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29 Level H- Bridge VSC for HVDC Application

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ABSTRACT*:* The advancement of VSC technology leads to efficient control and management of HVDC transmission system. There are various VSC topologies are available such as Diode clamped, flying capacitor, Neutral point clamped and cascaded H-bridge converters. This paper, a multilevel voltage source converter with ac side cascaded H-bridge cells is used for HVDC application. The converter is able to produce less harmonic distortion while compared to other topologies such as a modular multilevel inverter which is currently used for HVDC networks with the help of carrier based level shifted PWM. The paper also discusses the performance of VSC HVDC under steady state. A comparative study of control using PI controller and Fuzzy based PI controller is performed. Simulation is done using MATLAB/ SIMULINK.

KEYWORDS: Cascaded H-Bridge Cells, Carrier Based Level Shifted PWM, VSC-HVDC, PI Controller, Fuzzy Controller

I. INTRODUCTION

The VSC topology is a high power electronics technology used in electric power systems. The introduction of VSC made evolutionary changes in power transmission through HVDC network. Now HVDC transmission is an efficient and flexible method to transmit large amount of electric power over long distances by means of overhead transmission line or underground / submarine cables. It can also be used in order to interconnect asynchronous power systems [7],[8].

In the last decade, VSC-HVDC transmission systems have evolved from simple two-level converters to neutral point clamped converters and then to multilevel converters such as a modular converter. These converter evolutions are aimed to lower semiconductor losses and increase the power handling capability of VSC-HVDC transmission systems to conventional HVDC systems based on thyristor current source converter. The other goals behind new evolutions are to improve ac side wave form quality in order to minimize or eliminate ac filters, reduce stresses in voltage on converter transformers and to decrease converter overall cost and footprint[1]-[6] .

Here cascaded H-bridge multilevel converter is used in order to meet the requirements of the HVDC transmission system with the help of a carrier based level shifted PWM technique [13][14]. A brief overview regarding the performance of this converter in HVDC transmission system is provided in the following sections.

II. CASCADED MULTILEVEL CONVERTER

Consider a simple cascade multilevel converter with two H-bridges as shown in Fig. 1. To operate a cascade multilevel converter using a single DC source, it is proposed to use capacitors as the DC sources for all but the first source. The DC source for the first H-bridge (H_1) is a DC power source with an output voltage of V_{dc} , while the DC source for the second H-bridge (H_2) is a capacitor voltage to be held at V_{dc} / 2.

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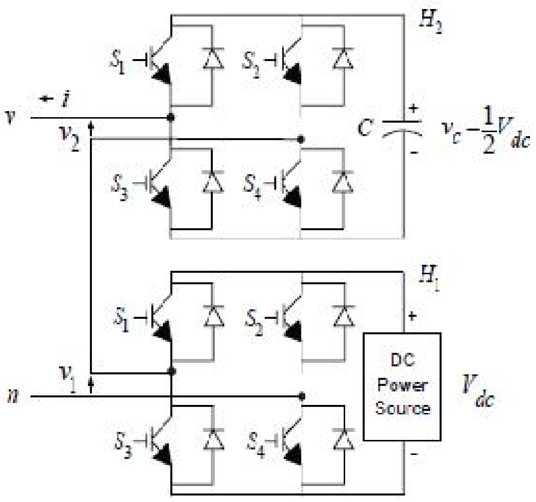

Fig 1: A Simple Cascaded multilevel converter with two H-bridges

The output voltage of the first H-bridge is denoted by v_1 and the output of the second H-bridge is denoted by v_2 so that the output of this two DC source cascade multilevel inverter is v (t) = v_1 (t) + v_2 (t). By opening and closing the switches of H_1 appropriately, the output voltage v_1 can be made equal to $-V_{dc}$, 0, or V_{dc} while the output voltage of H_2 can be made equal to $-V_{dc}/2$, 0, or $V_{dc}/2$ by opening and closing its switches appropriately.

Here there are seven H-bridge cells (H_1, H_2... H_7), which will be switched accordingly in order to attain 29 voltage levels by means of carrier based level shifted PWM.

III. CARRIER BASED LEVEL SHIFTED PWM

In Level Shifted PWM (LS –PWM), the triangular waves are vertically displaced such that the bands occupy are contiguous. The frequency modulation is finding out by $m_f = \frac{f_{cr}}{f_m}$ and amplitude modulation index is $m_a = \frac{V_{mA}}{(m-1)V_{cr}}$, where f_m and f_{cr} are the frequencies of the modulating and carrier waves, V_{mA} and V_{cr} are the peak amplitudes of modulating voltages and carrier voltages respectively. The amplitude modulation lies in the range of 0 to 1.

