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FLC-Based Analysis of LCC and MMC Hybrid HVDC Transmission System

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Abstract
To meet the high demand of electrical energy, reliable and stable transmission facilities are required. Due to several disadvantages in AC transmission lines such as thermal limits, corona effect, skin effect, etc. HVDC came into existence. HVDC has proved to be more durable and reliable in case of long distance and under water transmission. A new hybrid HVDC system, which combines the best features of line-commutated converter and VSC technology, is proposed. The proposed system constitute the robust performance and low capital cost and power loss of a line commutated HVDC converter, with the fast dynamic performance of a MMC system. It also describes the principles and control strategies of the proposed system. The most challenging issue in the operation of MMC is sub-module voltage balancing. The phase shifted multi carrier PWM technique is introduced in this proposed system to rectify the voltage balancing problem. The FLC controller is employed to provide the better stability of dc voltage. The voltage distortion of MMC was reduced and gives low THD. Finally, the MATLAB/SIMULINK simulation verifications have been carried out based on a 250-MW/ 110-kV LCC–MMC hybrid HVDC system and its dc network.

Keywords: HVDC, hybrid transmission, MMC, LCC, phase shifted multi carrier PWM technique, sub-module voltage balancing

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INTRODUCTION

For the bulk power transmission, the HVDC electric power transmission system uses direct current, in contrast with the more common alternating current systems. In the long-distance transmission, HVDC systems may be less expensive and have lower electrical losses. HVDC is useful in the underwater power cables, because it avoids the heavy currents required to charge and discharge the cable capacitance.

For shorter distances HVDC transmission is not economic hence the cost of DC conversion equipment is high compared to an AC system. Also, HVDC allows power transmission between unsynchronized AC transmission systems. The existing commercial VSC-HVDC system trip the ac circuit breakers to clear the fault in dc line obviously, this is the most economical and widely used method but the response of mechanical switches is slow.

To solve this problem, a line commutated converter (LCC)-modular multilevel converter (MMC) hybrid HVDC transmission system is proposed. This hybrid topology uses the LCC-based rectifier at its sending side and the MMC-based inverter at its receiving side.[1]

