OFFSHORE RENEWABLE PLANT HVDC POWER COLLECTOR AND DISTRIBUTOR

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ABSTRACT

It will be beneficial for future large scale renewable energy power generators (i.e. large offshore turbines) and plant (i.e. large offshore wind farms) to have a dedicated high efficiency, robust, flexible and low cost power collection, transmission and distribution technology. In this paper, a compact and effective hybrid HVDC transformer is proposed. The aim is to realise a highly robust and financially rewarding next generation multi-terminal HVDC power collection, transmission and distribution system for future offshore renewable energy power plant. This paper discusses the study outcome of the proposed hybrid HVDC transformer and the application of the HVDC collector and distributor in the offshore renewable energy industry, compared to the existing HVAC and VSC type HVDC systems.

INTRODUCTION

The driving force behind developing new power transmission technology is increased with the rise, in both quantity and power capacity, of the offshore renewable energy power plants (e.g. wind farms, tidal farms, etc.). Many commentators have expressed strong belief in the growth in environmental opposition to energy production and that the need for energy diversity will result in a dramatic growth in the application of HVDC schemes as a solution to the future power transmission challenges. With lower I^2R and eddy current losses, high voltage low frequency HVDC power transmission system, potentially, gives better efficiency. The down trend in power semiconductor costs (i.e. £/Watt) and the predicted up trend in copper costs has also stimulated the need for further HVDC power transmission development.

In renewable energy power generation, especially offshore wind, generating farms are formed by multiple small scale power generators (i.e. <10MW wind turbines). Project "Upwind" suggested that future large offshore wind turbines could be in the range of 10 MW-20 MW [1]. Even at this power level, Conventional HVDC systems, including the modern voltage source HVDC systems are in general too bulky and less flexible for the renewable power generation industry [2]. In principle, they were designed to serve the conventional hierarchy type of mass power generation and single line head to head transmission links. They were not design to function as a power collector for multiple "small", with respect to the conventional power station, power sources such as turbines in a wind farm. To the embedded power generation industry, such as offshore wind power generation, the upfront investment to deploy a large centralised offshore HVDC substation just for a short distance, medium capacity power transmission is still considerably high with respect to the long power transmission in traditional multi Giga-watts power stations. In principle, some of the existing voltage source HVDC systems could be modified, before deployment, to perform multi-terminal operations, this has never been demonstrated. As a whole, these systems are well suited in applications like DESERTEC [3] as the backbone of the SuperGrid to transmit high power over very long distances (i.e. >1000km).

Currently, HVAC systems are generally used to collect power within the farm, if not the transmission network too. One or multiple farm level substations are or will be needed to step up the AC or to convert the collected power into HVDC form. In offshore wind, such a substation is and continues to be very costly to build and maintain.

A novel hybrid HVDC transformer that can be used as a DC transformer interfacing between the MV converters and the earlier mentioned backbone HVDC transmission systems is suggested in this paper. The proposed hybrid HVDC transformer provides an easy and cost effective HVDC interface, not only to wind but also to other renewable energy sources such as PV and CSP. The project has investigated the feasibility of the proposed hybrid HVDC transformer and its application in a multi-terminal HVDC power collection and distribution compared to utilising the existing VSC-type HVDC systems. This paper will discuss, in detail, the control principle, potential cost savings on components and the efficiency impact on both the overall system and its sub-assemblies.

HVAC TRANSMISSION SYSTEMS IN OFFSHORE POWER PLANTS

All offshore renewable energy power plants utilise submarine cables to establish power connection from individual generators to the offshore satellite substation and subsequently to the substation on the shore, as shown in Figure 1. The vast majority of the existing offshore renewable power collection, transmission and distribution are in the form of high voltage AC (i.e. 33kV or higher). This makes HVAC transmission an obvious choice for the grid connection of many wind farms. However, HVAC cable transmission suffers from the excessive reactive current drawn by the cable reactive element. This increases the cable losses and reduces the power transfer capability of the cable. As a result, custom designed reactive shunt compensation is often required to absorb the excessive reactive power and avoid the over or under-voltage phenomenon. Recently, there are intentions in the offshore wind industry to increase the substation to substation voltage to a higher level (i.e. >66kV) [4].

