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Modeling and Analysis of a Novel Grid Connection Topology for Offshore Wind Farms Using MMC-HVDC Transmission

P. Lozada Ayala[1], J. L. Rueda Torres[1], C.G.A. Koreman[2], M.A.M.M. van der Meijden[1,2]
[1]Department of Electrical Sustainable Energy, Delft University of Technology, Delft, The Netherlands,
[2]TenneT TSO B.V., Arnhem, The Netherlands,
PLozadaA@gmail.com, J.L.RuedaTorres@tudelft.nl, Kees.Koreman@tennet.eu, Mart.vander.Meijden@tennet.eu

***Abstract*—To meet the goals of the Paris Agreement, the Netherlands is integrating large amounts of offshore wind energy into the power system and has ambitious plans for the coming years. A grid topology with transmission capacity above 1 GW connecting offshore wind farms (OWFs) at distances close to 100 km in a standardized, modular, and cost-efficient manner is the focus of this paper. An electromagnetic transient (EMT) model was built in PSCAD in which OWFs are connected with 66-kV cables to a centralized offshore platform and a transmission link with a capacity of 1050 MW. The 66-kV cables will be coupled to three converter transformers connected to each other on the valve side and not on the 66-kV side. The link to the onshore transmission network uses VSC-HVDC technology with MMC topology. A dynamic performance analysis was done to obtain a complete overview and understanding of the overall behavior.**

***Index Terms*—66-kV offshore grid, EMT model, MMC-HVDC transmission, offshore wind energy.**

I. Introduction

Europe, like the rest of the world, is in a process of transitioning from a fossil fuel-based energy economy to a sustainable, low-carbon model based on renewable energy sources. The European ambitions were defined with the 20-20-20 targets by 2020 in 2007 [1]. Additionally, through the Paris Agreement, ambitious plans were defined to combat climate change. National targets have been set by each country and even higher levels of penetration of clean energies are expected in some cases. In particular, the Dutch government is driving this transformation through the so-called Energieakkoord. These plans aim for a sustainable and reliable electricity system in the long term.

In April 2016 TenneT TSO was appointed as the offshore grid operator in the Netherlands, which implies that it will develop at least 3,500 MW of offshore connections until 2023. In March 2018 the Dutch government announced the 'Routekaart windenergie op zee 2030' which includes plans for additional wind farms with a total capacity of at least 7,000 MW. One of the new wind sites is the area known as IJmuiden Ver. This section is located approximately 80 km off the Dutch coast and approximately 4 GW are expected to be produced in this region [2]. Due to the longer distances compared to the nearshore wind farms being developed until 2023, one of the solutions to integrate all the wind power is to use high voltage direct current (HVDC) transmission instead of the standardized high voltage alternating current (HVAC) transmission concept TenneT is already implementing.

TenneT TSO is analyzing new offshore grid connection concepts to achieve a reliable and secure operation of the infrastructure connecting wind energy both in Germany and the Netherlands. One of the possible solutions is to connect the new wind farms with 66-kV cables to a centralized offshore platform with a connection capacity of 1050 MW. The link to the onshore transmission network uses HVDC technology based on voltage source converter (VSC) conversion techniques and modular multilevel converter (MMC) topology. It is expected that the 66-kV cables will not be coupled to a single busbar through paralleled converter transformers, but that this will be done with at least three converter transformers connected to each other on the valve side but not connected on the 66-kV side, as depicted in Fig 1.

The outline of this paper is as follows. In section II the tests system layout and the main parameters are presented. Afterward, in Section III, the control of the MMC-HVDC transmission scheme is explained. Section IV shows the results of the simulations in PSCAD. Finally, conclusions are drawn in Section V.

II. Test System Layout and Main Circuit Parameters

The test network designed consists of three identical OWFs with a nominal capacity of 350 MW using type 4 wind turbines (WTs), which are connected to the offshore ac/dc converter station through three different three-phase transformers.

These converter transformers are connected to each other on the valve side, but not connected on the low-voltage side, i.e. are not in parallel. The power produced by the WTs is transported to the onshore grid via a point-to-point HVDC link. On the onshore end, a dc/ac converter is connected to an equivalent point of the 380-kV ac transmission system. The system under study represented in PSCAD is presented in Fig. 1.