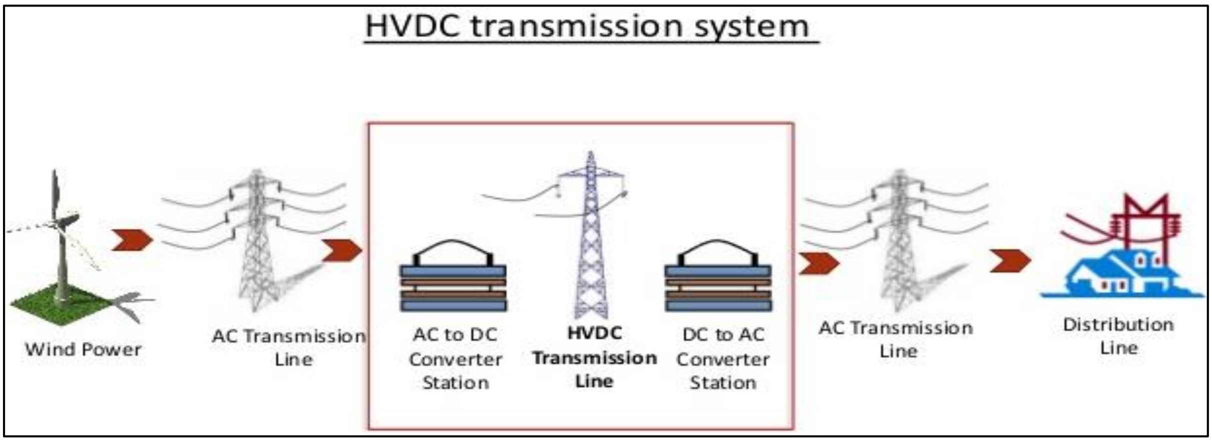


Fig. 1. *HVDC Transmission System.*

Most important, high-power diodes are installed between the smoothing reactor and the MMC at the inverter side for blocking the reverse current from the MMC to the dc line. This hybrid topology is still considered to be one of the most feasible solutions to the problem of high power transmission over a long distance in India, where the energy resources are mainly located in the west, and the loads are concentrated in the east. Therefore, there is an urgent need for detailed research on the design technique for this LCC–MMC hybrid HVDC topology. In order to withstand the voltage stress during the permanent dc-line fault, the rated voltage of the reverse current blocking diodes can be chosen as the rated dc voltage of the hybrid system. Also the LCC-based rectifier generates certain quantities of harmonic currents in the dc side, which will interfere with the nearby communication lines.[2,3]

LCC AND MMC TOPOLOGIES

The 12 pulse bridge converter consists of thyristors at the ac side. It depends on ac circuit for its commutation. The output voltage of the converter is controlled by controlling the triggering angle of thyristor. The merits of the LCC includes no commutation failure, less reactive power requirement and reduced losses. The basic module of an LCC HVDC converter is the three-phase full wave bridge circuit shown in Figure 2. This circuit is known as the Graetz bridge. The ac system side windings of the converter transformer are star-connected with grounded neutral. The gate control is used to delay the ignition of the thyristors. The “delay angle” or “firing angle” is denoted by α, which represents the time delay of α/ω seconds, where w is defined as the ac system angular frequency.[4]

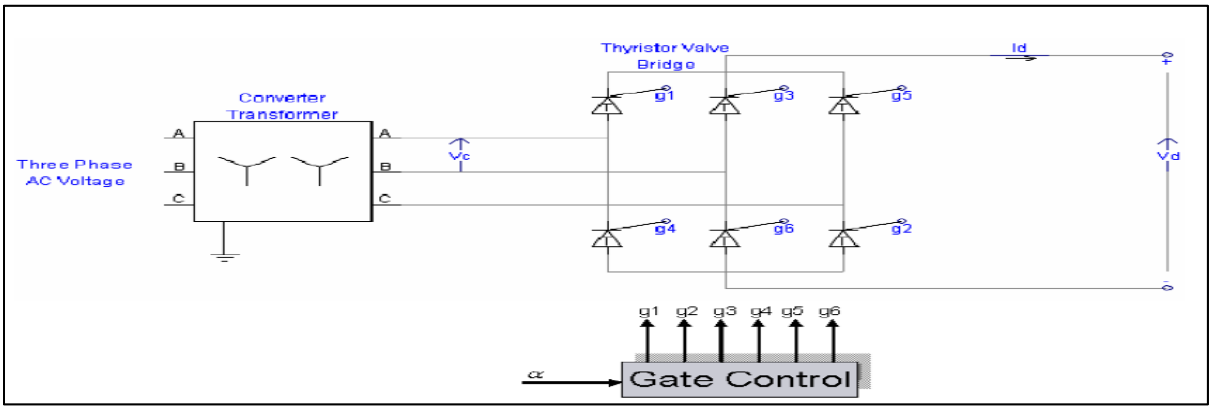


Fig. 2. *Three-Phase Full Wave Bridge Circuit.*

The effect of the firing angle is to reduce the average "ideal no load" direct voltage by the factor cosα. Under normal operating conditions, the LCC-based rectifier generates certain quantities of harmonic currents in the dc side, which will interfere with the nearby communication lines In order to limit the interference to a reasonable level, dc filters should be installed. For conventional HVDC systems based on line-commutated converters (LCC), the "tapped" series terminal requires topical reactive power stand, which may add significant cost. This problem could be solved by using a VSC-based tapping terminal A HVDC line can be established by using either a VSC-based or a conventional LCC-based HVDC rectifier.

