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Control of Bidirectional Power Flow in a HVDC Transmission System Based on Multilevel Converter

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Abstract: The recent attention in environment protection and preservation increased the interest in electrical power generation from renewable sources: wind power systems and solar systems are diffusing and are supposed to occupy an increasingly important role in world-wide energy production in coming years. Not only house utilities, but industrial applications and even the electrical network requirements display the importance that energy supply and control will have in the future research. As a consequence, power conversion and secondly control is required to be reliable, safe and available in order to accomplish all requirements, both from users and legal regulations, and to reduce the environmental impact. Voltage Source Converter (VSC) technology is becoming common in high-voltage direct current (HVDC) transmission systems (especially transmission of offshore wind power, among others). HVDC transmission technology is an important and efficient possibility to transmit high powers over long distances. VSC based topologies are considered to be the most promising choice because VSC's can change power flow through the reversal of current. This is in contrast with LCC (Line Commutated Converter) where the voltage must be reversed in order to reverse the power flow. VSC based HVDC has many advantages over conventional HVDC. Among several VSC based HVDC system, Modular Multilevel Converter (MMC) based HVDC system is very promising because of higher efficiency, fault tolerant operation, use of redundant sub module in case of cell failure, low filter requirement etc. HVDC transmission system based on multilevel converter (MC) is a promising and emerging development in power sector. In this paper converter stations, based on MC topology was connected to the HVDC grid. Each of these stations can operate either in rectifier mode or in inverter mode allowing easy flexibility of bidirectional power flow. In this paper, a MC based HVDC system was developed and its operation is analyzed. Simulation study at steady state during load change and power flow reversal was performed. The proposed system shows the bidirectional power flow among the converters
Key Words: HVDC,MC,SM,PWM.

I. INTRODUCTION

The development of new technologies and devices during the 20th century enhanced the interest in electric power systems. Modern civilization based operation on an increasing energy demand and on the substitutions of human activities with complexand sophisticated machines; thus, studies on electric power generation and conversiondevices become every day more and more important.

The recent attention in environment protection and preservation increased the interest in electrical power generation from renewable sources: wind power systems and solarsystems are diffusing and are supposed to occupy an increasingly important role inworld-wide energy production in coming years.Not only house utilities, but industrial applications and even the electrical networkrequirements display the importance that energy supply and control will have in thefuture researches.

As a consequence, power conversion and secondly control is required to be reliable, safe and available in order to accomplish all requirements, both from users and legalregulations, and to reduce the environmental impact.

Voltage Source Converter (VSC) technology is becoming common in high-voltagedirect current (HVDC) transmission systems (especially transmission of offshorewind power, among others). HVDC transmission technology is an important andefficient possibility to transmit high powers over long distances.

The vast majority of electric power transmissions were three-phase and this was thecommon technology widespread. Main advantages for choosing HVDC instead of AC to transmit power can be numerous but still in discussion, and each individual situation must be considered apart. Each project will display its own pro and conabout HVDC transmission, but commonly these advantages can be summarized: lower losses, long distance water crossing, controllability, limitation short circuitcurrents, environmental reason and lower cost.

In the last decade, large quantities of power transmissionthrough Voltage Source Converter (VSC) based HVDC hasbecome very popular. VSC based topologies are considered tobe the most promising choice because VSC's can change power flow through the reversal of current. This is in contrast with LCC (Line Commutated Converter) where the voltage must be reversed in order to reverse the power flow. VSC based HVDC has many advantages over conventional HVDC in manyaspects like low losses in power transmission, four quadrantoperation, independent control of Active and reactive powerand improved dynamic voltage stability.Among several VSC based HVDC system, ModularMultilevel Converter (MMC) based HVDC system is verypromising because of higher efficiency, fault tolerant operation,use of redundant sub module in case of cell failure, low filter requirement etc.

MMC was first proposed for HVDC application in 2003. MMC based HVDC system was first commercially used in the Trans bay cable project in San Francisco[5-6]. Since then, it has become quite popular and several manufactures have started to implement HVDC system based on modular converter technology

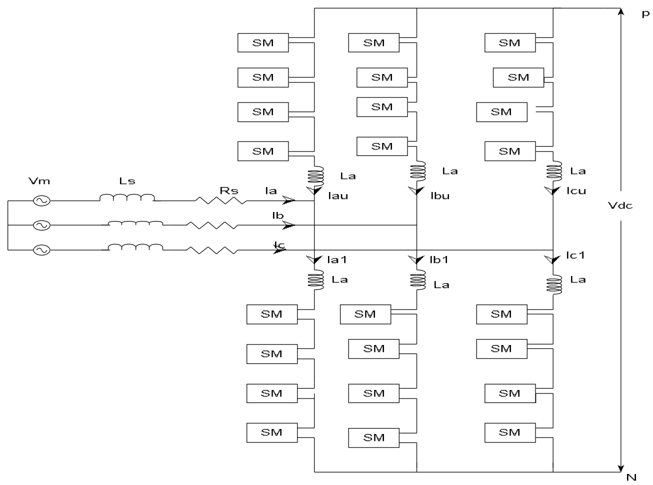

Fig. 1. A three phase Modular multilevel converter

II. MODELLING AND PRINCIPLE OF OPERATION OF MC

The equivalent circuit of MC is shown in the Fig.2. Each sub module supported by the capacitor act as an adjustable voltage source. With the help of the half bridge topology, they can be either inserted into or bypassed away from the circuit. The capacitor voltage of each sub module is maintained at its nominal voltage.

