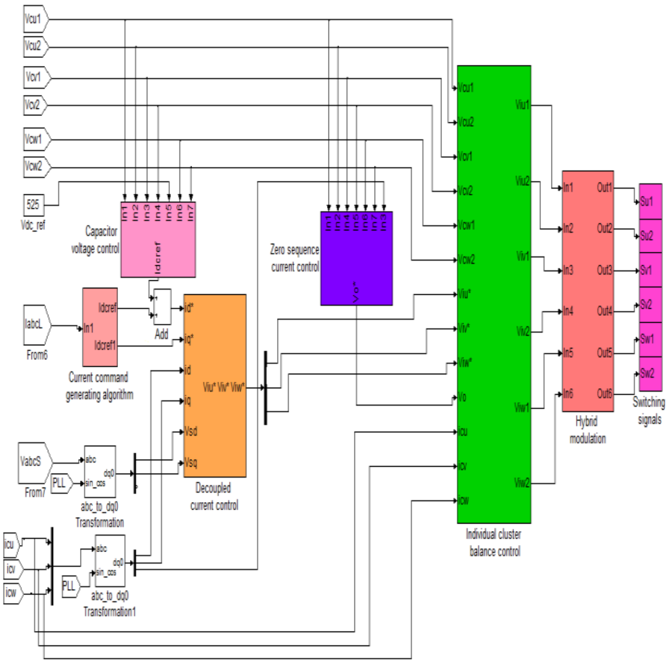

Fig -9: Matlab/Simulink model of total control scheme of hybrid multilevel H-bridge converter based STATCOM

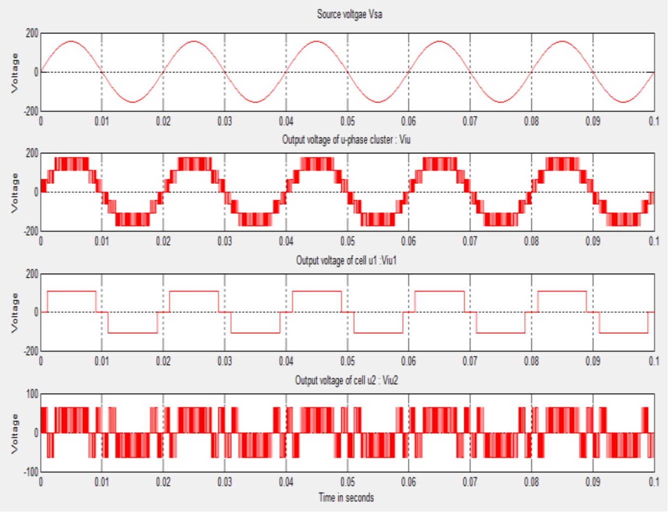

Fig -10: Source Voltage, Output Voltage, Output Voltage of Cell 1 and Output Voltage of Cell 2

Fig. 10 shows the experiment results verifying the effect of hybrid modulation. Output voltage of each phase cluster produces a nine level voltage. Output voltage of high voltage converter maintains at 110V and low voltage converter at 65V. Fig.11. shows the nine level inverter voltage separetely. Nine voltage levels of 0, ±45, ±65, ±110, and ±175 V are produced by each cluster.