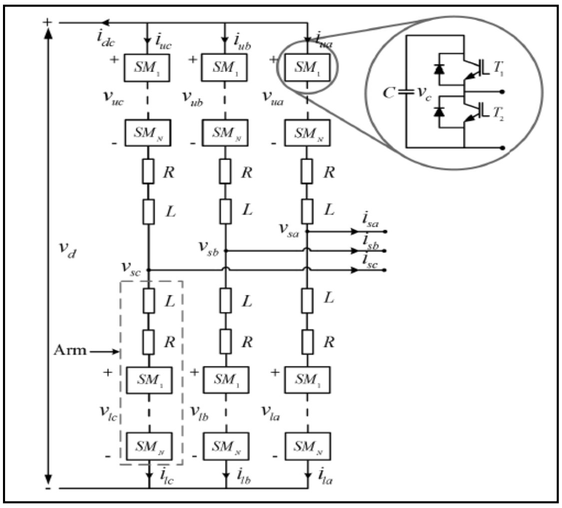


Fig. 3. *Topology of Half-Bridge Submodule of Three-Phase MMC.*

The inverter uses MMC which is based on IGBT. These devices are operated using PWM technique having high switching frequencies. It synthesizes high voltage level by increasing number of series connected sub modules. Interface transformer and filter at the output end can be eliminated, thus the cost is reduced. It has fault management capability and better fault ride-through capability. In MMC, there are three legs, or six arms. The arms are composed of many sub-modules in series, and each sub-module is a two-level converter. The arrangement of the basic components in the MMC can be seen in Figure 3.The sub-module itself consists of two IGBTs, two diodes and a capacitor, as seen in Figure 3. In fact, the sub-module can be simplified to a capacitor which is inserted as bypassed or blocked. During one fundamental period each sub-module capacitor in a multivalve can be both charged and discharged, depending on its mode. This allows separate and selective control of the sub-modules, and each phase unit can be viewed as a controllable voltage source. The total voltage in a phase unit equals the voltage in the DC line, and the output voltage of the inverter can be controlled in a sinusoidal looking way by carefully adjusting the modes of the sub-modules (Figures 4, 5, Table 1).[5,6]

Table 1. *Charging State of Submodule.*

State	SW1	SW2	Effect on V_c	V_{sm}
Inserted state	1	0	$I_{arm}>0$ – Charge $I_{arm}<0$ – Discharge	V_c
Bypassed state	0	1	Neither charges nor discharges	0

THE PROPOSED SYSTEM

The hybrid topology uses the LCC-based rectifier at its sending side and the MMC-based inverter at its receiving side. This method can be easily deduced and accurate in precision. The use of the LCC-based rectifier gives a low manufacture and operating cost, along with high-power transmission capability. The MMC-based inverter can eliminate a commutation failure problem which is inevitable in LCC-based converters. Due to the high flexible control of real and reactive power, the MMC-based inverter may operate like a reactive power source and supports the inverter ac side bus voltage. It also enables the hybrid HVDC system to clear the dc line temporary faults as fast as traditional HVDC systems. The LCC at sending end consists of the 12 – pulse converter bridge because of the low operating cost and elimination of commutation failure problem. And the MMC at receiving end includes an 11-level inverter with high flexibility in active and reactive power control. Thus by combining both the LCC and MMC hybrid system fault clearance, long distance transmission, simple, accurate and high efficiency can be obtained. The proposed methodology of hybrid LCC and MMC-HVDC transmission was modeled and their performance of the system was analyzed. The harmonics and distortions have to be rectified to bring down the THD to the lower value.[7]

MODELING OF THE PROPOSED SYSTEM

In this simulation model, the high voltage gets transmitted through DC line using LCC and MMC hybrid HVDC converter. The LCC is connected at the sending end and the MMC is connected at the receiving end. The LCC used in this model is 12 – pulse bridge rectifier and firing angle controller are employed.