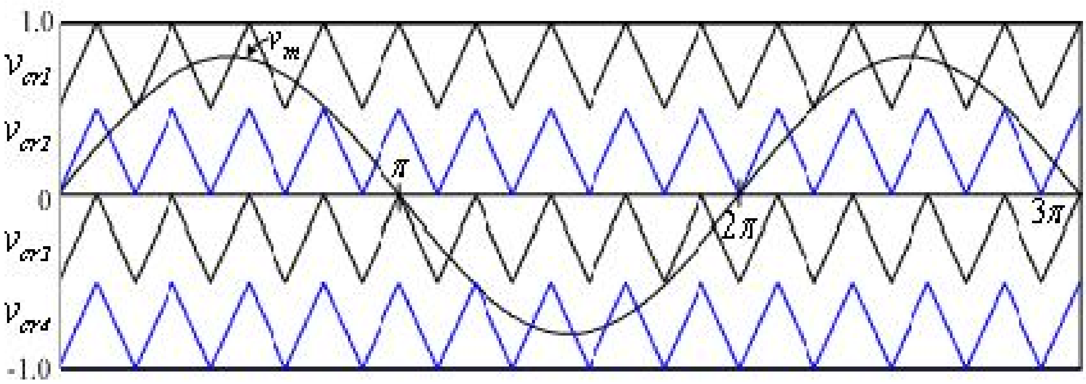

Fig 2: Level shifted carrier based Pulse width modulation

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The Fig.2 shows the Level shifted carrier pulse width modulation. Each cell is modulated independently using sinusoidal uni-polar pulse width modulation and bipolar pulse width modulation respectively, providing an even power distribution among the cells. A carrier level shift by 1/m (no. of levels) for cascaded converter is introduced across the cells to generate the stepped multilevel output waveform with low harmonic distortion.

IV. HYBRID MULTILEVEL VSC WITH AC-SIDE CASCADED H-BRIDGE CELLS

The Fig.3 shows 1- phase of a hybrid multilevel VSC with N H-Bridge cells per phase. It can able to generate 4N+1 level at converter terminal "a" relative to supply midpoint "0". Therefore, with a large number of cells per phase, the converter will produce a pure sinusoidal voltage to the converter transformer.