A. Offshore Wind Power Plant Layout

The 1050 MW offshore wind power plant is divided into three offshore wind farms rated at 350 MW. All wind turbine generators (WTGs) are assumed to be Type 4 wind turbines. A standard model of a 5 MW type 4 wind turbine was used. To represent an aggregated 350 MW OWF, 70 wind turbines were implemented. Each OWF is located at a distance of 30 km from the offshore MMC station.

A PSCAD module representing an aggregated offshore wind farm was used in the simulation. The type 4 wind turbine module uses an average converter model and a scaling component. The average model provides enough detail for the objective of this study. The total power of each wind farm is 350 MW. Three OWFs are implemented for a total power production of 1050 MW. This full aggregated model represents a cluster of wind turbines. There are also three independent control blocks to generate the incoming wind speeds in every wind park. According to [3], the wind speed at the reference height of 128 m in the wind site IJmuiden Ver, where the offshore wind power plants (WPPs) are expected to be located, is 11.9 m/s. The cut-in and cut-out speeds considered were 4 and 25 m/s respectively.

B. Inter-array Cable System

The inter-array cable system is rated at 66 kV. These cables will collect the output of the WTGs and route it to the offshore ac/dc converter where the voltage will be stepped up for the efficient onward transmission of power to the onshore transmission system. Among the advantages of a cable system operated at 66 kV instead of 33 kV are: possibly up to twice as much power can be transported, less array cabling, and substantial capital cost savings, in terms of both cable purchase and installation [4]. Another great benefit is the elimination of the ac collector substation platforms as the wind farm's 66-kV array cables are directly connected to the primary side of the offshore HVDC converter transformer. Removing the intermediate ac substation platform will result in significant investment savings (CAPEX) and will reduce overall maintenance costs (OPEX), as there are fewer components to fail [5].

Standard cable elements from the PSCAD library were used. The parameters for the cable system are based on data from TenneT projects. The inter-array cable system was modeled using the Bergeron model in PSCAD. An important aspect to be analyzed for the inter-array cable system is the reactive power that must be compensated. The capacitance of HVAC submarine cables is higher than that of overhead transmission lines and therefore has to be properly compensated. The submarine ac cable generates a considerable reactive current due to its high capacitance which reduces its active current-carrying capacity and increases its losses. A compensation device can solve these problems and improve the security and stability of the system. The fixed inductive reactive power generated in the submarine cable was estimated in 520 kVAr/km. Four cables were used for carrying the power for one OWF.

C. Converter Transformers

No special transformers are required for the MMC-HVDC technology [6]. Therefore, conventional transformers are used from the PSCAD library to model these elements. There are three offshore converter transformers which connect the wind farms with 66-kV cables to a centralized platform where the offshore end of the HVDC link is located, as illustrated in Fig. 2. The 66-kV cables will not be connected to a single busbar through parallel converter transformers as done in current standard topologies, but they will be connected to three transformers not in parallel. These transformers are connected to each other on the valve side but not connected on the 66-kV side. The transformers have identical nominal voltage ratio of 333/66 kV to connect the VSC station to the offshore grid at 66 kV. The nominal capacity of each transformer is 400 MVA. The leakage reactance is assumed to be 14%, typically the optimum reactance value [7].

