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MODULAR MULTI-LEVEL CONVERTER BASED HVDC SYSTEM FOR GRID CONNECTION OF OFFSHORE WIND POWER PLANT

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Abstract

This paper explores the application of modular multi-level converters (MMC) as a means for harnessing the power from off-shore wind power plants. The MMC consists of a large number of simple voltage sourced converter (VSC) sub-modules that can be easily assembled into a converter for high-voltage and high power. The paper shows that the MMC converter has a fast response and low harmonic content in comparison with a two-level VSC option. The paper discusses the modeling approach used, including a solution to the modeling challenge imposed by the very large number of switching devices in the MMC.

1 Introduction

Wind energy is an important renewable and green source of energy. The total installed worldwide capacity of wind power has doubled about every 3 years; from 24GW in 2001 to 159GW in 2009 [1]. A recent trend is to install large offshore wind power plants (WPP) because they offer higher energy yield due to a superior wind profile as compared with land-based installations, and provide a reduced level of irritation to the general public as noise, tower shadow and visual impact are not a significant problem [2].

Offshore wind power must be connected to the onshore power grid for the subsequent distribution and consumption of the generated power. For distant offshore wind power plants, high voltage dc (HVDC) transmission becomes favourable compared to high voltage ac (HVAC) transmission. In the latter case, the capacitive charging current drawn by the cables imposes a severe limitation on the current carrying capacity of long cables [3]. Moreover, HVDC provides asynchronous connection enabling operation of the offshore grid at variable frequency. However, since the offshore grid is inherently a weak grid, a voltage source converter (VSC) based HVDC system, also referred as VSC-HVDC, is favourable compared to the thyristor based classic HVDC system [4]. In addition to the fast control of both active and reactive power flow in either direction, a VSC-HVDC system also provide black start capability and a compact substation structure, which is an advantage for offshore applications. Fig. 1 shows a schematic diagram of a candidate offshore wind power transmission system. The wind power plant consists of several wind-turbine driven permanent magnet generators asynchronously connected to a WPP collector system using a full-scale converter (FSC) dc link. The power from the WPP system is evacuated to the on-shore grid by the submarine dc cables of the VSC-HVDC link.

Recently, Marquardt and Lesnicar have proposed a new converter topology referred to as the 'modular multi-level converter' for the VSC converter [5]. In the MMC, several elementary switching sub-modules are stacked together to attain the required dc operating voltage. Unlike other high-voltage VSC topologies, the MMC avoids the difficulty of connecting semiconductor switches in series. The voltage rating can be scaled by simply adding additional sub-modules to the stack. Thus, it becomes easier to construct VSCs with very high power and voltage ratings. The MMC arrangement also has significantly lower switching losses. In previously proposed multi-level topologies such as neutral point clamped or flying capacitor converters, only a limited number of levels, usually 3 or 5, can be practically realized [6]. The MMC on
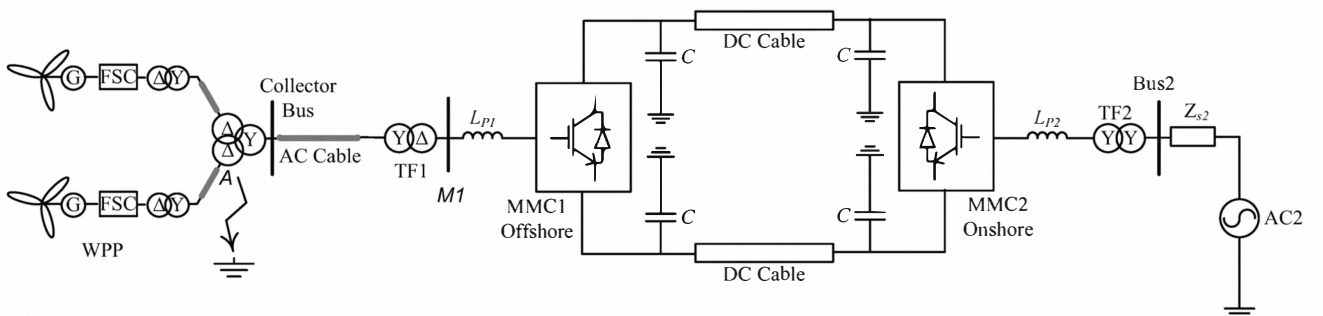

