Simulation of DC Grid Control Based on Modular Multilevel Converters

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***Abstract*--On-going transformation of global power systems towards sustainability is the driving force behind the evolution of modular multilevel converters which provide high efficiency, reliability, superior power quality. The Modular Multilevel Converter topology is discussed intensively as a crucial part of DC grids, especially to integrate offshore wind power and solar power. Generally voltage source converter models are usually utilized for multi terminal investigations, A MMC based DC grid framework with a tripartite focus on internal converter. Besides an evaluation of the implemented MMC model that incorporates the available arm sum voltage, AC and DC system control concept suitable to handle unbalanced voltage conditions is derived for HVDC applications. Combined with wind farms and photo voltaicsystem MATLAB/SIMULINK Software and sim power systems tools are used. Mainly control system tools, power electronics and electrical elements tools are used.**

***Index Terms*-- Generalized modular multilevel converter modelling, designing, HVDC grid control, power converter,MMC with large number of sub modules, wind and solar power integration.**

I. INTRODUCTION

The modular multilevel converter (MMC) has become the most attractive multilevel converter topology for medium/high-power applications, specifically for voltage sourced converter high-voltage direct current (VSC–HVDC)transmission systems[1].In comparison with other multilevel converter topologies, the salient features of the MMC include: 1)its modularity and scalability to meet any voltage level requirements, 2) its high efficiency,3)its superior harmonic performance, specifically in high-voltage applications wherea large number of identical sub modules (SMs) with low-voltage ratings are stacked up, thereby the size of passive filters can be reduced, and 4) absence of dc-link capacitors. The main intention of this paper is to provide a better understanding of the MMC and its associated technical issues for various applications. This provides review on operational issues, modelling, control, and modulation techniques of the MMC.

II. MMC TOPOLOGY

The MMC consists of a number of cascaded modules. as shown in Fig.1, consists of two arms per phase leg where each arm comprises *N* series-connected, nominally identical SMs, and a series inductor *Lo*. While the SMs in each arm are controlled to generate the required ac phase voltage, the arm inductor suppresses the high-frequency components in the arm current. The upper (lower) arm of three phase-legs are represented by subscript "*p*", "*n*".

A. Sub modules modelling

The SMs of the MMC of Fig.1 can be realized by the following circuits:
1)The half-bridge circuit [4], [5]: As shown in Fig. 2(a), the output voltage of a half-bridge SM is either equal to its capacitor voltage v_C(switched on/inserted state) or zero (switched-off/by passed state),depending on the switching states of the complimentary switch pairs, i.e., $S_1$and S_2[4].
2) The full-bridge circuit [15], [16]: As shown in Fig. 2(b), the output voltage of a full-bridge SM is either equal to its capacitor voltage v_C(switched-on/inserted state) or zero (switched-off/bypassed state), depending on the switching states of the four switches $S_1$to S_4.
3)The clamp-double circuit: As shown in Fig. 2(c),a clamp-double SMconsistsoftwohalf-bridgeSMs,two additionaldiodesandoneextraintegratedgatebipolar transistor(IGBT)withitsanti-paralleldiode.Duringnormaloperation,theswitch$S_5$is alwaysswitchedON andtheclamp-double SMactsequivalenttotwo series- connectedhalf-bridge SMs. the clamp-doubleMMChashighersemiconductorlosses thanthehalf-bridgeMMCandlowerthanthefull-bridge MMC[4].
4)Thethree-levelconvertercircuit:AsshowninFig.2(d),athree-level SMiscomprised ofeithera three-levelneutral-

point-clamped(NPC) orathree-Levelflying capacitor (FC)converter [17],[18].Thethree-level FC MMChasthesimilarsemiconductorlosseswiththe half-bridgeMMC.