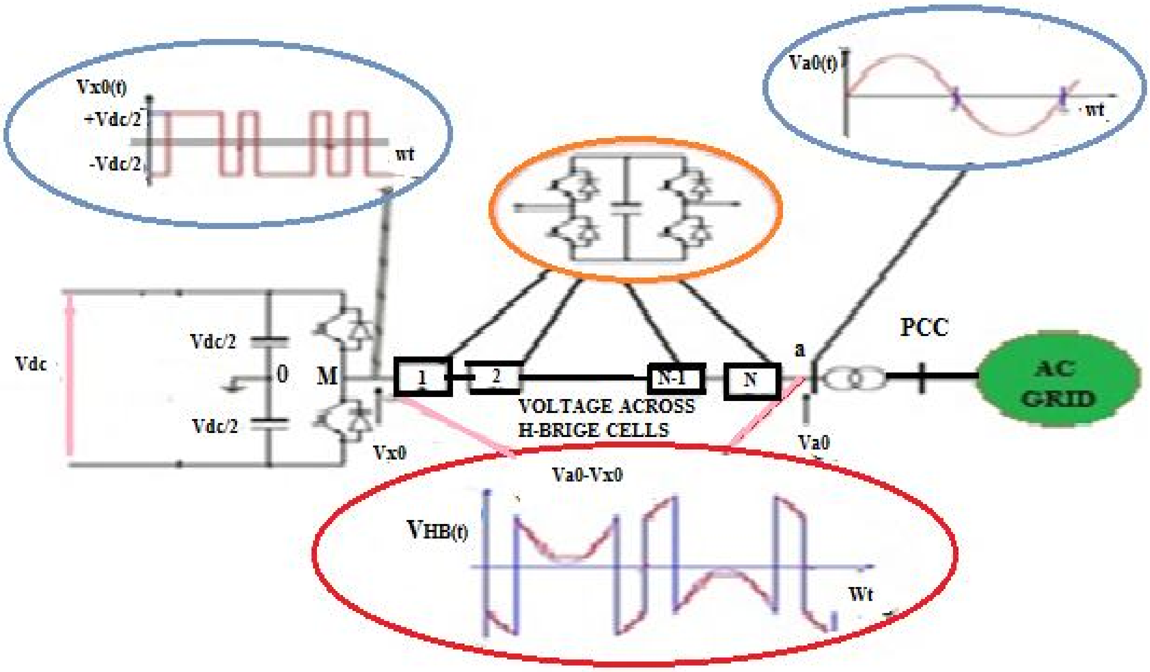

Fig 3: single phase representation of a hybrid multilevel VSC with N H-Bridge cells per phase.

The H-bridge cells between "M" and "a" are operated as a series active filter to attenuate the harmonics in voltage produced by two level converter bridge. In order to minimize the conversion losses in the H-bridge cells, the number of cells is reduced such that the voltage across the H-bridge floating capacitor sum to $V_{dc}/2$. As a result of using less number of H-bridge cells, a small converter station is required than that of modular multilevel converter. Here a seven cell topology is used which will capable to provide 29 level voltage at converter terminal. The effective switching frequency per device is only less than 150 Hz. However the operation of hybrid multilevel VSC requires a voltage balancing scheme which ensures that the voltage across the H-bridge cells are maintained at V_{dc}/N under all operating conditions, where the V_{dc} is the total dc link voltage.

V. CONTROL STRATEGY OF 29-LEVEL CONVERTER

A HVDC transmission system based on a hybrid multilevel VSC with ac-side cascaded H-bridge cells requires three control system layers. The inner control layer represents the modulator and capacitor voltage-balancing mechanism that generates the gating signals for the converter switches and maintains voltage balance of the H-bridge cell capacitors. The intermediate control layer represents the current controller that regulates the active and reactive current components over the full operating range. The outer control layer is the dc voltage (or active power) and ac voltage (or reactive power) controller that provide set points to the current controllers. The current, power, and dc link voltage controller gains are selected using root locus analysis, based on the applicable transfer functions.. Fig. 4 summarizes the control layers of the hybrid multilevel VSC. Here in this topology a control system is designed for DC voltage regulation by integrating fuzzy controller with a PI controller.

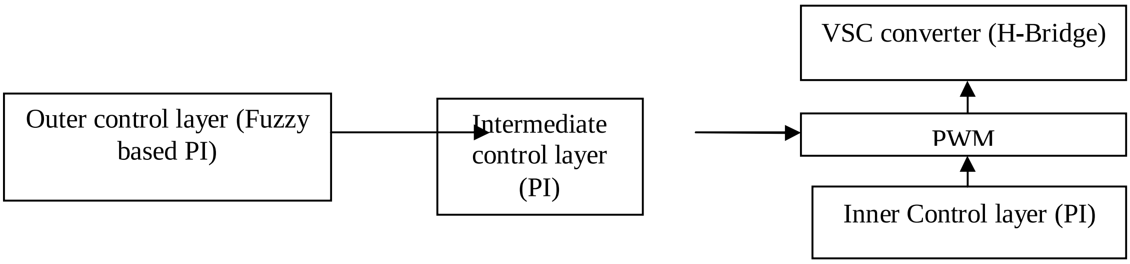

Fig 4: Block diagram illustrating overview of the control scheme.

A. Fuzzy and PI controllers

In case of a Fuzzy logic control scheme, the error (e $=V_{DC,\ ref}-\Delta V_{DC}$) and integration of error signal (∫e) are used as inputs for fuzzy processing. The output of the fuzzy controller after a limit is considered as the magnitude of peak reference current I_{max}. This current I_{max} comprises active power demand of the non-linear load and losses in the distribution system.