Fig. 1 MMC based HVDC system for WPP connection

the other hand, typically uses a hundred or more levels and creates an essentially sinusoidal ac waveform without the need for any additional filtering. Moreover, the balancing of capacitor voltages in an MMC is easier than in previous multi-level topologies [7]. It is also claimed that in comparison with two-level VSC topologies, with the MMC, the probability of dc bus short circuits is reduced, as is the magnitude of the short circuit current [8].

Therefore, the MMC is considered to be a highly attractive candidate in high voltage and high power transmission applications. The first application of this technology was for the ±200 kV, 400 MW Trans Bay HVDC cable project in California [8].

2 Modular Multi-level Converter

The basic building block [5] of the modular multi-level converter is a sub-module which comprises of two IGBT switches (T_1 and T_2) and a capacitor, C as shown in Fig. 2. The output voltage of the sub-module is given by,

$$V_{SM} = \begin{cases} V_C & \text{if } T_1 \text{ is 'ON'} ; T_2 \text{ is 'OFF'} \\ 0 & \text{if } T_1 \text{ is 'OFF'} ; T_2 \text{ is 'ON'} \end{cases} \quad (1)$$

where, V_C is the instantaneous capacitor voltage.

The sub-module is considered to be 'ON' when $V_{SM} = V_C$; it is 'OFF' when $V_{SM} = 0$.
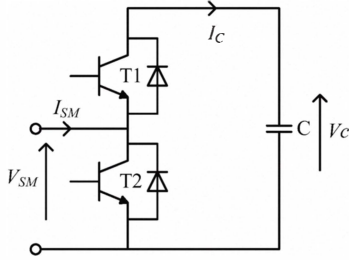

Fig. 2. Basic building block of MMC: Power sub-module

The phase arm of MMC scheme consists of a stack of power sub-modules connected in series as shown in Fig. 3, to form a 'multi-valve'. There are 2 multi-valves (upper and lower) in each phase, collectively referred to as a 'phase module'. Each multi-valve has an equal number (N_P) of sub-modules. Each of the sub-module capacitors is nominally charged to a voltage:

$$V_c = V_d / N_P \quad (2)$$

With this daisy chain connection of sub-modules, the individual output voltages from each sub-module add up to provide the net output phase voltage. With proper control of the sub-module switches T_1 and T_2, a multi-level near-sinusoidal output waveform can be created with a shape as shown in Fig. 4.

The phase reactors in Fig. 2 minimize any circulating currents resulting from any non-nominal voltages on the upper and lower multi-valves, resulting from momentary capacitor voltage unbalances.
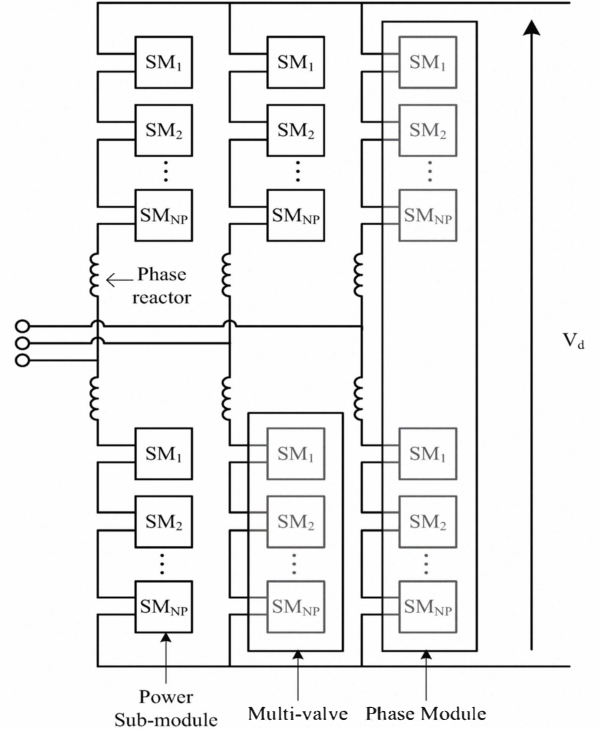