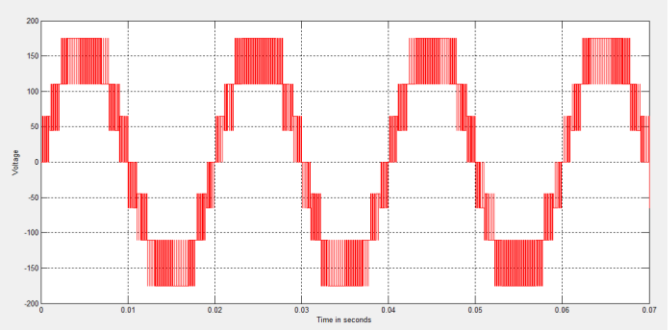

Fig -11: Inverter voltage

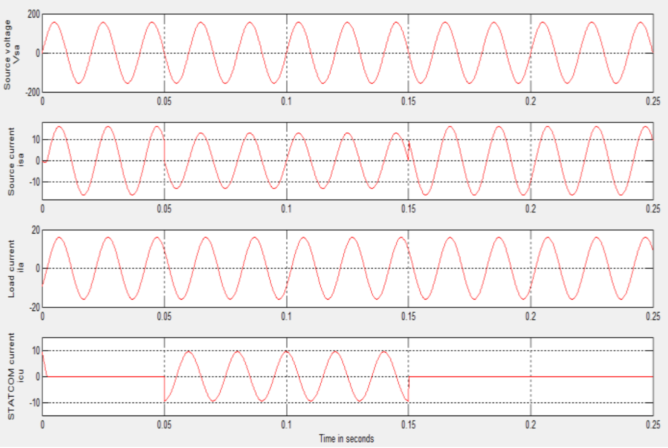

Fig -12: Waveform for verifying the effect of compensating balance load

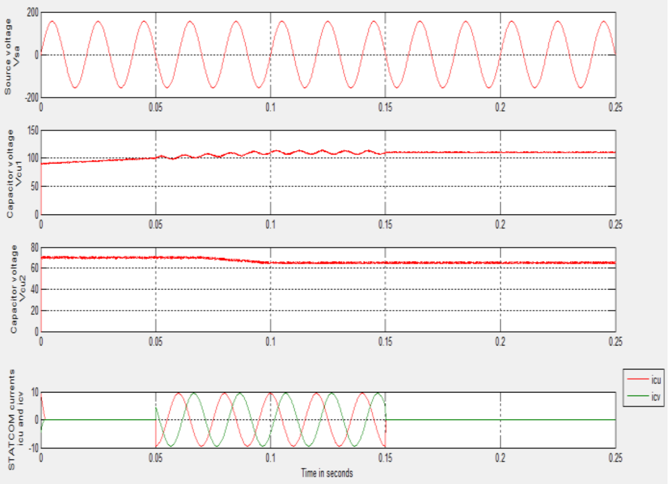

Fig -13:DC-link voltage of u-phase cluster in compensating balance load

Fig .12 and fig.13 shows the balanced load compensation. STATCOM is made to operate for 100ms and during that period RL load is compensated and become source current in phase with source voltage. While compensation dc link voltage maintains its dc mean voltage. Each cluster produce same magnitude of STATCOM current for balanced RL load compensation.

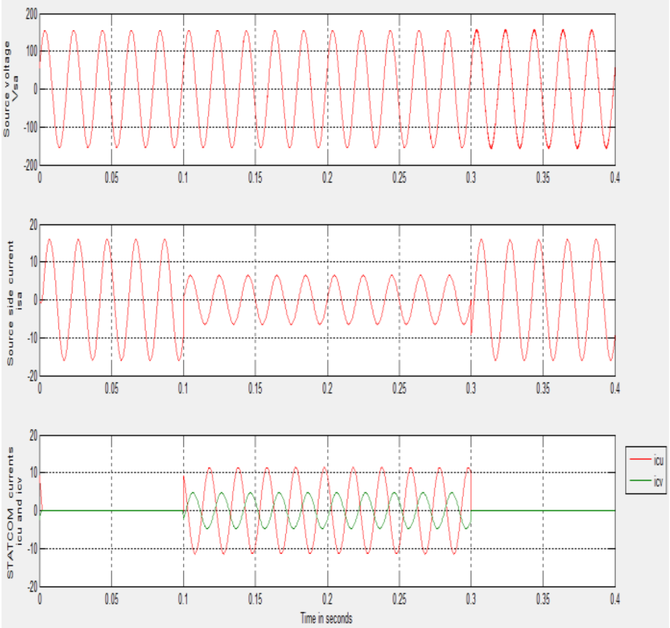

Fig -14: Waveform for verifying the effect of compensating serious unbalance load