TABLE I
FUZZY RULE

Δe \ e	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NM	NS	NS	ZE
NM	NB	NM	NM	NM	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PS	PM	PB
PM	NS	ZE	PS	PM	PM	PM	PB
PB	ZE	PE	PS	PM	PB	PB	PB

The peak reference current is multiplied with PLL output for determining the desired reference current. The TABLE I shows the fuzzy rule base. The rule is represented such as if e is NM and Δe is PS then u is NS.
In case of PI controller, the transfer function for the dc voltage controller is

$$\frac{V_{dc}(s)}{V_{dc}^{*}(s)} = \frac{\frac{K_{pdc}}{C}s + \frac{K_{idc}}{C}}{s^2 + \left(\frac{K_{pdc}}{C} - \frac{P_{ac}}{CV_{dc}^2}\right)s + \frac{K_{idc}}{C}}$$

The reference current for the current controller can be obtained from the outer dc voltage controller as follows:

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$$\Delta i_d^* = -\frac{1}{v_{cd}}(\Delta u_{dc} + i_d \Delta v_{cd} - \Delta I_{dc})$$

where v_{cd} and Δv_{cd} are normalized by V_{dc}^*.

Here in this topology an additional PI regulator is used to ensure that the cell capacitors are maintained at $\frac{Vdc}{N}$. Hence by considering voltage magnitude of each cell capacitor and phase current polarity, the H-bridge cells voltage balancing scheme can be realized in rotating the H-bridge cell capacitors.

VI. PERFORMANCE EVALUATION AND SIMULATED RESULTS

In order to access the performance of 29 level VSC based HVDC transmission network, a test system is designed to illustrate the viability of the hybrid multilevel voltage source converter HVDC systems four-quadrant operation and voltage support as shown in Fig. 5 and simulated in MATLAB/SIMULINK environment. The waveforms demonstrating the steady state operation of HVDC system based on hybrid voltage source multilevel converter with ac side cascaded H-bridge cells is shown in fig. 6.1 to fig. 6.8.

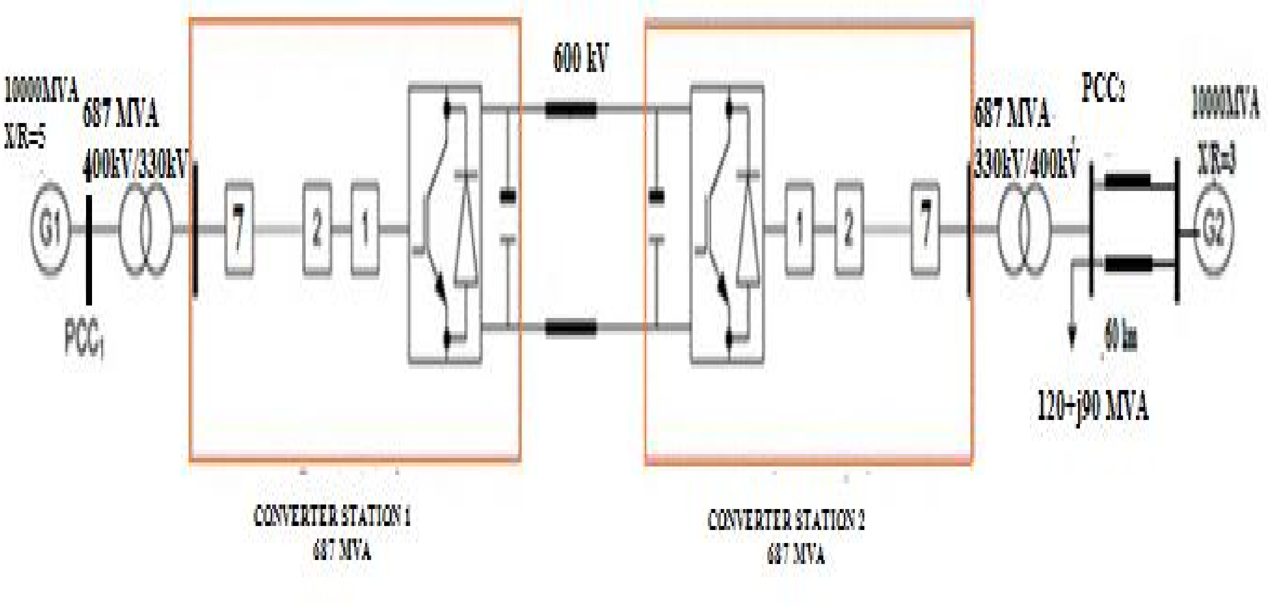

Fig 5: Test network used to illustrate the performance of the hybrid multilevel voltage source converter HVDC systems Four-Quadrant Operation and Voltage Support.