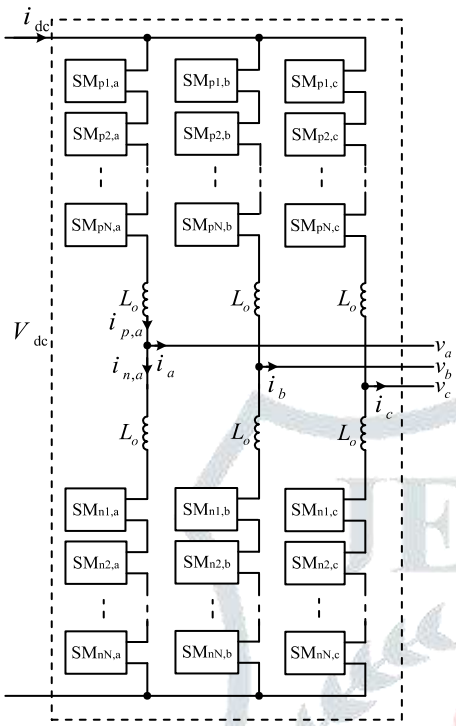
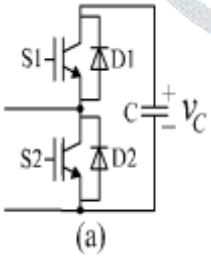
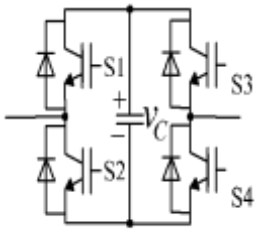


Fig.1Schematic representation of theMMC

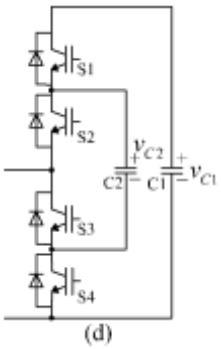
However,thethree-level NPCMMChas highersemiconductor lossesthanthehalf-bridge MMC andlowerthanthefull-bridge MMC. Fromamanufacturingperspectiveandcontrol,thisSMc ircuitis notvery attractive.



(a)



(b)



(d)

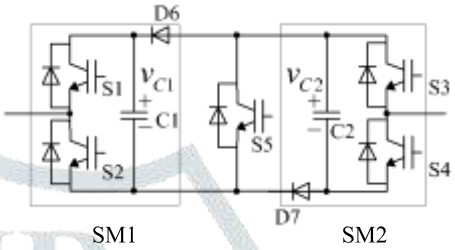


Fig.2.Various SM topologies:(a)the half-bridge, (b) the full-bridge.(c)theclamp-double,(d)thethree-levelFC.

B. The Operational Principle of MMC

In a three phase MMC, each of the phase units consistsof two multi valves, and each multivalve consists of N sub modulesconnected in series. The valves are made up of an IGBT and a freewheeling diode in antiparallel. In normal operation, only one of the valves is switched on at a given instant in time.Depending on the current direction the capacitor can charge or discharge. When only one IGBT is switched on, either that IGBT or the freewheeling diode in the same valve will conduct, depending on the current direction, and for this reason it makes sense to define a valve as on, indicating that either the IGBT or the diode is conducting.

Three possible switching states can be defined:

- In the ON or insertedstate s_1 is on, and s_2 is off. The sub module output voltage, V_{SM}, equals the capacitor voltage, V_C, and the capacitor charges if the multivalve current is positive and discharges otherwise.
- In the OFF or bypassedstate s_2 is on, and s_1 is off. The sub module output voltage, V_{SM}, is zero and the capacitor voltage is constant, i.e. the capacitor will not charge nor discharge.
- In the blockedstate, both valves are off, and the current can only conduct through the freewheeling diodes. The capacitor will charge if the current is positive, but ideally it cannot discharge.

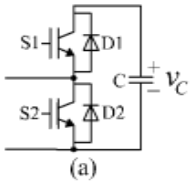


Fig .3 sub module circuit

The blocking voltage in each phase unit is twice the DC voltage. This can be explained from the situation when all the sub modules in the upper multivalve are bypassed, giving a phase voltage equal to the DC voltage. The lower multivalve must be able to block the voltage across itself, i.e. the DC voltage. The result is that each switch must be able to block the DC voltage, *Ud*, divided by the number of Sub modules in each multivalve, *N*, giving $V_{block}=\frac{Ud}{N}$The capacitors in the lower multivalve will also share the DC voltage and must be dimensioned in the same way as the IGBTs.