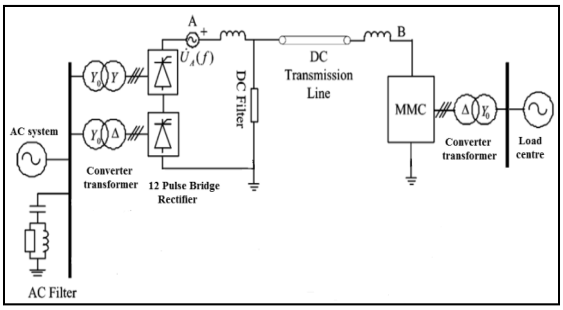


Fig. 4. *Schematic Diagram of the Proposed Hybrid HVDC Link.*

The DC line is 300 km length which is connected between the rectifier and inverter end. At the inverter end, an 11 level MMC is placed which is followed by converter transformer and the load center. The multicarrier PWM method is used to control the MMC voltages.

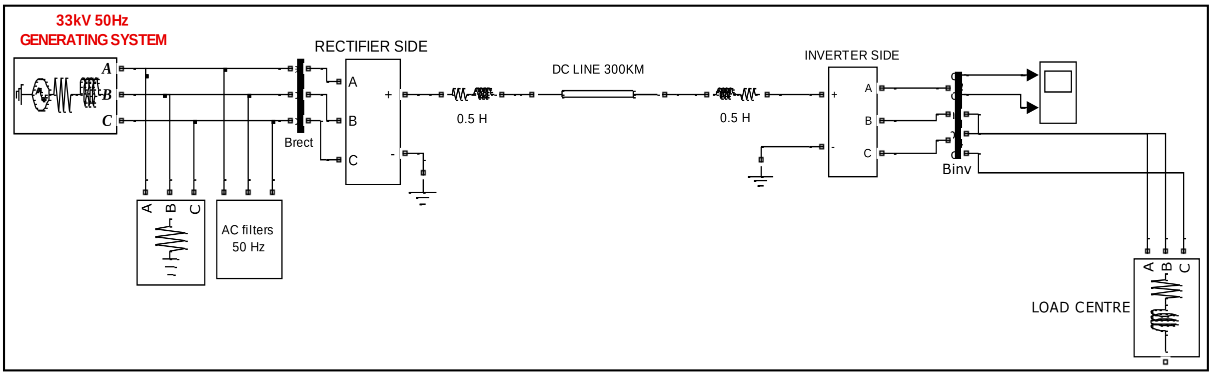


Fig. 5. *Simulation Model of the Proposed System.*

In Figure 6, the input AC voltage of 33 kV from the generating station which is to be transmitted is shown. This voltage is fed into dc link through converter transformer of 33/110 kV which is shown in the Figure 7. The AC input voltage is boosted by using converter transformer and fed to the LCC at the rectifier end. Thus the converter converts the 110 kV AC to DC, which is ready to be transmitted on the DC line of 300 km length. The output voltage of LCC is controlled using firing angle controller.

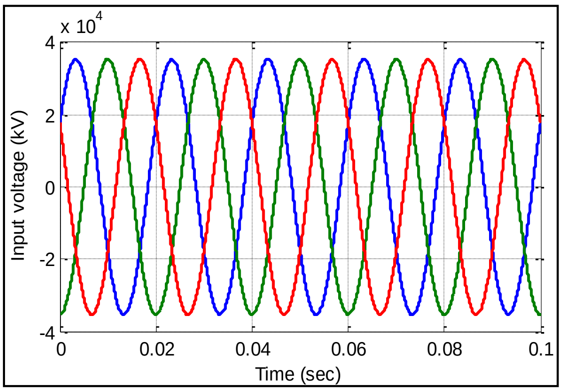


Fig. 6. *Input Voltage of Sending End Converter Station.*

Figure 7 shows that the dc link voltage starts from zero voltage and reaches 90% of the rated value in about 15 ms and reaches the reference value (110 kV) in about 25 ms.