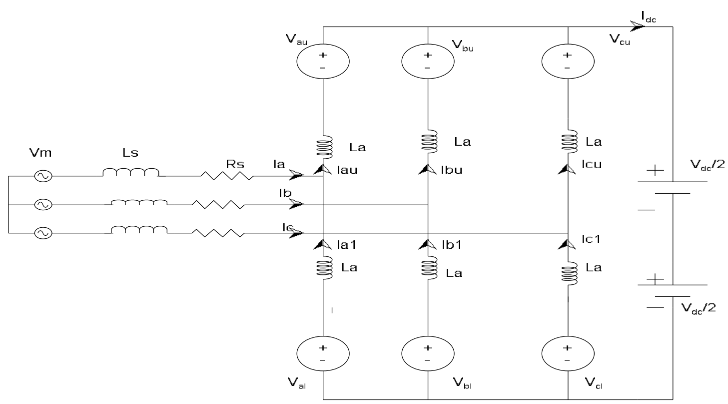

Fig.2. Circuit model of 3 phase AC-DC MC

Both upper and lower arm can be modelled as controllable voltage sources, where V_{au} and V_{al} are the upper arm and lower arm controllable voltages of "phase A "respectively. L_a is the branch inductor which is used to limit the arm circulating current and to limit the current during fault. L_s and R_s are the source inductance andresistance respectively. The voltage equations of the converters are derived using Following assumptions:

A. Voltage drop across the arm inductance and source inductance is neglected.

B. Switches are considered to be ideal.

On applying the KVL in the upper and lower loop for the phase A the following equations are obtained.

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$$V_{au} = \frac{V_{dc}}{2} - V_m \operatorname{Sin} wt \qquad (1)$$

$$V_{al} = \frac{V_{dc}}{2} + V_m \operatorname{Sin} wt \qquad (2)$$

Where Vm is the peak of input AC voltage and Vdc is the DC bus voltage.If

$$\frac{V_{dc}}{2} \geq V_m$$

from eqn. (1) and (2)

$$0 \leq \frac{V_{dc}}{2} - V_m \leq V_{xu} \leq \frac{V_{dc}}{2} + V_m \qquad (3)$$

$$0 \leq \frac{V_{dc}}{2} - V_m \leq V_{xl} \leq \frac{V_{dc}}{2} + V_m \qquad (4)$$

Where x can be either a, b or c phase.

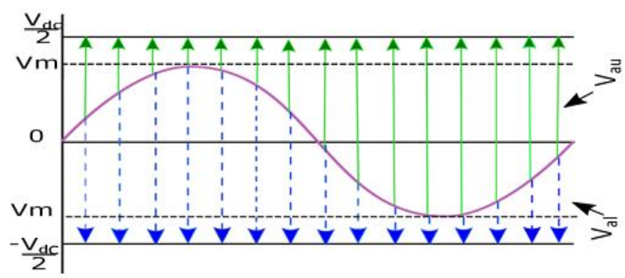

Fig.3. Voltage waveform when

$$\frac{V_{dc}}{2} \geq V_m$$

The equations are illustrated graphically in Fig.3. The solid arrows denote the voltage which is generated by the upper arm and the dotted arrow indicated the voltage which is generated by the lower arm. These voltages are generated in such a fashion that the total dc link voltage is maintained at V_{dc} or the sum of both the upper and lower arm voltage is equal to V_{dc}. Because of half bridge topology only unidirectional voltage is generated, and the voltage across each capacitor is maintained around.

$$\frac{V_{dc}}{2} \geq V_m \qquad (5)$$

Where N is the total number of sub modules used in the arm and V_c is the voltage across capacitors.

III. SYSTEM DESCRIPTION

Fig.4. shows the topology of the proposed MC based HVDC system. MC-1 acts as rectifier stationand MC-2 acts as inverter station with a passive load. Each MC has 8 sub modules(SM) in each leg with half bridge topology. MC-l converter station operates at 220kV, 50 HZ and MC-2 is at 220kV, 60 Hz. The dc bus voltage is maintained at 400kV. This system shows the connection of asynchronous links. This type of system is very convenient for the connection of off-shore wind power plants with the on-shore AC grid.