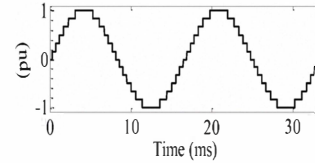Fig. 3 Three phase MMC scheme for an 'NP' level arrangement

Fig. 4. Multi-level waveform (pu) of a MMC with 12 sub-modules per multi-valve

3 Modelling of Modular Multi-level Converter (MMC) and Wind Power Plant (WPP)

3.1 MMC Model

The excessively large number of switching devices in the MMC (up to a thousand) imposes a challenge for modelling the MMC on an electromagnetic transients simulation (EMT) program. The admittance matrix of the converter becomes very large and its re-factorization at each switching operation is computationally very time consuming.

On the other hand, an averaged model [9] is too simplistic. Therefore, a computationally efficient yet mathematically exact model of the MMC [10] was developed using the nested fast and simultaneous solution approach [11] summarized below.

An equivalent circuit for the sub-module can be obtained by representing the IGBT switches as two state (R_{ON} and R_{OFF}) resistive devices [12] and representing the capacitor as an equivalent voltage source, V_{cEQ} and a resistor, R_C [13] as shown in Fig. 5.
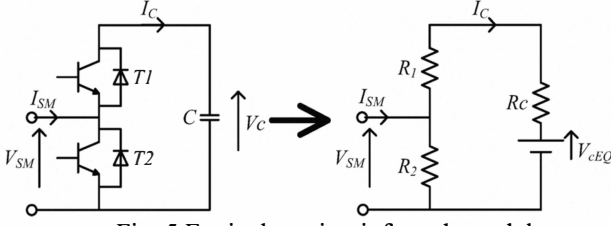
Fig. 5 Equivalent circuit for sub-module

By series-connecting the sub-module equivalent circuits, a Thévenin equivalent can be obtained for each multi-valve of MMC as shown in Fig. 6. The multi-valve equivalent is a single 2-node element in the main EMT solver thereby greatly reducing the number of nodes in the simulation. This reduces the size of the resultant admittance matrix of the circuit and reduces CPU time by approximately 2 orders of magnitude without sacrificing accuracy [10].
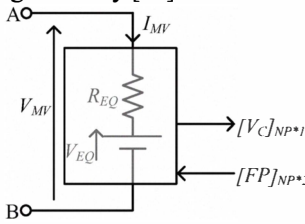

Fig. 6 Thévenin equivalent of a multi-valve of MMC

3.2 WPP Model

To verify the performance and validity of the MMC based HVDC system and its control strategies in wind power plant (WPP) connections, a comprehensive model was developed in PSCAD/EMTDC simulation program for a 400MW off-shore WPP, connected via MMC-HVDC to a strong receiving end network as shown in Fig. 1. The WPP model comprises a pair of aggregated wind turbine generators (WTG) connected to the offshore WPP-grid with a back to back full scale VSC dc link (FSC) as in Fig. 7. The FSC link provides the decoupling from the offshore ac grid frequency enabling the wind turbine generator to be efficiently controlled over a wide speed range. The generator side converter of the FSC controls the generator speed to produce the desired power (possibly by following a maximum power tracking algorithm). Its reactive power order is set to zero to provide unity power factor. The WPP-grid side FSC link converter's real power order is regulated to maintain a constant dc link voltage, and the reactive power order can be externally specified. In order to simplify the model, the FSC converter was represented by an averaged model [14], and the turbine/generator represented by a first order transfer function.
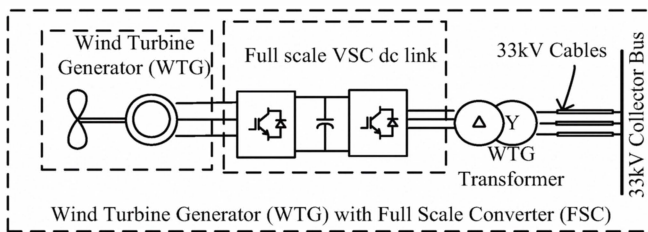