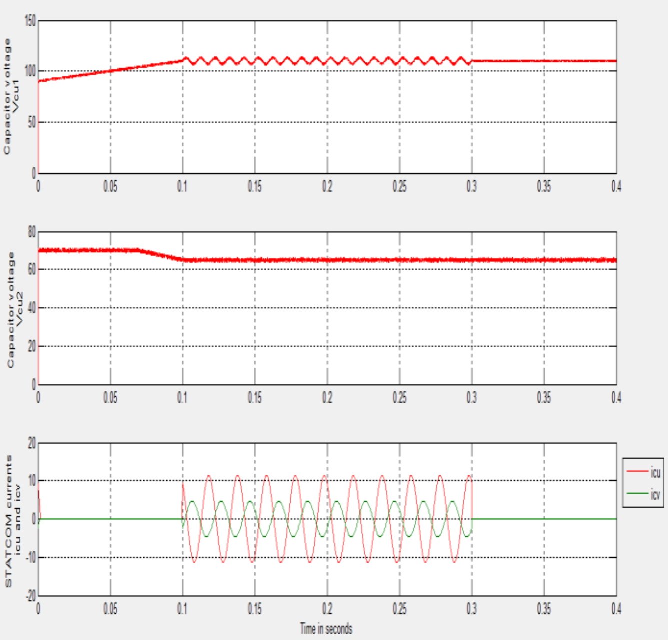

Fig -15: DC-link voltages in compensating serious unbalance load

Fig .14.– fig.16. shows unbalanced load compensation. When an unbalanced RL load is compensated dc link mean voltage are also maintained with in their rated values

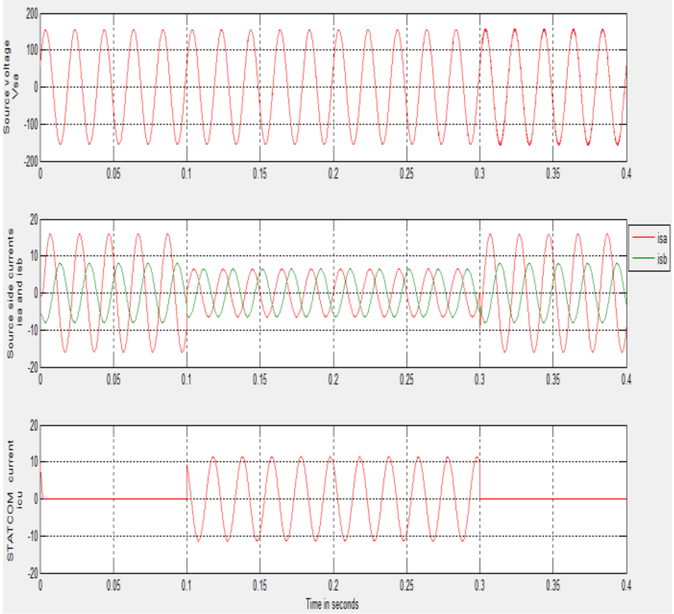

Fig -16: Source voltage and current in compensating serious unbalance load

6. CONCLUSIONS

Analyzed the fundamentals of dc voltage control based on cascaded hybrid multilevel H-bridge converters and hybrid modulation for multilevel converter is verified by using MATLAB/SIMULINK. The control scheme is characterized by the capability of maintaining the unequal dc voltage at the given value without any additional circuit as well as by the ability of compensating serious unbalanced load. This control strategy has taken full advantages of the available switching devices by operating the high-voltage device at low switching frequency and low-voltage device at high frequency. This control method along with the STATCOM system has the merits of producing high-quality output waveforms, reducing switching loss and improving whole systems efficiency.

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