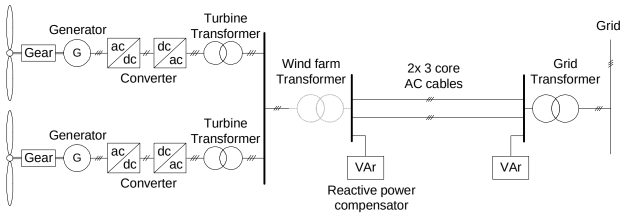

Figure 1: Typical offshore wind AC grid connection

Cable capacitance is usually distributed along the entire length of the cable; the longer the cable the higher the capacitive effect and hence the resultant charging current. With a higher transmission voltage being suggested to minimise resistive line losses and the voltage drop, the charging currents also increase, thereby aggravating the situation. The charging current can be estimated by the following equation:

$$Charging\ \ Current\ \ (I_c) = \omega C_{cable} V_{line} \qquad \text{Eq 1}$$

Cable capacitance (C_{cable}) is a function of the cable geometry and the type of insulator. V_{line} is the transmission line voltage. The ampacity of the cable to carry useful load current (i.e.,the active current (I_p)) is affected by the existence of the charging current (I_c) as follows:

$$I_p = \left(I_T^{\,2} - I_C^{\,2}\right)^{1/2} \qquad \text{Eq 2}$$

where I_T is the cable rated ampacity.

In addition to introducing charging currents, cable capacitance will also create over-voltage, high harmonic current distortion, and undesirable resonances. In some cases, special circuit breakers with a high capacitance current switching capability and an additional power conditioning system might be required. In order to improve the ampacity for active current and to maintain system voltage level, reactive power has to be injected from both ends of the transmission line. These requirements further complicate the power transmission process, reduce the robustness and increase both capital and O&M costs.

PROPOSED HVDC SYSTEMS

HVDC systems in general have advantages such as lower transmission losses, fully controllable power flow, grid decoupling and fault propagation prevention. In addition to these advantages, another attraction of using HVDC in both the onshore and offshore renewable industries is the possibility of utilising low weight extruded DC submarine and land cables. This could significantly reduce the cost of deployment. Unlike HVAC transmission systems, there is no reactive power generation or absorption in modern HVDC transmission systems, which makes it very suitable for transmitting power using cable.

HVDC transmission systems can be categorised, by the converters used, into three main categories. Due to the limitation in the allowable paper length and fundamental differences in technologies, “classic HVDC systems” such as Line Commutated Converter (LCC) and Capacitor Commutated Converter (CCC) HVDC systems will not be presented in this paper. The focus will be placed in the modern Voltage Source Converter (VSC) type HVDC topology.

The VSC-based HVDC transmission system is a relatively modern HVDC system which is developed based on self-commutated devices, thereby overcoming the shortcomings of the LCC-based HVDC system such as black start, reactive power compensation, and so on. However, this does come with at an increased converter cost and with potentially higher converter losses. In general, Insulated Gate Bipolar Transistors (IGBTs) are used as the switching devices in the VSC-based HVDC systems for high power and high frequency operation. The turn-on and turn-off capability of the IGBT gives line independent commutation processes to the converter. Therefore, with the use of self-commutated devices, VSC-based HVDC systems are capable of supplying passive load and energising a dead network during a black start. However, due to the higher VSC-terminal costs and converter losses, the VSC-based HVDC systems are more expensive than the LCC-based HVDC system. Nevertheless, studies show that VSC development in the last decade has brought down the system losses by more than 60% since the development of the first system and it is believed that the losses and cost can be further improved with the development of improved high power semiconductor devices. A trend curve, presented by Noriyuki Iwamuro [5] shows the technology improvement in power semiconductors over a 20 year period, which matches the above 60% improvement claim.

In general, the core characteristics of the existing VSC based HVDC systems are very similar. Converters used in these systems utilise multi-level three-phase bridges with multiple valves, each consisting of series-connected semiconductor switching devices (i.e. IGBTs). Figure 2 shows the simplified block diagram for the existing VSC-based HVDC systems.

The proposed alternative approach introduced by this paper has an entirely different power collection and distribution mechanism with respect to the existing HVDC systems. It introduces greatly increased flexibility and redundancy, and reduced O&M cost. Without relying on the line frequency components (e.g. AC reactor, AC filters, etc.), it is possible for the proposed power collection system to be designed in such a way that, at the power collection site, it is compact enough to be installed in the tower or nacelle of an individual turbine. This allows the generated power to be collected directly from the DC bus of a fully rated converter and stepped up to a predetermined HVDC level. Therefore, individual turbine outputs can be coupled together and transmitted in HVDC form. This could potentially remove the need of the offshore substation and reduce the cable losses incurred in conventional wind farm power collection and distribution. A simplified system block diagram for the proposed HVDC system is shown in Figure 3. Note that this system is mainly focused on wind turbines with a fully rated converter as the interface (and another potential application is a medium size solar plant).