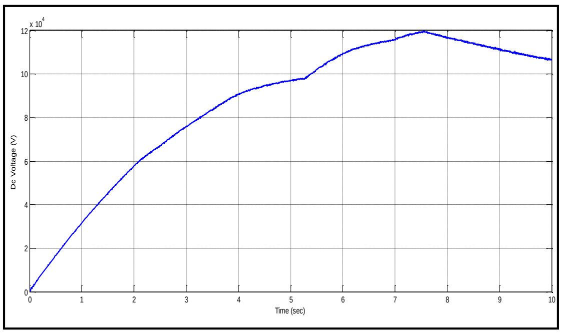


Fig. 7. *DC Link Voltage of HVDC Transmission.*

The high voltage DC link voltage is converted into AC by means of MMC HVDC converter. The MMC topology has many advantages as it has the possibility of synthesizing high voltage levels by increasing the number of series connected submodules. In addition, the MMC adds a high reliability, availability and lower cost for the system due to the low switching losses and elimination of the ac filters and their switchgears. When using MMC-HVDC, there is an extra advantage compared with the classical HVDC as it can control the active and reactive power independently. As the proposed model in this project uses a detailed modeling method, only an 11 level MMC was used with total number of 60 switches is shown in the Figure 8 (Figure 9).

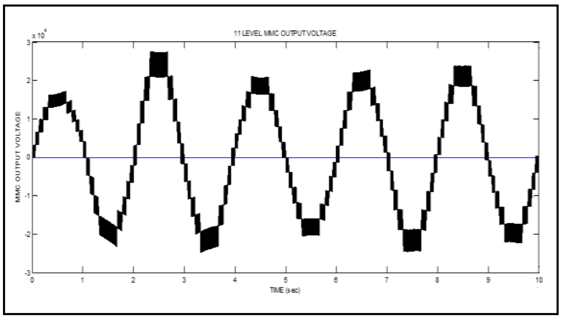
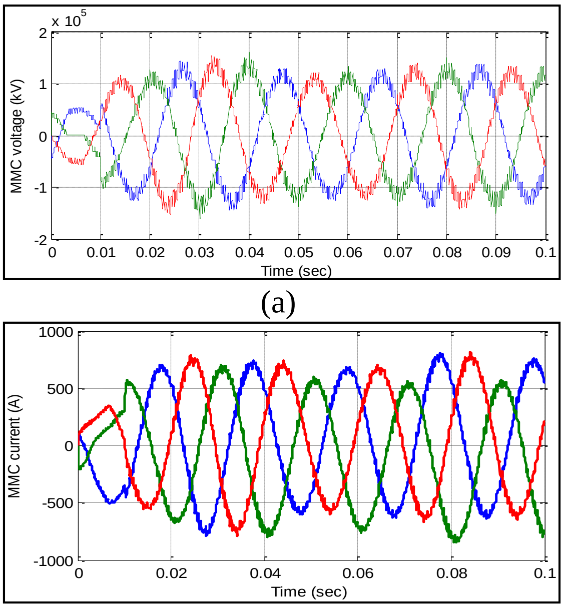


Fig. 8. *11 Level MMC Voltage of One Phase.*

The system can start from zero voltage and charges all the sub-modules capacitors in a relatively acceptable time. The MMC ac voltage of 110 kV is again step down by using converter transformer of delta/wye connection to 33 kV ac voltage. Due to the presence of modularity and complexity in the system, the power transfer capabilities were affected is shown in the Figure 10. Although the THD was observed as 6.61% while in the existing method it was mentioned as 16.3% as shown in Figure 11.



(a)

(b)

Fig. 9. *(a) Graphical Representation of MMC Voltage, and (b) MMC Current.*

FUZZY LOGIC CONTROLLER

Fuzzy logic idea is analogous to the human being's notion and inference process. The fuzzy logic control is a range-to-point or range-to-range control. The output of the fuzzy controller is derived from fuzzifications of both inputs and outputs using the associated membership functions. A crisp input will be converted to the different members of the subsidiary membership functions based on its value. The output of a fuzzy logic controller is based on its memberships of the disparate membership functions, which can be reckoned as a range of inputs. To implement fuzzy logic technique, it necessitates the following three paces:

(1) Fuzzification – convert classical data or crisp data into fuzzy data or membership functions (MFs)
(2) Fuzzy inference process – combine membership functions with the control rules to deduce the fuzzy output
(3) Defuzzification – The process exercises different methods to calculate each associated output and lay them into a table: the lookup table. It has to pick up the output from the lookup table based on the current input during an application.