For the purpose of demonstrating four quadrant operation and voltage support capability of the presented VSC-HVDC system, converter station 1 is commanded to increase its output power export from grid G_1 to G_2 from 0 to 0.5 pu (343.5 MW) at 2.5 pu/s. At time t=1s it is commanded to reverse the active power flow in order to import 343.5 MW from grid G_2, at 2.5 pu/s. At t=2s a load of 120+j90 MVA is introduced to PCC_2, illustrating the voltage support capability of converter station 2 during network alteration.

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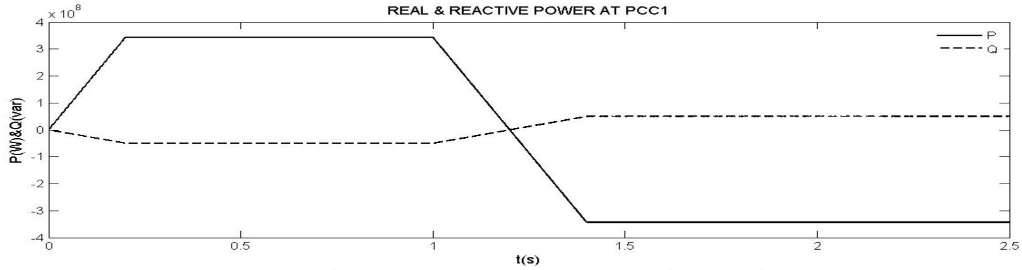