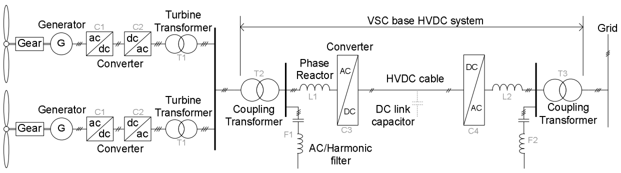

Figure 2: Existing VSC-HVDC block diagram

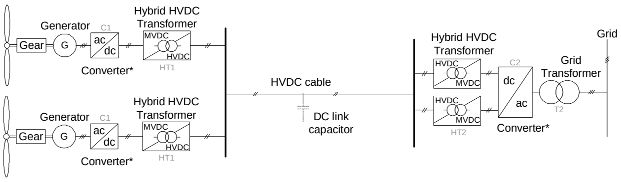

Figure 3: HVDC grid connection using proposed hybrid HVDC transformer

At the generator end of the suggested topology, the MVDC voltage from the 'in turbine' MV converter will be conditioned and stepped up via the proposed hybrid HVDC transformer to a level that is suitable to for interfacing onto the local HVDC network. At the receiving end of the HVDC line, the proposed hybrid HVDC transformer with reversed operation could be used to convert and step down the HVDC to a suitable MVDC level. This MVDC can then be connected to a commercially available grid connection MV inverter. Alternatively, a conventional HVDC grid connection converter can be used as an interface to the AC grid.

Unlike the neutral-point clamp (NPC) HV converter that has been used in many of the existing HVDC systems, in the proposed system, series connected power semiconductor devices (e.g. IGBTs, IGCTs, etc.) are suggested to withstand the voltage stress in the HV section. This allows all the switching devices to be treated as a single module by the gate drivers and allows use of simpler switching algorithm to minimise false firing. In addition, the use of force commutated devices allows additional protection functions to be built in.

The proposed system, in principle, will have the following advantages compared to the existing HVDC systems:

- Highly flexible system that can accommodate various voltage and power levels (with modular design)Allows the use of off the shelf inverters/converters
- Reduced transformer costs
- Potentially lower harmonic distortion hence a potentially reduced harmonic filter cost
- Potentially eliminates/minimises the need of offshore substation

Figure 4 shows the simplified schematic for the proposed hybrid transformer. Maximum voltage level in this case, with $n = 4$, will be lower than 24kV. 150kV require $n > 30$. Here, n equals the number of series connected power switching devices in half of the bridge arm. The number of series connected devices is proportional to the HV level voltage; the higher the HV voltage, the higher the n. Use of a 3-phase, 2 (or multi) level converter topology, as previously mentioned, in modern VSC-based HVDC converters, implies that $6n$ switching devices will be required to withstand the high voltage stress on both sides of the bridge. In the proposed system, the converter will only require $4n+8$ switching devices. This assumes that 2 series cascaded switching devices will be sufficient to withstand the MV voltage stress (e.g. $\leq$ 6kVdc) on one side of the bridge. . For example, more than 30-off6.5kV rated switching devices (n >30) will be required to be connected in series to withstand a 150kV dc voltage. Therefore, for systems using 6.5kV switching devices, to achieve 150kVdc, a minimum of 180 switching devices will be required in existing modern VSD-base HVDC systems. However, the proposed system requires only 128 switching devices, which is about a 29% saving in power semiconductors used. Figure 5 shows the power semiconductor component count comparisons between the existing VSC-based HVDC system and the proposed hybrid HVDC transformer at different voltage levels.

The hybrid transformer based on dual active bridge topology is shown in Figure 6, as an example 6 IGBTs were modelled hypothetically on each bridge arm to achieve bi-directional power flow operation. It was modelled using MATLAB/Simulink. For simplicity and to reduce the simulation time, the magnetic coupling transformer was simplified (i.e. step up ratio of 1:1 was used) and a low value inductor (L_l) was used to model the leakage inductance for coupling purposes. The method to determine the number of required switching components was mentioned earlier. The IGBT model used was based on the ABB HV IGBT - 5SNA 0750G650300, which has 6.5kV voltage and 750A steady state current ratings. Capacitors, C1 and C2 were modelled using a constant voltage source and the snubber circuits used in both the HV and MV side were identical. The model was operated in an open loop condition with both a manually adjustable voltage displacement angle (δ) and amplitude (v_a & v_b) to achieve the desired active and reactive power flow.