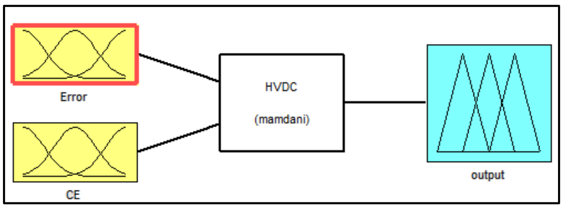


Fig. 10. *Fuzzy Logic Controller.*

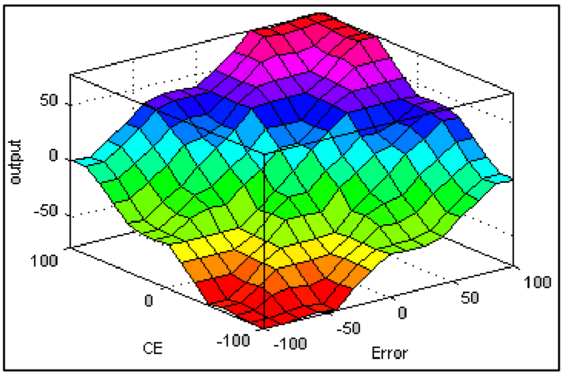


Fig. 10a*. Surface Viewer.*

The controller was provided at the sending end station in order to get dc flow. The rules in this controller is 25. Hence, the desired output of loss free power flow and dc flow can be obtained.

LEVEL SHIFTED PWM (LS-PWM) TECHNIQUE

With augumented number of levels, high voltage with reduced voltage stress on switching device and extremely low total harmonic distortion can be incurred. While, a high number of power electronic devices and switching redundancies bring a higher level of complexness which are comparative with a two-level inverter similitude. This ramification could be used to add the additional capabilities to the modulation technique, videlicet, shrinking the switching frequency, minimizing the common-mode voltage or balancing the dc voltages.[8]

Level-shifted PWM (LSPWM) is the natural extension of bipolar PWM for multilevel inverters. Bipolar PWM uses one carrier signal that is compared to the reference to decide between two different voltage levels, typically the positive and negative bus bars of a VSI. By generalizing this idea, for a multilevel inverter, *m−1* carriers are needed. They are arranged in vertical positions.

Each carrier is set between two voltage levels. They are arranged in vertical positions. Each carrier is set between two voltage levels. Since each carrier is associated to two levels, the same principle of bipolar PWM can be implemented, allowing that the control signal has to be directed to the appropriate semiconductors in order that the related levels shifts instead of the phase-shift used in PS-PWM.

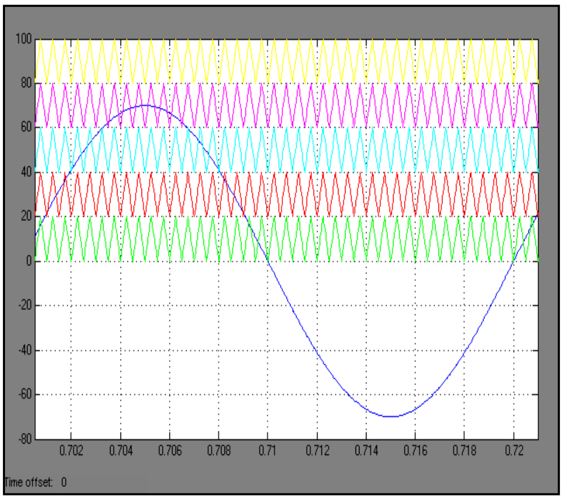


Fig. 11. *Phase Shifted Multicarrier PWM Waveform.*

The carriers span the complete amplitude scope that can be sired by the converter.