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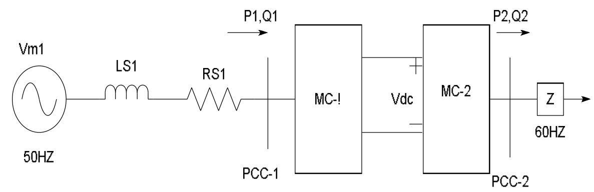

Fig.4. Proposed topology of the MMC based HVDC system

IV. CONTROL STRATEGY FOR THE HVDC

The overall control system hierarchy of MC based HVDC system is shown in the Fig.5. Synchronous reference frame is used in the upper/high control system where the D component of current is responsible to maintain DC voltage or the active power and the Q component of current maintain reactive power. The reference voltage V_{ac}^* is given to the lower level control system where level shifted PWM operation and the capacitor voltage balancing happens [14].

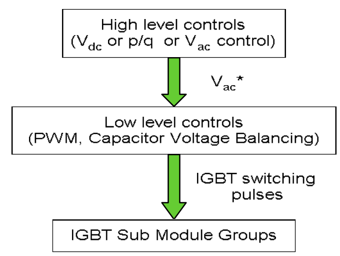

Fig.5. Hierarchy of the MC-HVDC control system

The control structure consists of outer and fast inner control loops. Outer loop includes the DC voltage controller, the AC voltage controller, the Active power controller and the reactive power controller. Reference of the active component of current is obtained by the DC voltage control or from the active power control, while the reference of the reactive control is obtained by the reactive power control or from the AC voltage controller.

A. Rectifier Side (MC-1) Control

Fig.6. shows control system diagram of the MC-1 and MC-2. Both MC-1 and MC-2 works in rectifier mode of operation. The main objective of control of MC-1 and MC-2 is to maintain the DC bus voltage constant. In Fig.6, V_{dc}^* and Q^* are the DC bus voltage reference and input reactive power reference respectively. The feedback of measured DC bus voltage (V_{dc}) is compared with the reference dc voltage (V_{dc}*) and the error is passed through the proportional integral (PI) controlled. It generates the reference for D component of source current(I_{dref}) which is compared with the computed D component of source current and passed through a PI to generate a D component of voltage reference after the cross coupling term and the feed forward term of voltage (V_{sd}) are added.

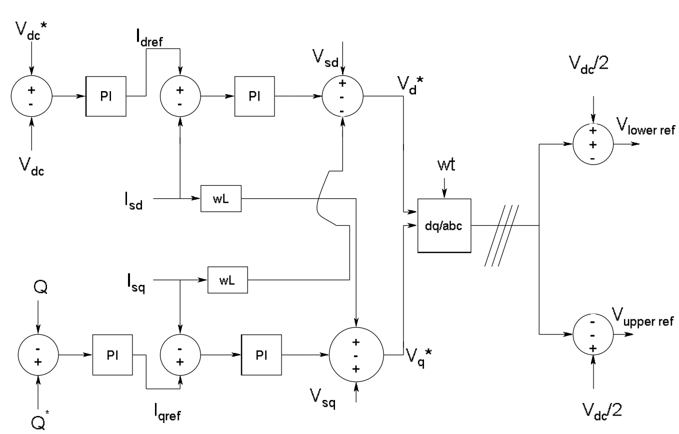

Fig.6. Rectifier side controller

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In order to maintain the unity power factor (UPF) operation at the source stations input reactive power reference (Q^*) is kept zero. Q^* is compared with the computed reactive power of the system(Q) and then passed through the proportional integral (PI) controller to generate I_{qref} which is then compared with the computed Q component of source current and then passed through a PI to generate Q component of reference voltage

$$Q = \frac{3}{2}[V_{sq}i_{sd} - V_{sd}i_{sq}]$$

These D and Q reference voltage signals are converted to three phase reference signal. These AC reference signals are then properly shifted according to the required DC voltage to generate $V_{lowerref}$ and $V_{upperref}$ as per eqn. (1) and eqn. (2) and then level shifted PWM operation is carried out using these two reference signals.
Here the V_{dc}^* and Q^* are in the outer control loop and the current control is the inner control loop

B. Inverter Side (MC-2) Control

$$P = \frac{3}{2}[V_{Ld}i_{Ld} + V_{Lq}i_{Lq}] \quad (7)$$

$$Q = \frac{3}{2}[V_{Ld}i_{Ld} - V_{Lq}i_{Lq}] \quad (8)$$

Where V_{Ld}, V_{Lq} are the load voltage and i_{Ld}, i_{Lq} are the loads current in d-q reference frame.
The purpose of this Controller is to maintain active and reactive power of the load to its reference value. In Fig.7 $P^*$and Q^* are the active power reference and reactive power reference respectively.