Fig 6.1: active and reactive power converter station 1 exchanges with PCC_1

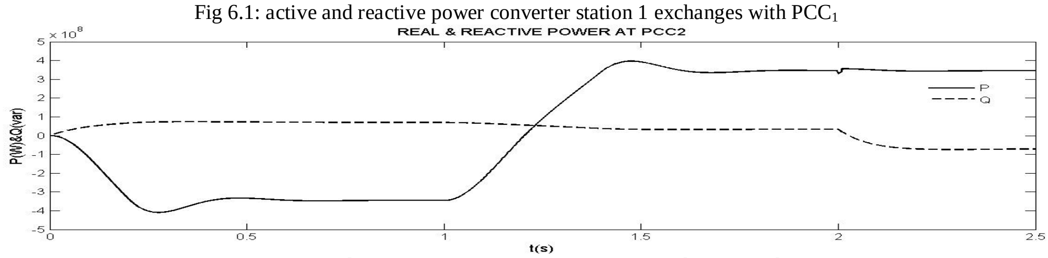

Fig 6.2: active and reactive power converter station 2 exchanges with PCC_2

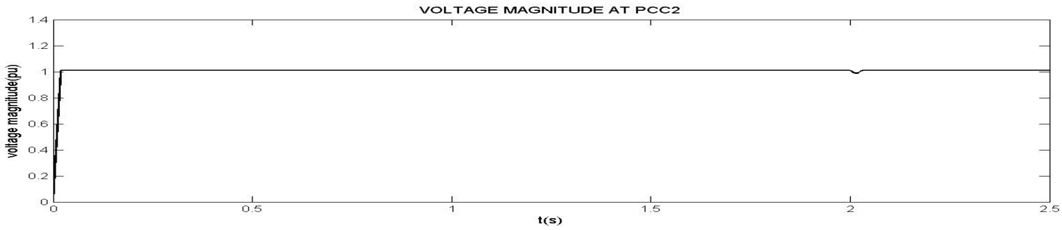

Fig 6.3: Voltage magnitude at PCC_2

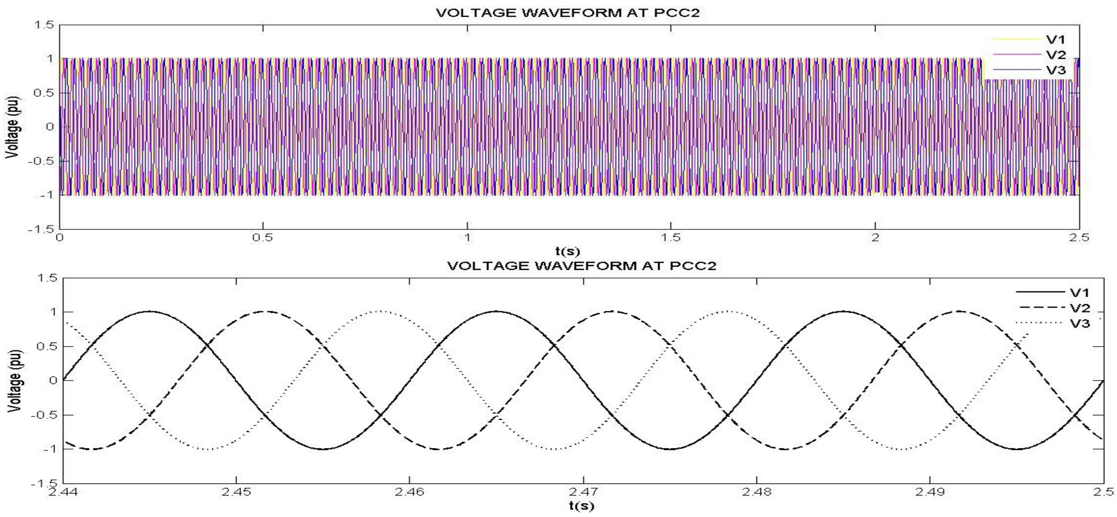

Fig 6.4: voltage waveforms at PCC_2 (full and expanded waveforms)

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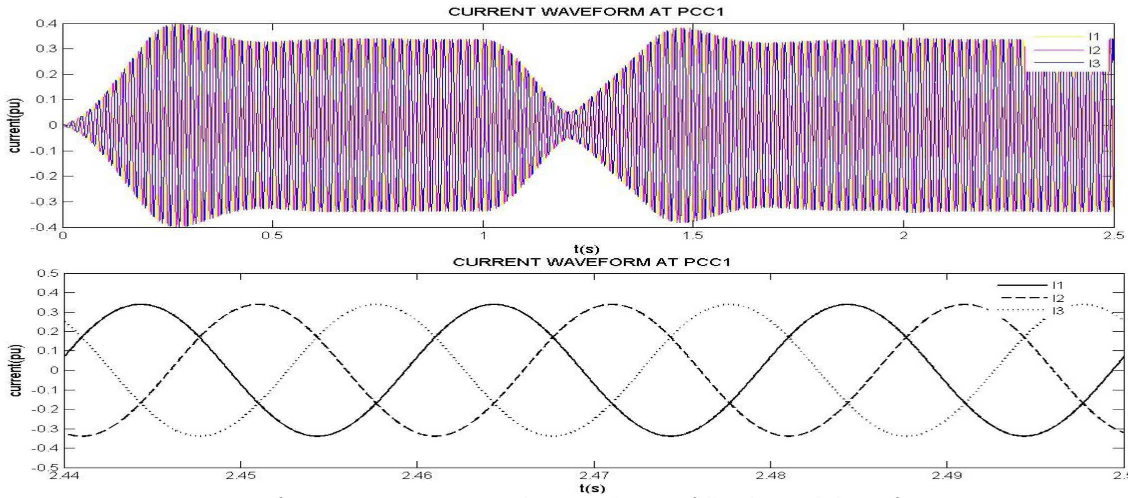

Fig 6.5: current waveforms converter station 1 exchanges with PCC_1 (full and expanded waveforms)