Considering the same case and a negative I_{SM}relative to each IGBT in the upper valve must be able to block the voltage across the capacitor in the same sub module. This is one of the reasons why capacitor voltage balancing is important.

C. *Sub module Capacitor Voltage Balancing*

Similar to any other multilevel converter topology, the MMC needs an active voltage balancing strategy to balance and maintain the SM capacitor voltages. The capacitor voltage balancing is achieved by assigning appropriate PWM pulses to the SMs of each arm. This voltage balancing strategy does not require the measurement of arm currents, which adds to the control simplicity and reduces the number of sensors. The most widely accepted voltage balancing strategy is based on a sorting method [8]. To carry out the capacitor voltage balancing task based on the sorting method, the SM capacitor voltages of each arm are measured and sorted.

If the upper (lower) arm current is positive, out of *N* SMs in the corresponding arm, $n_{p,j}(n_{n,j})$ SMs with the lowestvoltages are identified and inserted. Consequently, the correspondinginserted SM capacitors are charged, and their voltages increase. If the upper (lower) arm current is negative, out of *N* SMs in the corresponding arm, $n_{p,j}(n_{nj})$ of the SMs with the highest voltages are identified and inserted.

Consequently ,the corresponding inserted SM capacitors are discharged, and their voltages decrease [8]. Regardless of the direction of the upper(lower) arm current, if an SM in the arm is bypassed, the corresponding capacitor voltage remains unchanged.Although the sorting method guarantees capacitor voltage balancing under all of the MMC operating conditions, it produces unnecessary switching transitions among the SMs.

Even if the number of required on-state SMs with in two consecutive control periods are not changed, the SM insertion/bypassing may happen. This results in increased switching frequency and subsequently power losses, which are undesirable, specifically for high-power systems.

D. *Circulating Current Control*

Circulating currents flowing through the three-phase legs ofthe MMC originate from the voltage differences among the threephase legs [12], [13] and contain negative sequence components with the frequencies twice the fundamental one [13]. Circulatingcurrents do not have any impact on the ac-side voltages andcurrents.

However, if not properly controlled/suppressed, they increase the peak and rms values of the phase-leg currents, which consequently increase the converter power losses as well as the ripple magnitude of the SM capacitor voltages. Although proper sizing of the arm inductors cansuppress the circulating currents to some extent [12].

III. MMC OPERATION UNDER SPECIAL CONDITIONS

A. *Unbalanced Grid Conditions*

Control of the MMC under unbalancedgrid conditions has been reported in [8], [9].Under unbalanced grid conditions, the main control objectivesare:

i)To keep the ac-side currents balanced by suppressingtheir negative-sequence components,

ii)To regulate the net dc busvoltage, and

iii)To control the circulating current and SMcapacitor voltages.

A dc-voltage ripple suppressing controller is introduced to remove the zero-sequence voltage components of the dc side under unbalanced grid conditions and to keep the net dc bus voltage constant.

The circulating currents are analysed as three components: positive-, negative-, and zero-sequence circulating currents under unbalanced grid conditions Moon *et al.* [14] propose a circulating currents control method with ac-side positive and negative-sequence current control to minimize the circulating currents and reduce the ac-side real power ripple under unbalanced conditions.A control strategy is proposed to eliminate the dc power ripple by removing the harmonics in the zero-sequence circulating currents under unbalanced grid conditions.