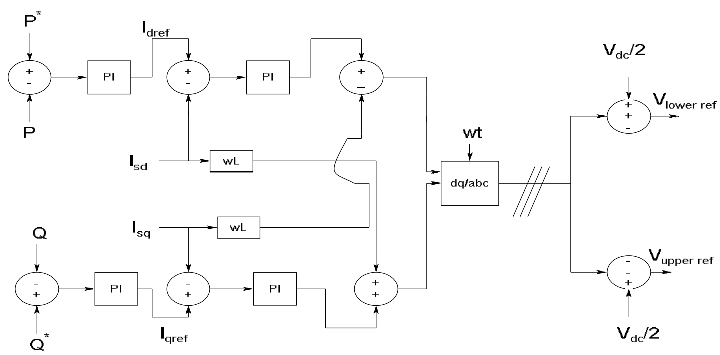

Fig.7. Inverter side controller

The actual active and reactive power is obtained as per the eqn. (7) and eqn. (8). The computed load active power (P) is compared with the reference active power (P^*) and the error is passed through the proportional integral (PI) controller to generate reference for D component of current (I_{dref}) as shown in control diagram. For the reactive current component reference (I_{qref}), Q^* is compared with the computed load reactive power of the system (Q).
Here the phase disposition type of level shifted SPWM technique is used, where all carrier signals are of same amplitude and frequency. These signals are compared with the modulating signal and based on the amplitude of modulating signal the output is either high or zero. This technique leads to improved voltage quality and low harmonics.
In order to equalize the stress across all the capacitors a capacitor sorting algorithm is designed. Here all the capacitor voltages are arranged in ascending order and based on direction of arm current direction it is decided which capacitor should be charged or discharged first

V. FUZZY LOGIC CONTROLLER

The Fuzzy control is a methodology to represent and implement a (smart) human's knowledge about how to control a system. A fuzzy controller is shown in Figure.8. The fuzzy controller has several components:

A. A rule base that determines on how to perform control

B. Fuzzification that transforms the numeric inputs so that the inference mechanisms can understand.

C. The inference mechanism uses information about the current inputs and decides the rules that are suitable in the current situation and can form conclusion about system input.

D. Defuzzification is opposite of Fuzzification which converts the conclusions reached by inference mechanism into numeric input for the plant.

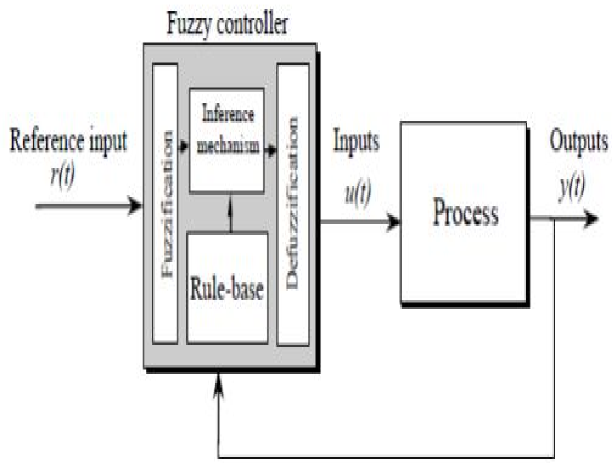

Fig.8 Fuzzy Control System

Fuzzy logic is a form of logic that is the extension of boolean logic, which incorporates partial values of truth. Instead of sentences being "completely true" or "completely false," they are assigned a value that represents their degree of truth. In fuzzy systems, values are indicated by a number (called a truth value) in the range from 0 to 1, where 0.0 represents absolute false and 1.0 represents absolute truth. Fuzzification is the generalization of any theory from discrete to continuous. Fuzzy logic is important to artificial intelligence because they allow computers to answer ‘to a certain degree’ as opposed to in one extreme or the other. In this sense, computers are allowed to think more 'human-like' since almost nothing in our perception is extreme, but is true only to a certain degree.

Table 1
IF-THEN rules for fuzzy inference system

u(t)		**e(t)**						
		NB	**NM**	**NS**	**ZO**	**PS**	**PM**	**PB**
Δe(t)	**NB**	NB	NB	NB	NB	NM	NS	ZO
	NM	NB	NB	NB	NM	NS	ZO	PS
	NS	NB	NB	NM	NS	NS	PS	PS
	ZO	NB	NM	NS	ZO	ZO	PM	PM
	PS	NM	NS	ZO	PS	PS	PB	PB
	PM	NS	ZO	PS	PM	PM	PB	PB
	PB	ZO	PS	PM	PB	PB	PB	PB

The fuzzy rule base can be read as follows

IFe(t) is NB and Δe(t) is NB **THEN** u(t) is NB**IF** e(t) is <negative big> and Δe(t) is <negative big>**THEN** u(t) is <negative big>

VI. MATLAB/SIMULINK RESULTS

The parameters and ratings used for the system are given in Table.2

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Table 2
Parameters and ratings used for the simulation