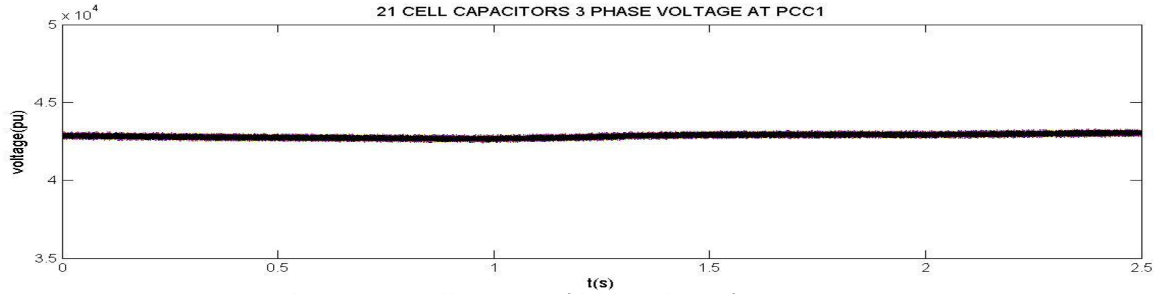

Fig 6.6: Voltage across 21 cell capacitors of the three phases of converter 1

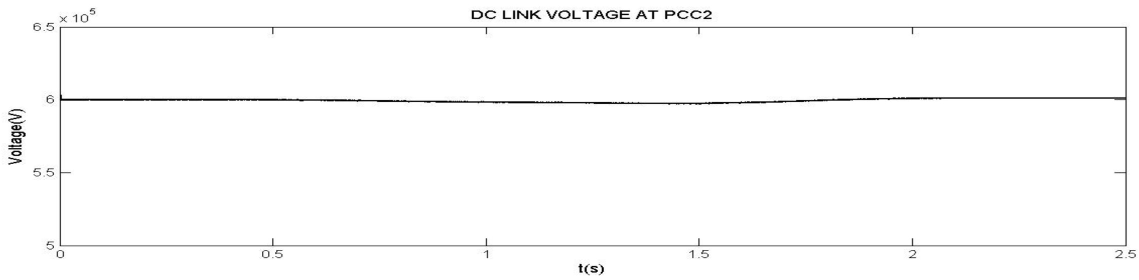

Fig 6.7: voltage across the dc link of converter station 2.

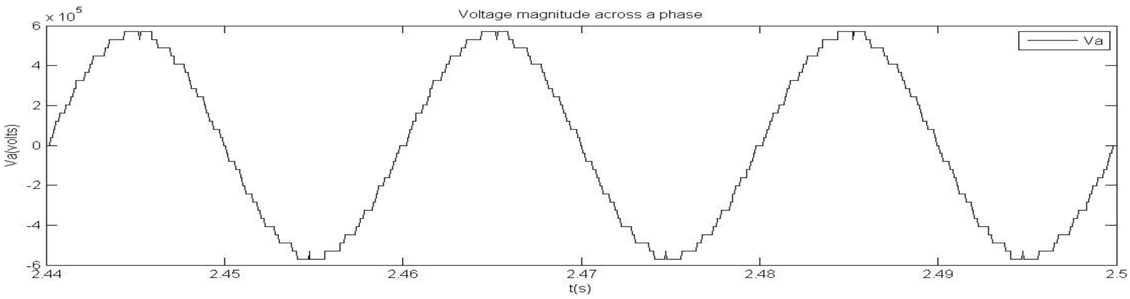

Fig 6.8: 29 level voltage waveform across a single phase.

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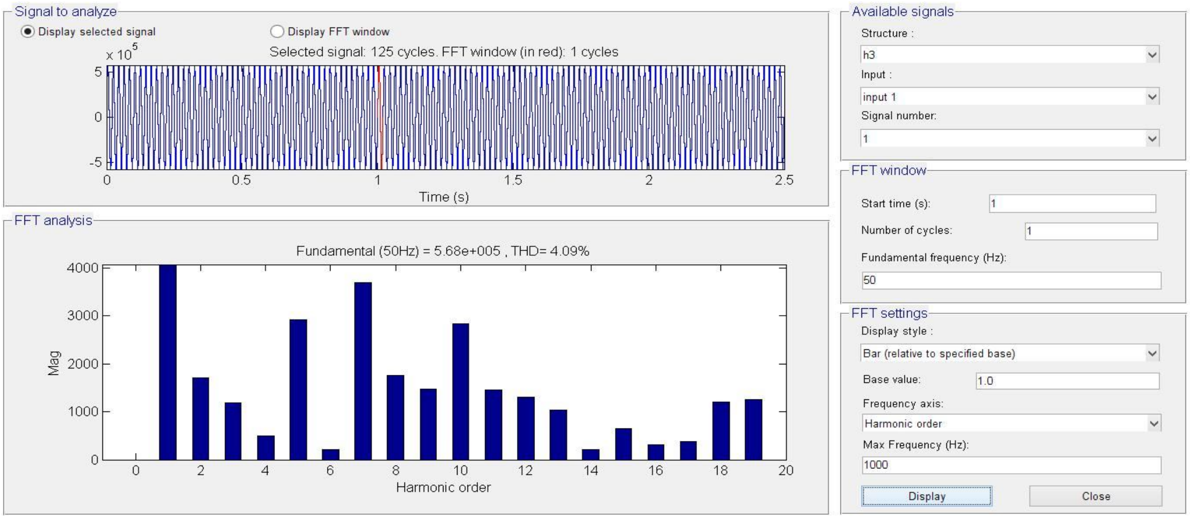

Fig 6.9: FFT analysis showing THD across 29 levels Voltage waveform.