B. *Fault Tolerant Operation*

As mentioned earlier, the structural modularity of the MMCadds to its redundancy and fault tolerance. In case of any component/SM failure, the failed SM needs to be detected and bypassed.When an open-circuit fault occurs, the output voltageand current of theMMC are distorted. Furthermore, the capacitorvoltage of the failed SM may rise up, leading to further, vastdestruction.Given the large numbers of identical SMs and the symmetricalstructure of the converter, locating a faulty SM is challenging. In case of a half-bridge MMC–HVDC system, during a dc side short-circuit fault, the fault current,as shown in Fig.4(a),flows from the ac-sidetowards the dc side through the antiparallel diodes of the SMs.Therefore, the half-bridge SMs do not provide any capability of blocking the dc-side short circuit fault current for the MMC–HVDC system. As shown in Fig. 1, the arm inductors *Lo* are used to limit the rate of the fault current, i.e., $\frac{d\,i_{dc}}{dt}$.The equivalent circuit of the MMC of Fig. 1 during dc-side short-circuit fault when all the switches are blocked is shown in Fig.4 In case of a full-bridge MMC–HVDC system, subsequent to a dc-side short-circuit fault, when all of the IGBTs of the SMs are blocked, the capacitor voltages can generate reversed voltages to block the ac-side currents, as shown in Fig. 4(b). Thus, the full-bridge SMs can provide dc-side short-circuit fault handling capability

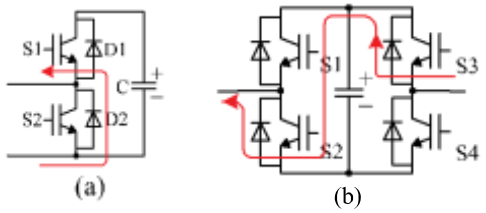


Fig.4. DC-side short-circuit fault current path for: (a) a half-bridge, (b) a full-bridge

IV. MMC–HVDC SYSTEMS

One of the major challenges associated with the MMC–HVDC system with the conventional half-bridge SMs is the lack of dc-side short-circuit fault handling capability.This problem is of severe concern ,particularly for HVDC transmission systems with overhead lines.The existing solutions to interrupt and clear the dc-side short-circuit fault of the MMC–HVDC systems can be summarized as follows:

1)Employing the dc-side CBs. Although a solid-state dc CB for HVDC applications has recently been developed, the technology is not sufficiently mature and cost effective [13].

2) Embedding the dc fault handling capability in the HVDC converter configuration [4], [13].

V. MULTI TERMINAL DC GRID INCLUDING OFF SHORE WIND AND SOLAR

This section briefly highlights, in addition to the presented converter control concept, DC grid control strategies, offshore wind integration as well as collection grid layout and suitable topologies for converter transformers.

A. *DC Grid Control Strategies*

HVDC grids are increasingly seen as a possible and feasible solution to manage the future power system with large amounts of renewables in a secure and cost-effective manner. However, systems with significant amounts of DC transmission behave in a fundamentally different manner when compared to the traditional AC power system.

a) Rectifier(DC/DC converter)

The offshore converter must absorb the available power fed in from the wind turbines, and photo voltaic systems and feed to grid to provide continuous power to load see [16], [17].

b) Converter Transformer

To ensure that no AC zero sequence current propagates into the DC system and affects the system behaviour, converter transformers for high voltage applications are carried out in a star-delta configuration and ensure zero sequence to zero Alternatives like the one presented in [15] tackle the problem from another perspective, but do not offer beneficial symmetrising characteristics during one or two phase faults so the interfaced components are subject to higher stress.

For this reason a star-delta transformer setting is chosen for the following investigations

c) Photo voltaic systems

The demand for renewable energy has increased significantly over the years because of shortage of fossil fuels and greenhouse effect. Among various types of renewable energy sources, solar energy and wind energy have become very popular and demanding due to advancement in power electronics techniques. Photovoltaic (PV) sources are used today in many applications as they have the advantages of being maintenance and pollution free. Solar-electric-energy demand has grown consistently by 20%–25% per annum over thepast 20 years, which is mainly due to the decreasing costs and prices.