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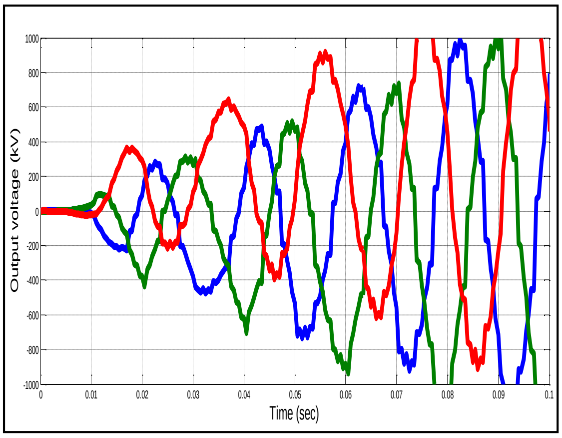
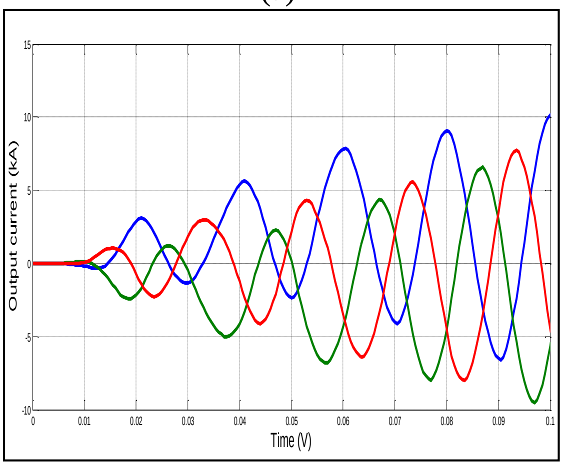
They can be arranged in vertical shifts, with the every last signals is in phase with each other, called phase disposition (PD-PWM); with all the positive carriers in phase with one another and in opposite phase of the negative carriers, known as phase opposition disposition (POD-PWM); and alternate phase opposition disposition (APOD-PWM), which is obtained by alternating the phase between adjacent carriers.

THD ANALYSIS FOR THE LOAD CENTRE

The simulation results and THD spectrum analysis of proposed hybrid system is shown in the respective Figures 12–17.

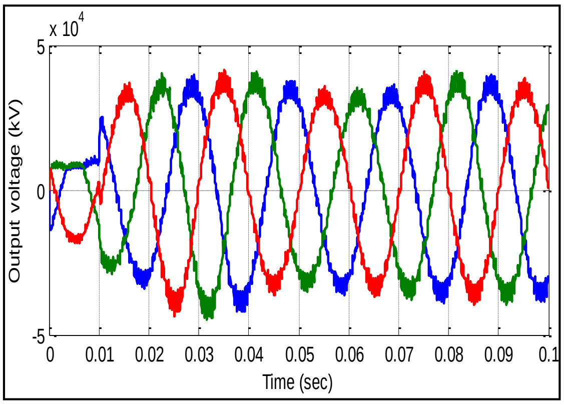


(a)

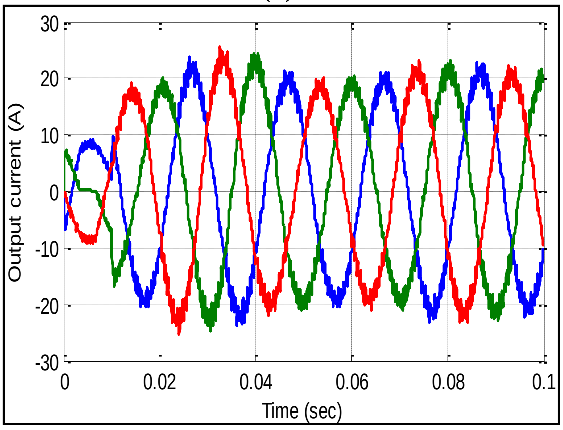


(b)

Fig. 12. *Without Controller (a) Output Voltage, (b) Output Current.*



(a)



(b)

Fig. 13. *With Controller (a) Output voltage, (b) Output Current.*

The output voltage and current waveform is shown in the Figure 10(a),(b). Since the simulation time is more for this detailed analysis, the system takes more time to reach its steady state because of its complex nature of MMC. This model takes about 20 min to run a five second simulation with 20 ms sampling time.