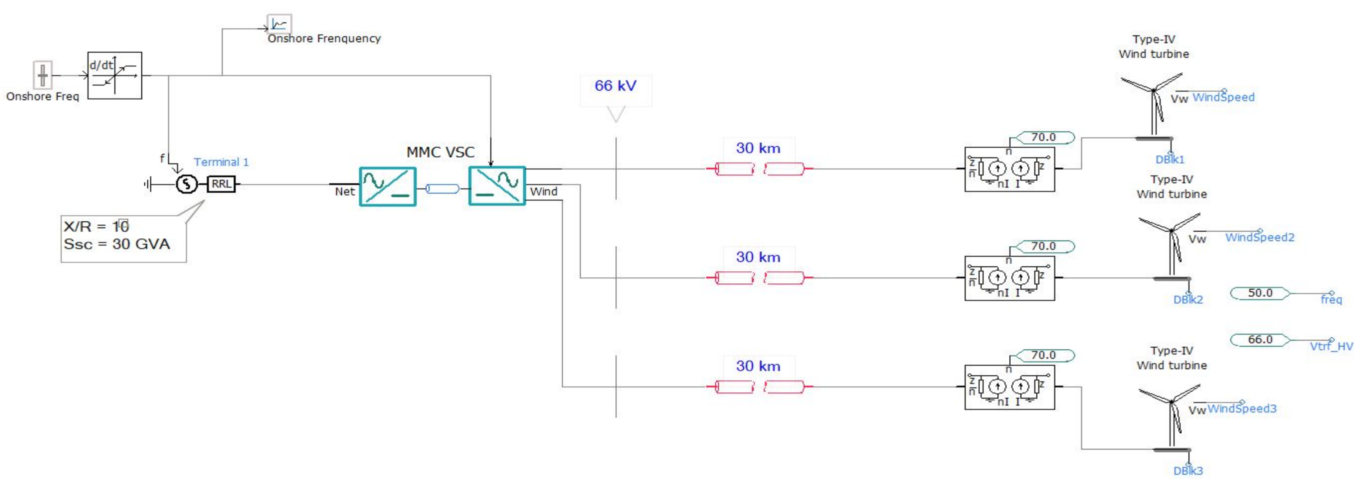

Figure 1. Test network in PSCAD.

For the onshore side, the nominal voltage ratio of the three-phase transformer modeled in the test network is 380/333 kV as it interfaces the ±320 kV MMC-VSC station with the 380-kV onshore grid. The leakage reactance is assumed to be 18%, and the losses are 0.5% no-load loss and 0.5% full load copper loss. The parameters of the converter transformer have been taken from the MMC-HVDC system that interconnects the 400-kV systems of France and Spain (INELFE) [8]. The secondary winding of each transformer is connected in delta to block the zero-sequence voltages generated by the MMC.

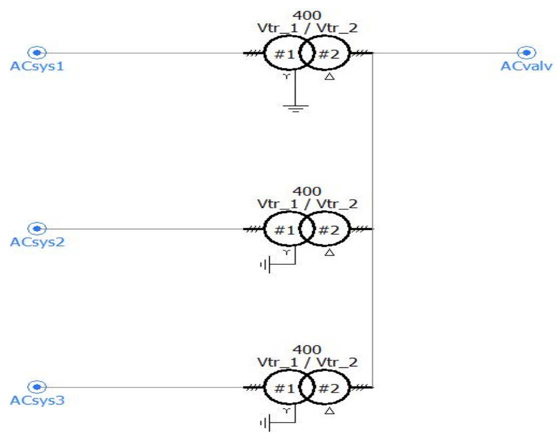

Figure 2. Three converter transformers at the offshore end.

D. Modular Multilevel Converters

The converters have a design based on series-connected half-bridge submodules. The converter stations are connected following a symmetrical monopole configuration with a rated dc voltage of ±320 kV (positive-negative pole) and ac voltage of 333 kV, as the real HVDC link presented in [8]. The amount of power submodules per arm inside the MMC of the test network is 300.

The arm reactor helps control and balance circulating currents in the phase arms and limiting fault currents and has a value of 0.15 p.u on the system impedance base, i.e. 48 mH. The capacitance of the submodules inside the MMC considering the recommendations given in [8] is 10.7 mF. The detailed equivalent model of the MMC available in PSCAD, named type 4 in [9], assumes that IGBTs and diodes can be treated as two-state resistive devices. With this approach, each arm is replaced by a Norton equivalent circuit. The switch "on" and "off" resistance values are selected as 500 μΩ and 100 MΩ, respectively.