Source 1 voltage rating	V_{s1}	220kV
Source 1 frequency	F_{s1}	50Hz
Source inductance	L_s	9mH
Source Resistance	R_s	0.569Ω
Load voltage rating	V_{s2}	220kV
Load frequency	F_{s2}	60Hz
Load Active power		784MW
Load Reactive power		159VAR
LOAD CHANGE		
Load Active power		500MW
Load Reactive power		100VAR
CONVERTER PARAMETERS		
Bridge cell count per arm	N	5
arm inductance	L_a	20mH
PWM carrier frequency	F_s	5kHz
DC capacitor	C	6mF

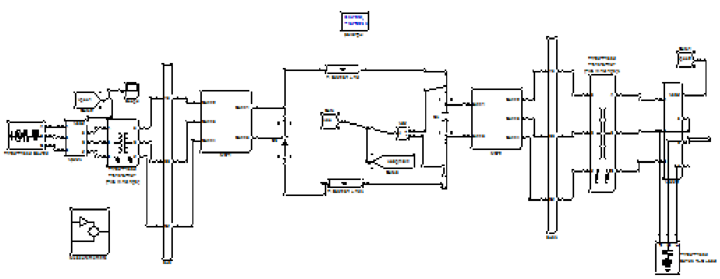
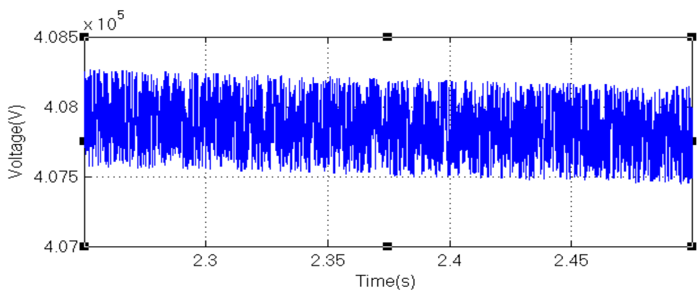
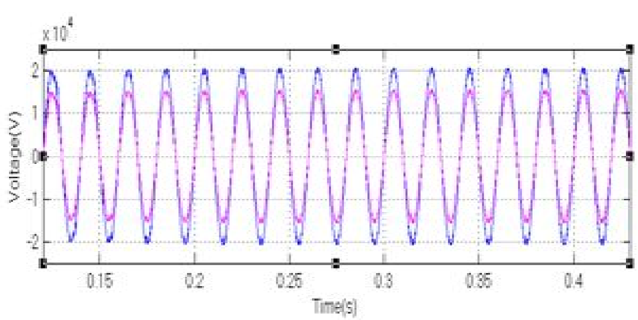


Fig.9 Simulink block of the MMC based HVDC system



(a) Dc bus voltage



(b) Source 1 UPF operation

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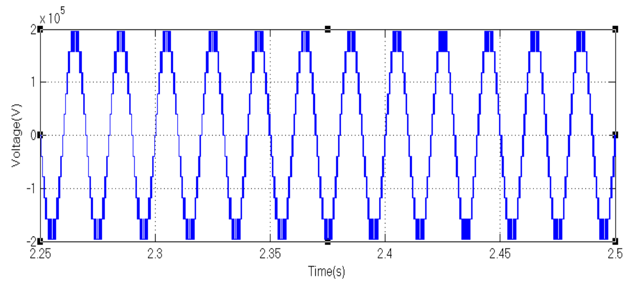
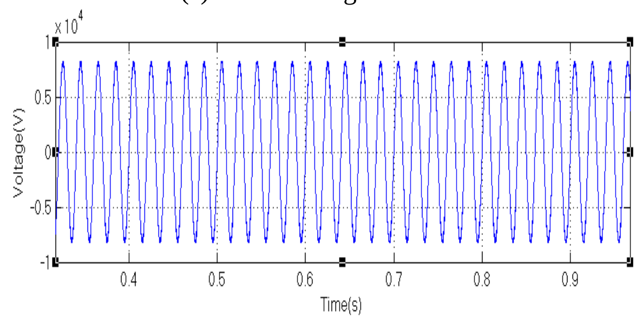
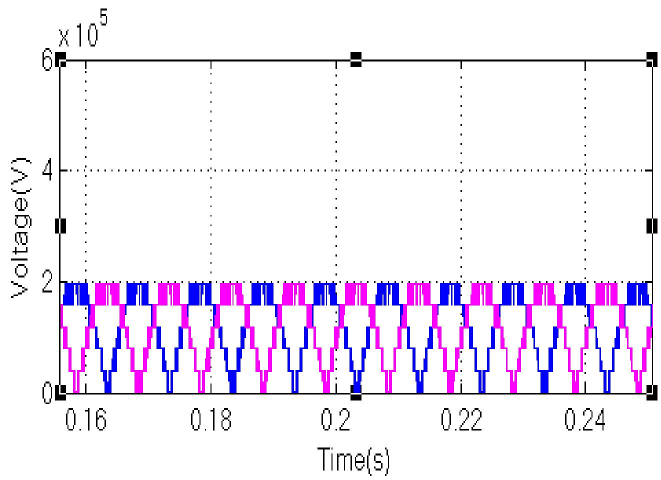