In operation, proposed hybrid HVDC transformer will be controlled to maintain the voltage level by changing the amount of power flowing through the transformer. With reference to Figure 6, the generator side converter (C1) will extract the generated power by carrying out the wind turbine MPPT control. When wind speed changes, power extracted by C1 will change and this will reflect on the voltage level at the DC side of C1, where the Hybrid Transformer 1 (HT1) MVDC is connected. HT1 responsibility is to maintain the MVDC level by either controlling the power transfer to the HVDC side. Hybrid Transformer 2 (HT2) that is connected to the AC grid will be controlled to maintain the voltage level at the HVDC grid. This can be achieved by controlling the amount of power being exported to the AC grid. Grid converter (C2), as a common industrial practice, will have the control mechanism to maintain its DC voltage level. Excessive power that causes the increase of the C2 DC link voltage will be delivered to the connected grid. In reality, depends on the power level and design requirement, multiple HT2 can be replaced by a conventional VSC based at the ac grid end.

Control algorithms mentioned above are the local control for the individual hybrid HVDC transformer. To form a HVDC grid, a system or grid level control is required to establish the communication amongst the HT1 and HT2 or grid side HVDC converters. This allows power demand to be sent to determine the level of power that HT2 should export to the AC grid. An overall system DC voltage supervisory mechanism will be required for this level of control to be performed.

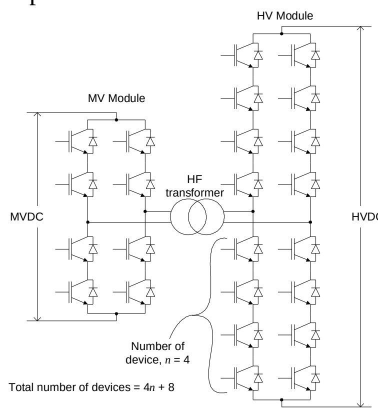

Figure 4: Simplified hybrid HVDC transformer schematic

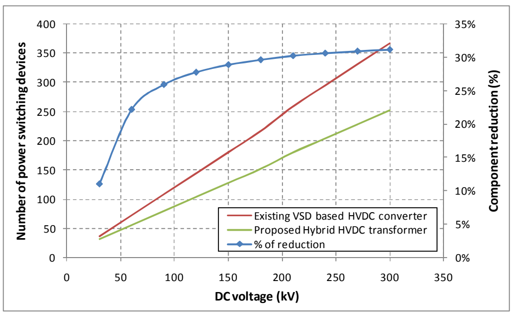

Figure 5: Component count comparisons

CONCLUSION

Conclusions in several aspects of the proposed concept have been made from the above system and component level studies.

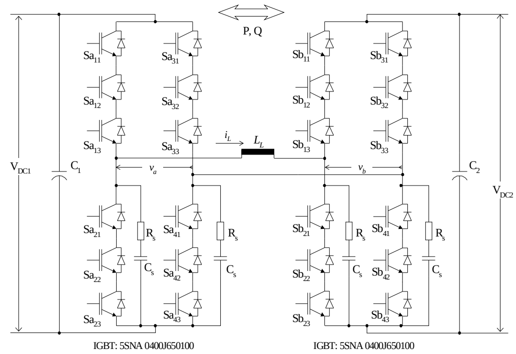

Figure 6: Schematic for the modelled hybrid HVDC transformer

For renewable energy applications, as an alternative to the single line, i.e. point to point, bulk capacity power transmission topology used in the existing HVDC systems, the proposed hybrid HVDC topology is suggested as a suitable installation in every single power source (e.g. large wind turbine, medium PV site, etc.). This will significantly increase the flexibility and redundancy of the entire HVDC system. With the same volume of power, the cost of the power block (e.g. transformer, switching devices, etc.) should remain at a similar level in both HVDC systems. For example, it is predicted that a 100MW power block in conventional VSC-based systems and 20 x 5MW power blocks in the proposed system will have very similar costs. It is also predicted that additional manufacturing, installation and unit costs of multiple controllers, multiple DAQ, additional communication requirements, multiple special high frequency magnetic transformers and rare HVDC breakers can be balanced out with the savings gained by minimising the need of offshore substations, the use of fewer power semiconductors, the removal of ac filters and the use of less copper. In addition, unique features such as greater flexibility, higher redundancy, higher system availability, higher system reliability and potentially better efficiency should all produce a positive impact on the O&M costs of these renewable energy applications in the long run.

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