Fig. 7 Aggregated WPP model

4 Simulation of a WPP with a MMC Based HVDC Link

The aggregated wind generator FSC model for the WPP and the computationally efficient MMC converter model were connected together to represent the system of Fig. 1. The converter transformers, DC cables and the remaining ac network were modelled in detail for electro-magnetic transient simulation.

The MMC based VSC link asynchronously connects the onshore and offshore grids. Each MMC multi-valve consists of 60 sub-modules, with a nominal voltage of 5.0 kV, giving a dc line rating of ±150 kV. The complete system data is given in Appendix I.

4.1 Controls of MMC-HVDC

The control system for the MMC-HVDC system consists of lower level converter firing control blocks, and higher level control blocks that regulate system level quantities such as voltage, power or reactive power. These are described below.

1) Basic Converter Firing Control:
In this controller, a sinusoidal reference having the required magnitude, phase and frequency is converted into a multi-step reference waveform which can be used to determine the corresponding level order signal. The value of level order signal reveals the required number of capacitor voltage steps to be added to form the multi-step waveform at any instant and hence, the number of sub-modules, n_U to be turned on in the upper multi-valve. The waveforms for an MMC with 12 sub-modules per multi-valve are shown in Fig. 8.
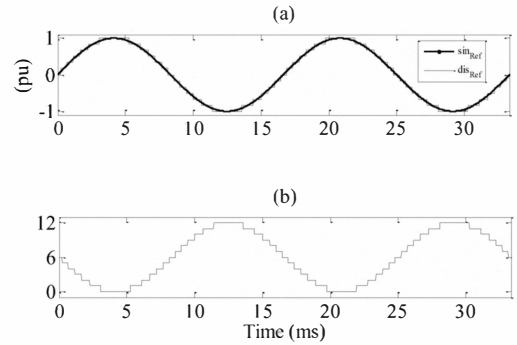

Fig. 8(a) Sinusoidal reference and multi-step reference signals and (b) Level order signal n_U for an MMC with 12 sub-modules per multi-valve

Capacitor Voltage Balancing Controller
For proper operation of the MMC, each sub-module's capacitor voltage must be kept equal to each other, at a value V_c shown in Equation (2) [5]. Consider the sub-modules in the upper multi-valve. When a sub-module is in the 'ON" state and carries a positive current (i.e.: $I_{SM} > 0$ in Fig. 2), its capacitor's voltage increases. It decreases for $I_{SM} < 0$. The level order signal in Fig. 8(b) only gives the number n_U sub-

modules, which are to be 'ON'; however, it is the capacitor voltage balancing algorithm that selects these n_U sub-modules from the N_P sub-modules in the multi-valve. The capacitor voltages are first sorted according to increasing voltage magnitudes. If $I_{SM} > 0$, the n_U capacitors targeted for turn on are the ones with the smallest voltages, because they will charge to higher voltages in the 'ON' period. Similarly, if $I_{SM} < 0$, the n_U sub-modules with the largest capacitor voltages will be turned on. Note that as the sub-modules are series connected, each sub-module in the multi-valve carries the same current I_{SM}. The same procedure is also applied to the lower multi-valve. In this manner, the capacitor voltages can be controlled in a narrow band [5].