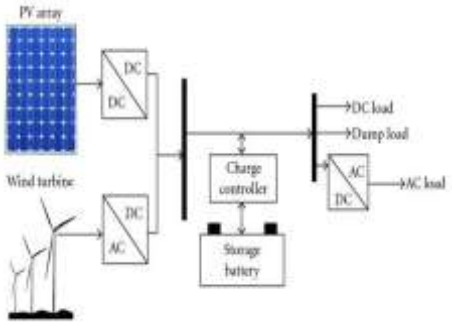
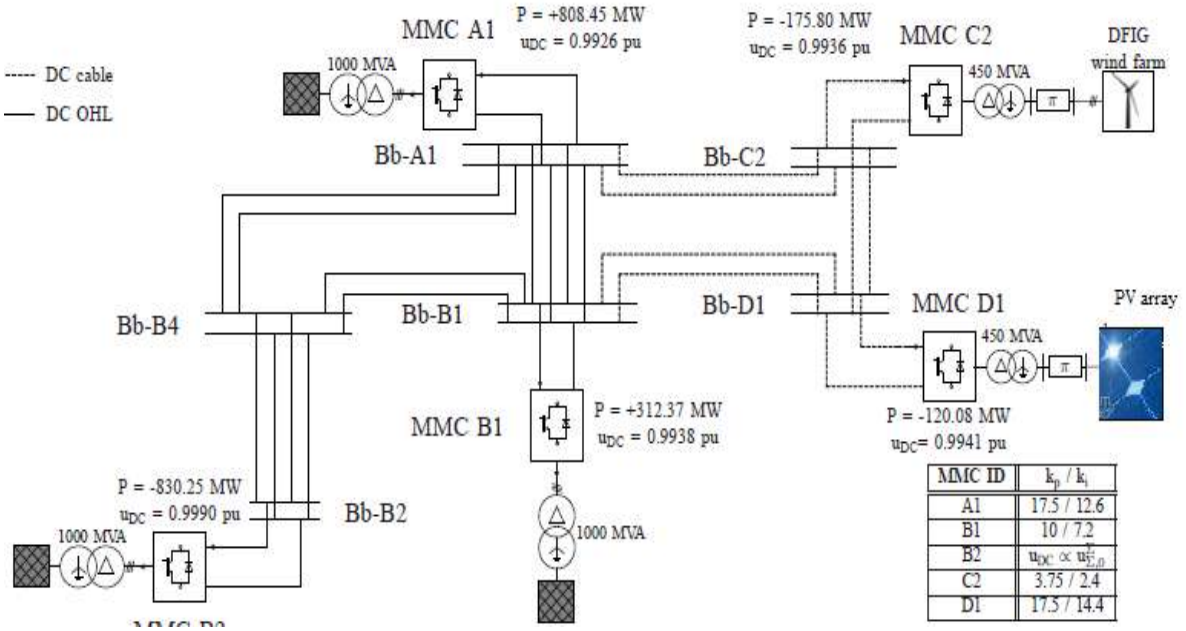


Fig .5 basic hybrid array and wind turbine system.



MMC ID	k_p / k_i
A1	17.5 / 12.6
B1	10 / 7.2
B2	$u_{DC} \propto u_{\Sigma,0}^2$
C2	3.75 / 2.4
D1	17.5 / 14.4

Fig .6 Five terminal DC grid system with hybrid wind farm and PV array

VI. SIMULATION RESULTS

This section introduces grid topology and main parameters of the investigated multi terminal DC system. Simulations are carried out in MATLAB/Simulink software where a fixed step solver witha time step of 25 µs is applied.The step size is chosenaccording to considerations provided in [5] and takes intoaccount the controller sample time of 50µs.A positive powervalue represents an AC side in feed.

Multi terminal DC grid configuration

As visualized in Fig.6 a five terminal grid based on a modified part of the HVDC Test System with

subsea cable sections (adapted insulation thickness, C′ = 0.152μF/km) and overhead lines is investigated, see [18].Terminal MMC C2 and MMC D1 are connected to DFIG wind farm arrays and PV arrays and absorb the generated power. The three remaining converters located on the mainland are connected to AC grids and MMC B1 and MMC B2 participate in active DC grid primary control tasks according to their assigned role, DC and AC lines.