The fig.6.1 and fig 6.2 shows the capability of converter 1 and converter 2 to exchange active and reactive power with PCC_1 and PCC_2 respectively. It is clear that converters are able to adjust their reactive power exchange with PCC_1 and PCC_2 in order to support the voltage during the entire operating period. Fig. 6.2 and fig.6.3 shows that converter 2 adjusts its reactive power exchange with PCC_2 when the load is introduced at t=2 s to support the voltage magnitude. Fig. 6.4 and fig.6.5 shows that converter 2 injects and presents high-quality current and voltage waveforms into PCC_2 without any need of ac filters. Fig. 6.6 demonstrates that the voltage stresses across the H-bridge cell capacitors of converter 1 are controlled to the desired set point during the entire period. Fig. 6.7 displays that the total dc link voltage across converter 2 would regulated at desired value (i.e., 600kV). The fig 6.8 shows voltage levels across a single phase, and from the waveform it is clear that the shape is nearer to pure sinusoidal. The fig 6.9 illustrates that THD of the voltage waveform is very low as compared to other converters, which is only 4.09 %. Based on these results, the proposed VSC-HVDC system is able to meet basic steady-state requirements, such as provision of voltage support and four quadrant operation without compromising the voltage and current stresses on the converters switches.

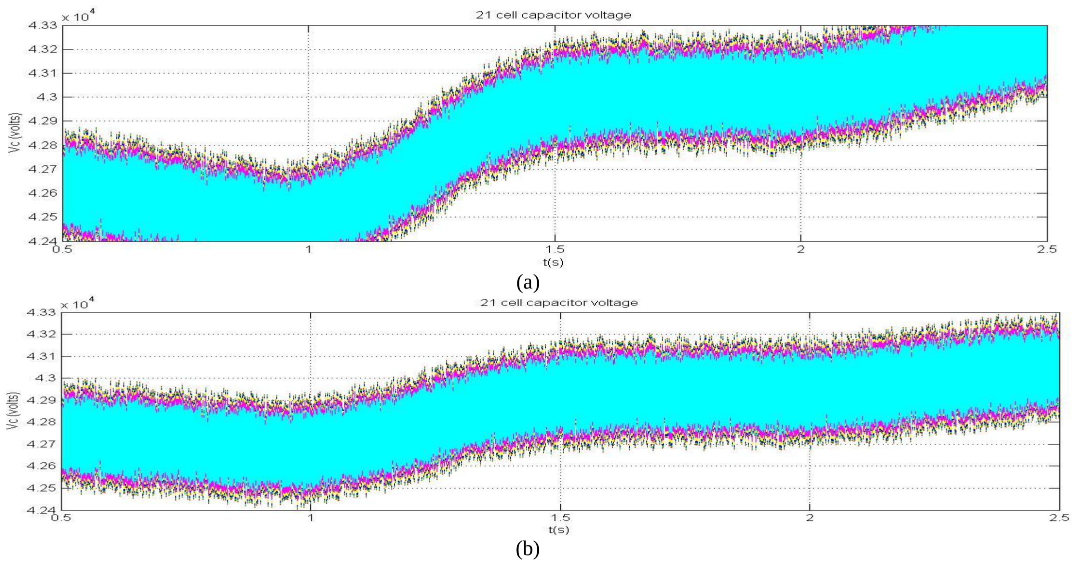

Fig 6.10: 21 Cell capacitor voltage (a) with PI controller (b) with Fuzzy based PI controller.

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The fig 6.10 proves the ability of a Fuzzy based PI controller to regulate the capacitor voltage more steadily. While considering the entire period, from Fig 6.6 it is found that the voltage stresses across the H-bridge cell capacitor are maintained at the set point. But still there is a small fluctuation occurs like as shown in Fig 6.10(a), due to the fact that cell capacitors contributes to regulate dc link voltage, which regulates active power. The Fuzzy controller provides better result as shown in Fig 6.10(b), since it contribute effectively to control small fluctuations, that might cause large consequences to system during network alterations.

VII. CONCLUSION

A VSC-HVDC transmission system based on 29- level converter with ac-side cascaded H-bridge cells topology is used. The advantages of the proposed system are improved voltage profile with less total harmonic distortion ; low filtering requirements on the ac sides along with four quadrant operation and black start capability. The capacitor voltage variation has been reduced effectively by means of a Fuzzy based PI controller for DC voltage regulation, which further proves its voltage support capability. Additionally, it offers features such as smaller footprint and a larger active and reactive power capability curve than existing VSC-based HVDC systems.

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BIOGRAPHY

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