2) WPP-side MMC controller
The VSC terminal of the HVDC system regulates the offshore grid's voltage and frequency as shown in Fig. 9. A voltage controlled oscillator generates the reference angle from the ordered frequency, and the d and q axis voltages are regulated using PI controllers that generate d and q axis current orders [15].
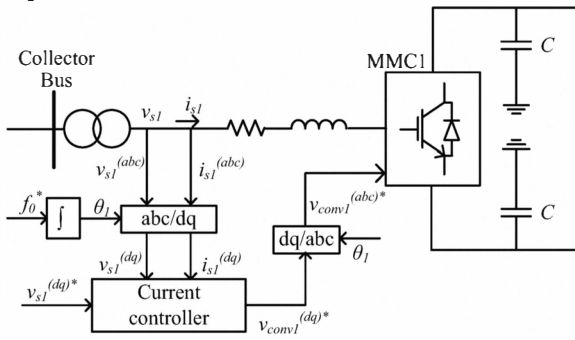

Fig. 9 WPP side Converter Control
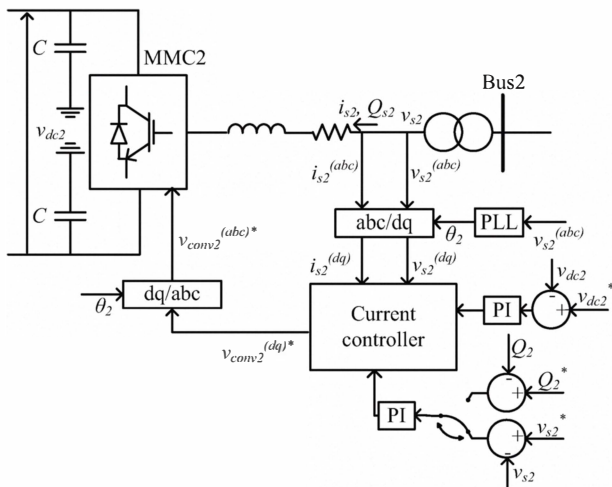
3) On-shore MMC controller

Fig. 10 Onshore grid side controller

The onshore converter-MMC2, inverter regulates the voltage of the MMC dc link via control of the active power.

The reactive power can be directly ordered or indirectly controlled to regulate ac voltage as shown in Fig. 10. In this case, a Phase locked loop (PLL) is used to synchronize the converter output voltage waveforms with the ac grid.

4.2 Simulation of System Operation

Several simulations were conducted to investigate the operation of the above MMC converter based wind power evacuation system.

1) Response a power order changes
The power order was decreased from rated power (400MW) to half power and then restored back to the rated value. Fig. 11(a) shows the reference power order (for each turbine-generator), the actual power output of one of the turbine-generators and the power delivered to the onshore grid. The MMC dc link responds to the power changes in step with the generation change. Fig. 11(b) shows the response of onshore MMC to a sudden change in reactive power order from 0 Mvar to 50 Mvar. It is achieved in 80 ms, without any effect on real power, confirming the de-coupling of real and reactive power control loops. During these transients, the dc link voltage is regulated to 300 kV (Fig. 11(c)), and the sending end ac phase voltage to 122.5 kV peak (Fig. 11(d)).
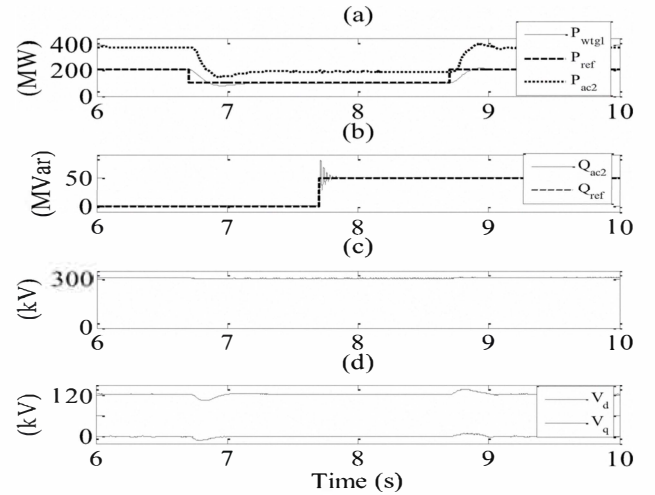