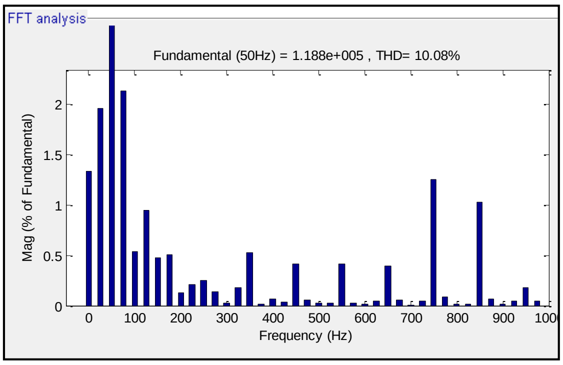


Fig. 14. *THD Spectrum of MMC Voltage.*

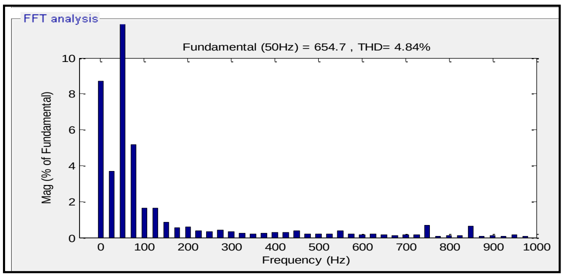


Fig. 15. *THD Spectrum of MMC Current.*

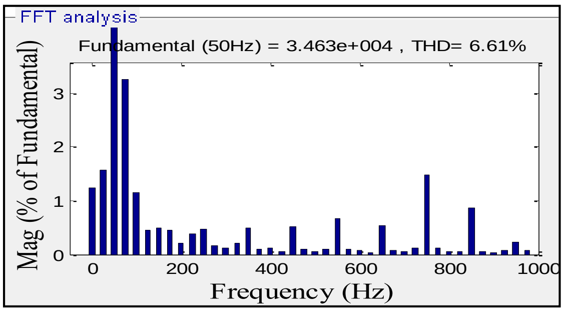


Fig. 16. *FFT Analysis of Output Voltage.*

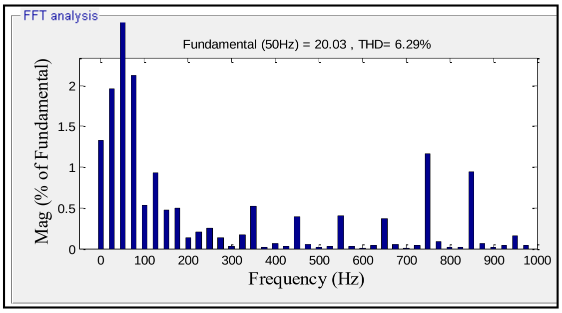


Fig. 17. *FFT Analysis of Output Current.*

From the FFT analysis, the THD of the ac output current of the load is obtained as 6.29%, while in existing method it has higher value of THD as shown in the Figures 11 and 12.

Thus the rectified voltage of 110 kV is transmitted in the dc line and inverted back to ac voltage and stepped down using transformer is achieved using this proposed method. Because of MMC lower THD value is observed and the power transfer capability is increased and the efficiency is achieved about 80%.[9–12]

CONCLUSION

The LCC-MMC hybrid HVDC system is observed to have a lower cost and would give less switching losses and MMC is used at inverter side.

The hybrid-HVDC system is advantageous because of its ability to independently control active and reactive power.

Also the MMC's ability for independent control of output voltage magnitude and phase angle is an outstanding feature that enables a wide number of control objectives to be achieved in the connected AC network.

By the evaluation of hybrid systems, it is observed that system with firing angle control at rectifier side control and phase shifted PWM control at the inverter end shows a better performance and fast response.

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