Gains for the current and energy PI controllers are initialized considering further information provided in [10] and [16]. In addition, all relevant measurement delays as well as the FIR filters have to be considered.All phase module current dynamics are adjusted to improve the transient DC network behaviour.

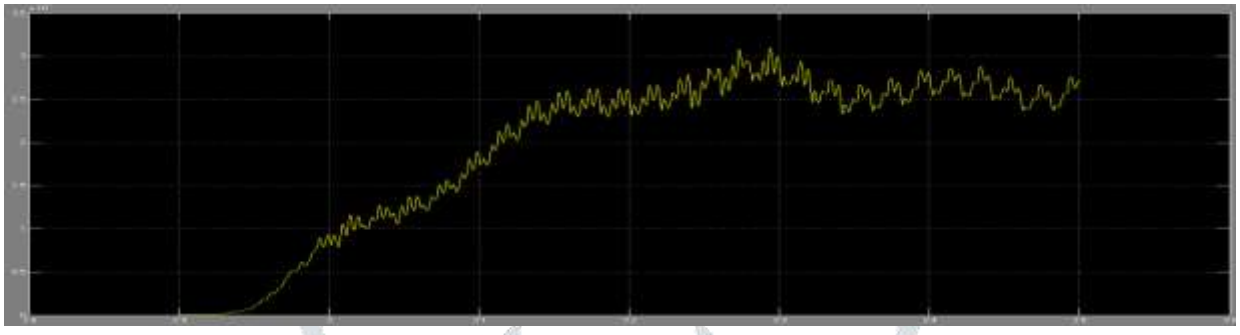


Fig. 7current output of modular multilevel converter of MMC1

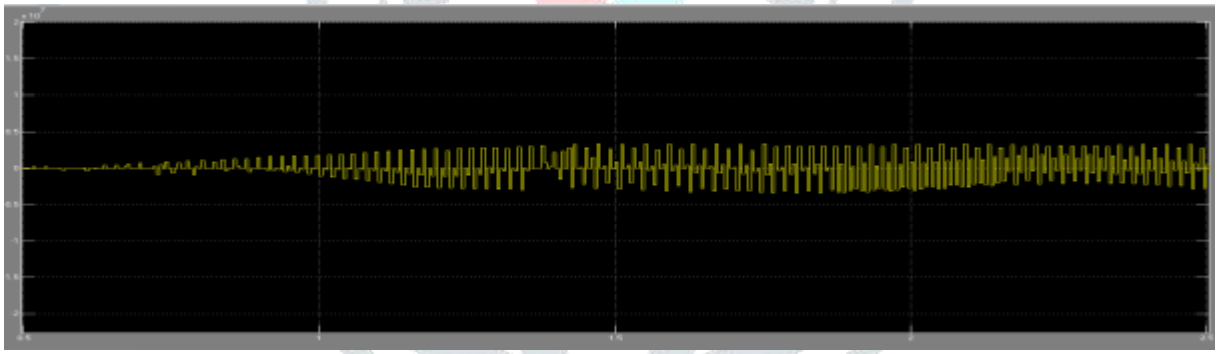


Fig.8, voltage output of sub module in modular multilevel converter 1.