Fig. 11 HVDC system responses for power order changes: (a) turbine power and its reference, and dc link power, (b) receiving end reactive power and its reference, (c) dc voltage and (d) sending end ac voltage

The above simulation shows that the overall system is able to operate as intended in evacuating the offshore wind power.

2) Simulation on a offshore grid L-G fault
A line to ground single phase fault is applied on the 33 kV collector bus (point A in Fig. 1) at 20 ms. It is cleared 150 ms later at 170 ms. The fault current, off-shore grid side ac voltage (at bus M1 in Fig. 1), power, and dc voltage are shown in Fig. 12. As seen in Fig. 12(c), the dc power recovers to within 90% of its pre-fault value in 40 ms (at 210 ms) after
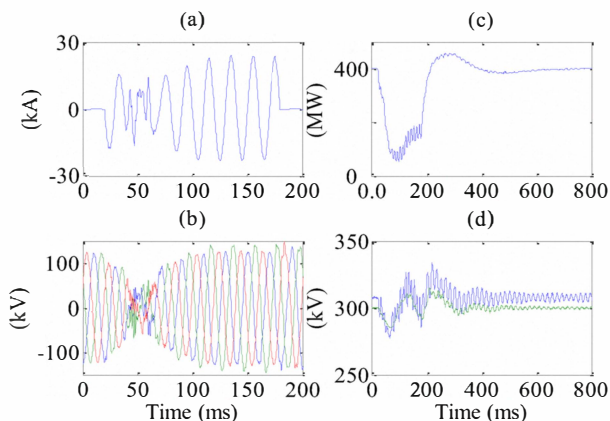
Fig. 12 System responses during a L-G fault, applied for 150ms on phase 'A' at 20ms; (a) fault current, (b) collector side bus voltage, (c) real power fed to dc link, and (d) MMC1 and MMC2 dc voltages

fault clearance, and reaches steady state in approximately 200 ms (at 370 ms) after fault clearance. The dc voltage in Fig. 12 (d) also recovers within 200ms after fault clearance. The pre-fault portion of the ac bus voltage waveform shown in Fig. 12 (b) is sinusoidal; thereby indicating that filters are not needed with the MMC topology.

5 Conclusion

A typical application of MMC based HVDC transmission system was presented. The wind power plant was modelled as an aggregated system connected to the offshore grid. An accurate Thévenin equivalent model for the converter was used to simulate the MMC on an electro-magnetic transient simulation program. Several simulations were carried out to demonstrate the behaviour of the MMC based HVDC system in WPP connections. The MMC topology can be effectively used to transmit power generated by the offshore wind turbine-generators. The ability to operate the converter without filters is a distinct advantage in WPP systems to accomplish the compact design requirement.

Appendix I

TABLE A1
PARAMETERS OF MMC-BASED HVDC SIMULATION SYSTEM

Offshore grid	Onshore grid	
$V_{BUS1(L-L)}$ = 230 kV	$V_{BUS2(L-L)}$ = 150 kV	
L_{P1} = 0.0193 H	L_{P2} = 0.0193 H	
	SCR = 25	
Transformer 1	Transformer 2	
S = 445 MVA	S = 445 MVA	
Ratio = 150/150 kV	Ratio = 150/400 kV	
X_{TF1} = 12 %	X_{TF2} = 12 %	
DC System		
DC filter	C = 35.5µF	
DC rated voltage	V_{dc} = ±150 kV	
DC cable	R_{dc} = 14mΩ/km	
	L_{dc} = 0.112mH/km	
	C_{dc} = 0.28µF/km	
	Length = 200km	

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