E. Export HVDC Cables

For VSC-HVDC power transmission, extruded dc cables have been successfully applied in many projects at up to 320 kV voltage rating and up to 1000 MW power rating [10]. The major insulation material is cross-linked polyethylene (XLPE). A very important characteristic of the VSC HVDC technology that has led to increasing the applications for extruded HVDC cables is the non-voltage reversal feature. The same pole voltage polarity is always maintained, whereas the current flow direction is reversed to change the direction of the power flow from one converter station to the other.

The cable representation in PSCAD uses a frequency dependent phase model. The distance between cables is 50 cm (wide spacing). For submarine cables, the resistivity of the return path is close to the resistivity of seawater, i.e. ρ = 0.2 Ω·m and the depth measured from the center of the cable and the ground surface is 1.5 m (but 50 m deep in the water) [9]. The nominal power rating of 1050 MW at ±320 kV dc voltage requires a current flow of 1.64 kA. The cable parameters used in the PSCAD model are based on the parameters given in the CIGRE DC Grid test system [9] for the 400-kV cable.

F. Onshore Grid Equivalent

The onshore transmission grid is represented by a Thevenin's equivalent of a 380-kV voltage source with series impedance. The grid impedance is estimated based on the short circuit power at the point of grid connection. The resistive and inductive parts of the impedance are determined from the grid angle. Assuming a strong grid at the point of common coupling (PCC) of the HVDC link and following the reference parameters presented in [9] for the CIGRE DC Grid test system, short circuit power = 30 GVA and X/R = 10, the equivalent parameters are Zth = 4.813 ∠84.3° Ω, Rgrid = 0.478 Ω, Xgrid = 4.789 Ω, and Lgrid = 15.245 mH.

G. Additional Components

The pre-insertion resistor has a value in the order of magnitude of kΩ and is project specific. A circuit breaker with a pre-insertion resistor is required to be installed at the MMC station to suppress the inrush current due to the saturation of the converter transformer and avoid severe voltage dips at the PCC during the energization of the MMC station [11]. The pre-insertion resistor was located at the onshore MMC station. For the start-up sequence of the converter in the PSCAD simulation, a value of 100 Ω was implemented [12] as it allows for a faster simulation.

The grounding reference for the symmetrical monopole configuration used here is obtained by a special grounding device, a star-point reactor which is installed between the converter transformer secondary side and the ac side of the converter arms. The star-point reactor consists of three star-connected inductors with their neutral connected to the ground through a resistor [5]. The values of the star-point reactor parameters in the PSCAD model are 5000 H and 5000 Ω, respectively based on [9].

The dynamic braking system (DBS), also referred to as dc chopper is a common element in the HVDC topology connecting OWFs. The main function of the onshore DBS is to regulate the dc voltage by dissipating the surplus energy in the system which can arise when the MMC stations are not able to export all the wind power. For the power of 1050 MW, the resistor of the DBS has a value close to 500 Ω.

Surge arresters are part of the equipment installed to protect the components of the HVDC transmission scheme from any abnormal overvoltages. The values of the surge arresters in the PSCAD model were selected based on the guidelines given in [13].

III. Control of the MMC-HVDC Transmission Scheme

The control levels of an MMC-HVDC station are classified into three levels: dispatch control, upper level control and lower level control [9]. The upper control of the converter consists of two parts, the outer and inner loops. The faster vector controller which is the inner loop and the outer controllers which supply the references for the vector controller. The outer controllers include the active power controller, dc voltage controller, reactive power controller, ac voltage controller, and frequency controller.

The most appropriate control modes for MMC-HVDC stations at the receiving end of a link connecting OWFs are ac voltage control and dc voltage control [14]. These two control modes are configured in the modules available in the PSCAD representation of the converters for the test network under study presented here. The onshore converter has a grid following behavior. The onshore MMC connected to the ac grid detects the frequency and phase from the system at the PCC to synchronize the converter and control accordingly. This action is performed by the phase-locked loop (PLL) system which synchronizes with the ac voltage. With this reference, the PLL will produce the phase angle θ necessary to transform the voltages and currents from the abc to the dq reference frame. The onshore converter station can also operate in a STATCOM style mode.