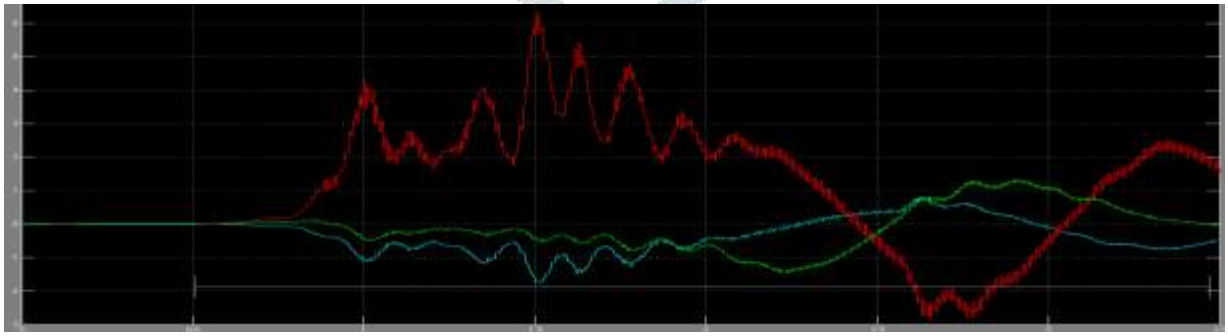


Fig 9 Power response of MMCs in MW when DFIG wind farm connected

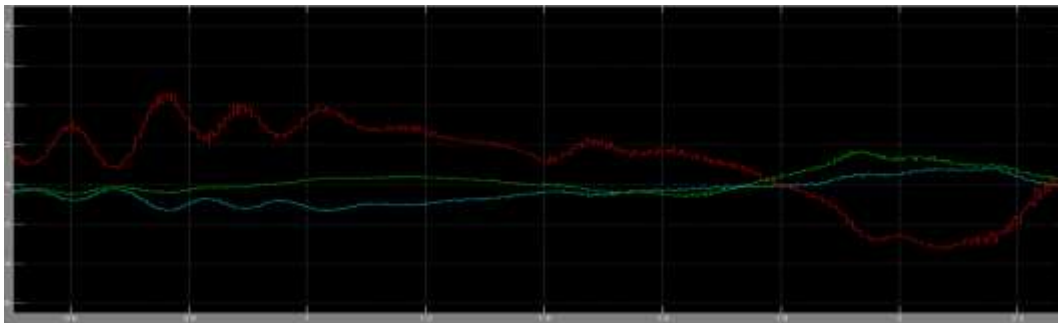


Fig.10 Power response of MMCs in MW with DFIG wind farm andPV array system

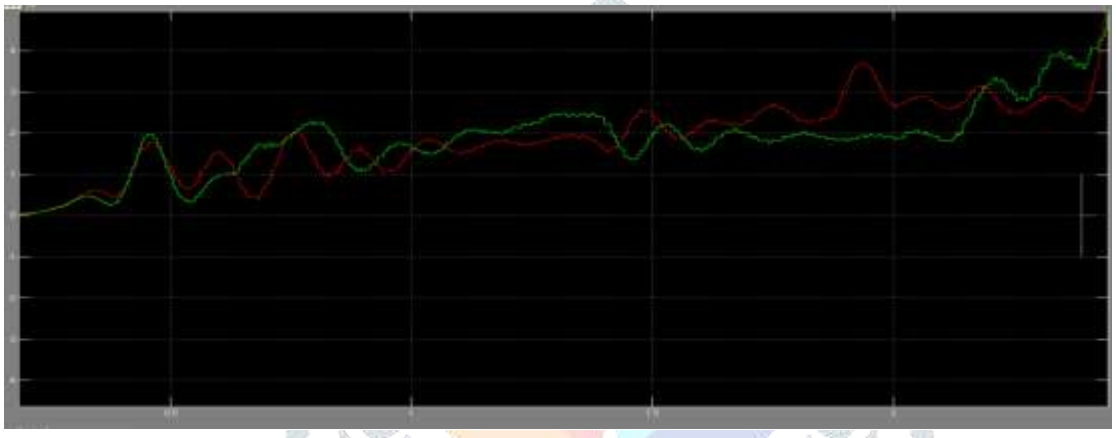


Fig.11 voltage response of MMCs in kV.

VII. CONCLUSION

In this paper, a simulation framework for MMC based multi terminal HVDC system with PV system and wind farms presented. Paper also discusses about detailed modular multilevel converter like modelling of converter, designing of sub modules and control strategies. Besides the feature of handle unbalanced voltage conditions in one of ac interfaced networks. In particular the possibility to resume to an initially set energy distribution within each converter terminal offers a wide range of novel evaluation opportunities. These are DC grid control and their interplay with offshore wind capacities, transient response to AC grid frequency deviations and active handling of AC harmonics. Results based on a five terminal system in MATLAB/Simulink are studied.

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