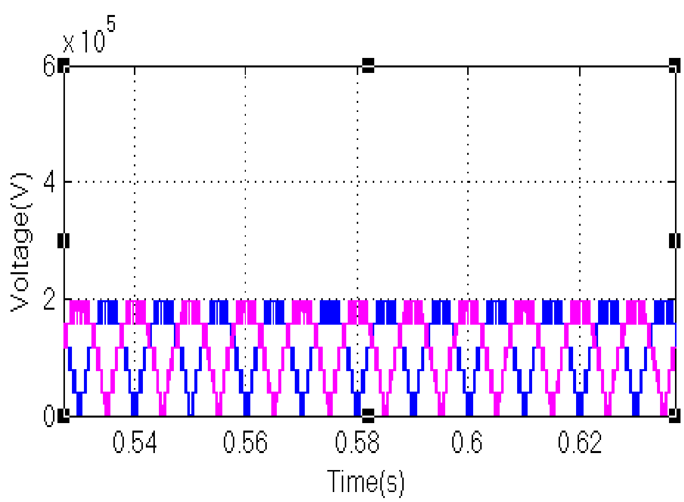
(c) Load voltage



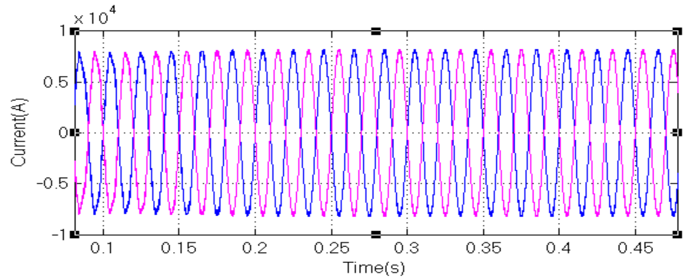
(d) Load current



(e) Arm voltage of MC-1



(f) Arm voltage of MC-2



(g) Arm current of MC-2

Fig 10 Waveform under rated load condition

Fig.10(a) shows the DC- bus voltage which is maintained at 400kV with a very low ripple by the MC-1. Fig.10(b) shows the input phase voltage and current for MC-1. Fig.10(c) shows Load phase voltage at rated condition at a power factor 0.98. Fig.10(d) shows Load current at rated condition at a power factor 0.98.The load current is sinusoidal but the load voltage is having multi levels. The number of sub modules used here is 5 so number of levels is 11 levels. If the number of sub modules is increased, then the load voltage will also come near to sinusoidal. Fig.10(e) and Fig.10(f) shows the upper and lower arm votage for phase A. Fig.10(g) shows the upper and lower arm currentfor MC-2 for phase A.As seen from waveform, there is a shift in the arm current due to circulating current.

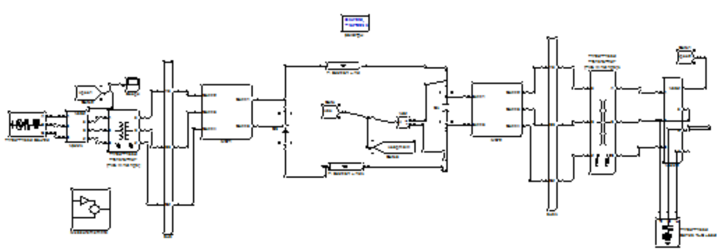
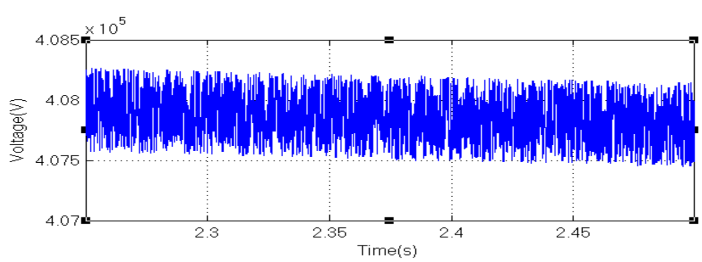
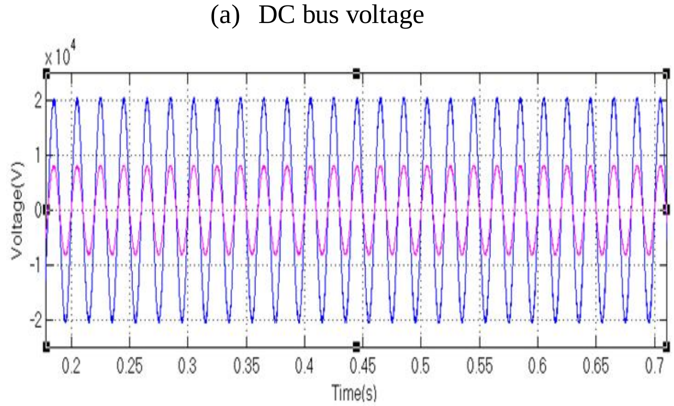