For the sending end, the converter station works in ac voltage control mode and islanded mode, which means that the offshore MMC station controls the frequency of the offshore ac grid by generating the angle reference of the voltage waveform by an independent voltage controlled oscillator (VCO). No PLL is used because the angle is provided by the frequency regulator. The offshore converter has a grid forming behavior and must be capable of accepting and delivering the power generated by the OWFs and transfer it to the onshore station and enforce the power balance and protect the integrity of the operation of the WTGs units within the offshore WPP [15]. Since all generating units are type 4 WTs, the rotating inertia directly connected to the island grid is zero. The frequency control of the offshore grid is driven by the MMC terminal. The offshore converter operates as a power slack bus.

For the inner control, the objective of the vector-current control strategy is to regulate the instantaneous active and reactive powers independently through a fast inner current control loop. Three-phase currents are transformed into d and q axis quantities based on abc to dq transformation. The references of the inner current control, id and iq, are generated by the two outer controllers which can use the d component to control the active power or dc voltage or droop control (P/Vdc), and the q component to control reactive power or ac voltage at the PCC.

Considering the topology under analysis here, the PCC is chosen as one of the 66-kV busbars of the converter transformers, which will be the leader and the other two transformers will adjust the values accordingly based on a leader-follower scheme possibly including tap changers.

The lower level control structure comprises basically the circulating current suppression control, modulation, and capacitor voltage balancing control. The lower level controls associated with standard MMC VSC converter stations were not modified.

The third harmonic injection method to distort the converter voltage is used as an additional control structure. The objective of this practice is to improve the operating efficiency by reducing the magnitude of the ac current that contributes to the converter losses. Another important control function is the current reference limiter, which is designed to avoid damage of the semiconductors due to large transient currents considering the MMC has no overload capability.

IV. Operation of the MMC-HVDC Transmission Scheme

This section presents a disturbance state which is one of the expected operational modes of the MMC-HVDC transmission scheme proposed. The control modes and set points of the MMC units are dc voltage control, Vdc ref = ± 320 kV and ac voltage control, Vac ref = 1 p.u for the onshore converter. Islanded mode and ac voltage control, Vac ref = 1 p.u for the offshore converter. Evaluating the response of the system to fault disturbances with precision is only possible using an electromagnetic transient (EMT) model.

The perturbation simulated in the grid is a sudden large disconnection. In this case, the circuit breaker of the OWF 2 trips and the dynamic performance of the grid is obtained. The three wind parks are operating at nominal wind speeds. After six seconds the event is applied to the network. The following figures present the behavior of the system. The OWFs were connected at 1.2, 2.2, and 3.2 seconds, respectively.

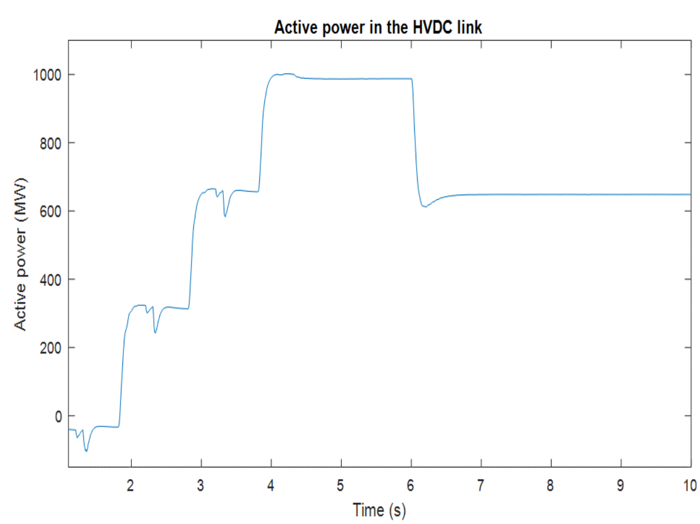

Figure 3. Active power flowing through the HVDC link.

The disconnection of the OWF 2 have no impact on the voltage at the onshore side as both ac systems are interconnected through the HVDC link. The Vdc is affected with a dip because there is a sudden trip and the power flowing into the HVDC link is reduced abruptly. The frequency of the offshore ac grid is perturbated by the disturbance as generation is lost. The dc voltage and currents at the dc side decreased, temporarily and permanently respectively. The voltages at the 66-kV busbars are shown in the next figures.

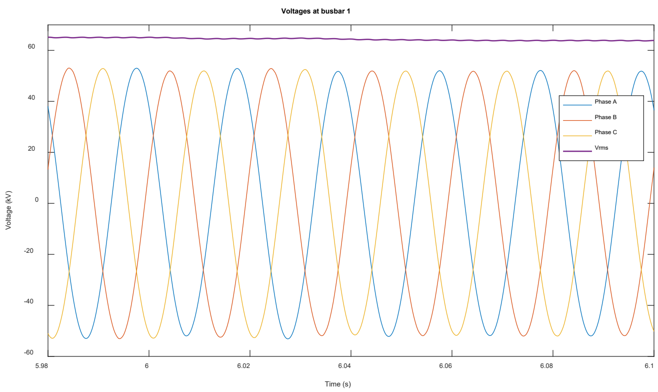

Figure 4.Voltage at busbar 1.

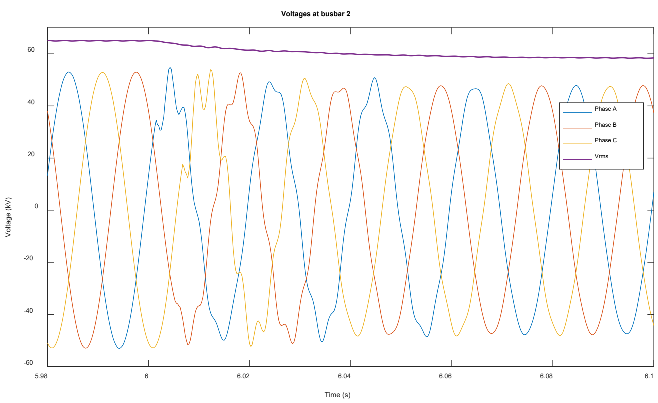

Figure 5. Voltage at busbar 2.

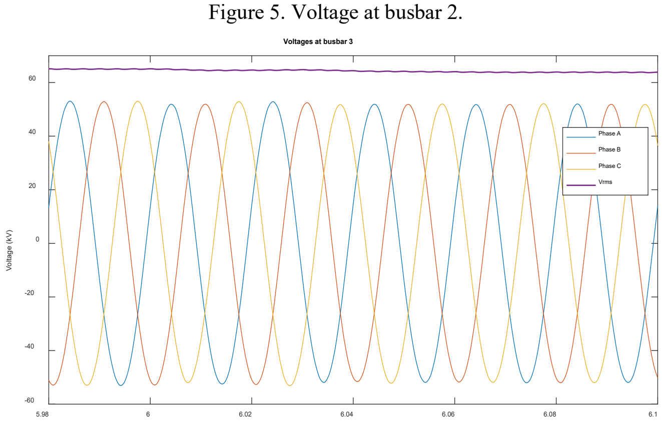

Figure 6. Voltage at busbar 3.

The circuit radially connected to the busbar 2 associated with the OWF 2 is in no-load condition after the trip of the circuit breaker. Minimum disturbances occur for busbars 1 and 3. The network is stable after the disturbance. These results provide an overview of voltage variations during the simulated scenario.

V. Conclusions

A new topology for the integration of large-scale wind power generation in the North Sea to the Dutch power system in a standardized, modular, and cost-efficient manner using HVDC technology based on VSC conversion techniques and MMC topology is presented in this paper. With the new topology, it is possible to avoid the so-called collector platform. The modeling in PSCAD is explained thoroughly. The control structures currently applied to MMC-HVDC transmission schemes for the interconnection of offshore wind parks such as outer controls for the active power, the dc voltage, the reactive power, and the ac voltage can be used with no problems in the new connection topology. The typical control modes of the MMC terminals are also valid.

The test network was stable during steady state and disturbances as demonstrated by simulations. More detailed studies must be performed in later stages of the project as in this moment these results are very conservative. The EMT model developed here does not have all the capabilities of a control scheme of a real network. However, extra functionalities could be added in the future to improve the controllability of the system for comparative assessment.

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