Fig 11 Simulink block of the MMC based HVDC system for load change



(a) DC bus voltage



(b) Source 1 UPF operation

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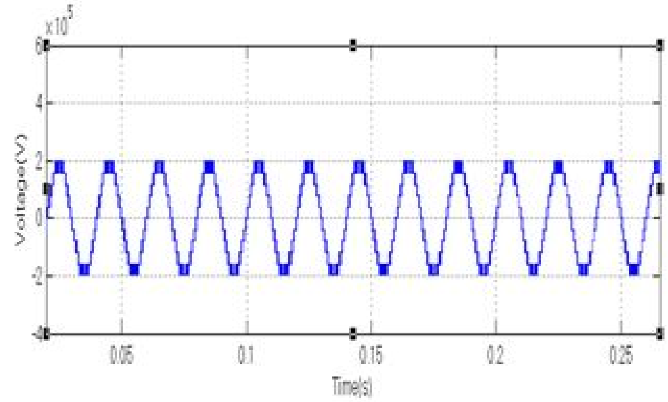
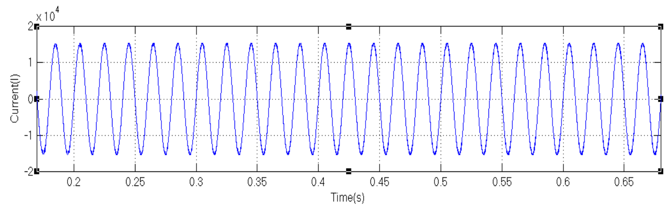


(c) Load voltage



(d) Load current

Fig 12 Waveform under after load change

Fig.12(a) shows the DC- bus voltage which is maintained at 400kV with a very low ripple by the MC-1 after the load change. Fig.12(b) shows the input phase voltage and current for MC-1. Fig.10(c) shows Load phase voltage after load change. Fig.10(d) shows Load current after load change.

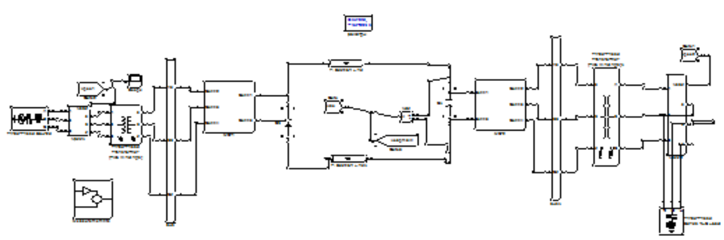
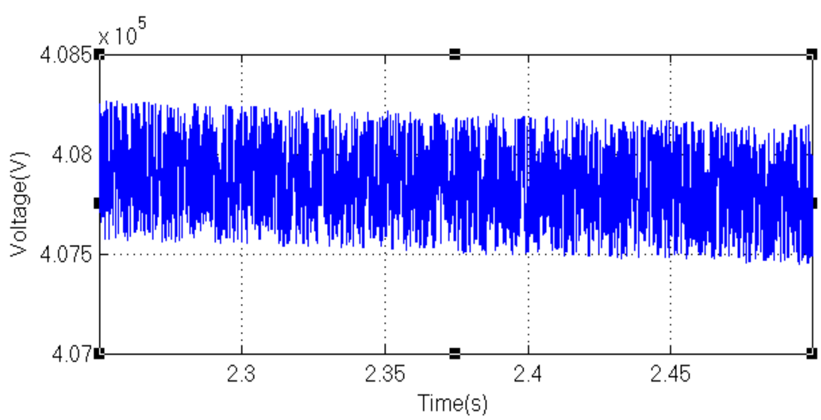


Fig 13 Simulink block of the MMC based HVDC system for power reversal



(a) DC bus voltage

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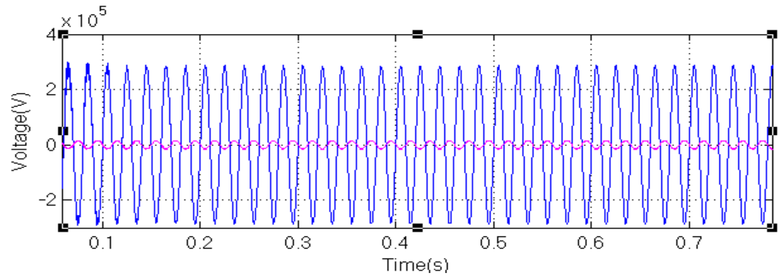
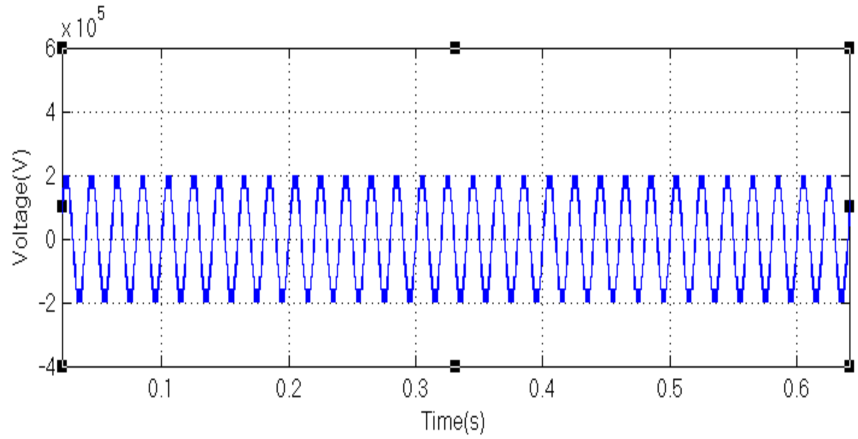
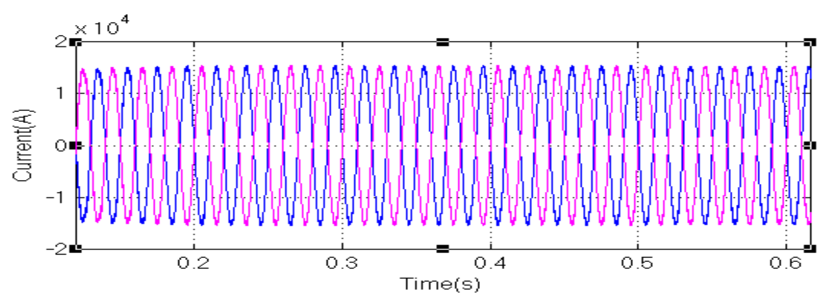


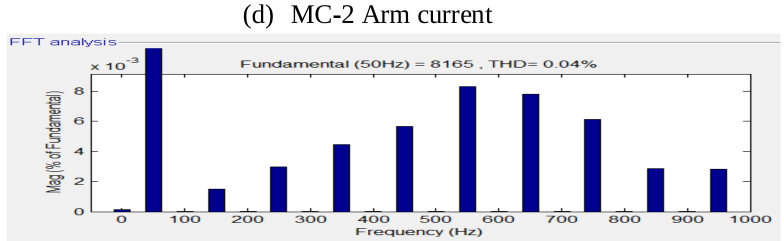
(b) Source 1 180° UPF operation



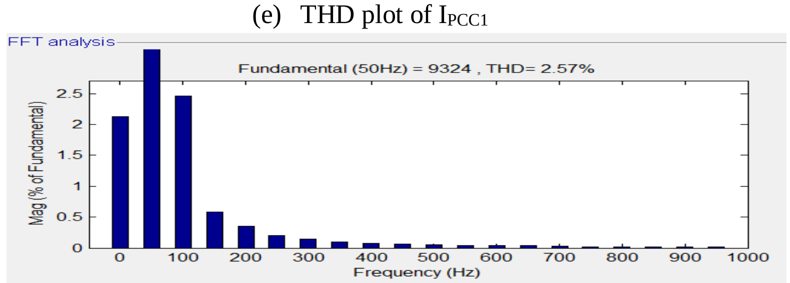
(c) Load voltage



(d) MC-2 Arm current



(e) THD plot of I_{PCC1}



(f) THD plot of I_{PCC2}

Fig 14 Waveform with power reversal operation

Fig.14(a)Dc bus voltage. Fig.14(b) Source-1 180° UPF operation. Fig.14(c) Load voltage. Fig.14(d) MC-2 arm current Fig.14(e) THD plot of I_{PCC1} the fuzzy is used to reduce the total harmonic distortion(THD) while using PI in controller the THD is 1.47% which is reduced to 0.04% in fuzzy in I_{PCC1}.Fig.14(f) THD plot of I_{PCC2} while using PI in controller the THD is 5.22%, for fuzzy logic THD is 2.57% in I_{PCC2}.

VII. CONCLUSION

This paper discusses the multilevel converter based HVDC system which connects various asynchronous AC system through a common DC link. This proposed topology is very promising in the connection of off shore wind power plant with the existing AC grids. A mathematical model of the system is developed and level shifted SPWM technique is introduced in this paper. A control strategy is proposed for this system and different simulation results at steady state during load change and power flow reversal is explained. The simulation result shows that the proposed system can be used both in the rectifier and inverter mode of operation with unity power factor.

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