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Flexible HVDC Transformer for Next Generation Renewable Energy Industry

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Abstract: The growing demand on non-fossil fuel energy has escalated the desire for mega-scale renewable energy power generation, which can no longer be satisfied solely by relying on onshore renewable energy power plants. Outcomes from a recent project funded by the Sixth European Union Framework Programme (FP6), Project "Upwind" concluded that larger offshore wind turbines (i.e., > 10 MW) are feasible and cost effective. It will be beneficial for such 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. Proposed in this paper is a compact and effective hybrid HVDC (high voltage direct current) transformer that allows realisation of a highly robust and financially rewarding next generation multi-terminal HVDC system for future offshore renewable energy power plant. This concept, potentially, allows the elimination or minimisation of the need for a centralised local offshore HVDC platform or substation in each wind farm, solar farm, or tidal farm. This paper discusses the study outcome of the proposed hybrid HVDC transformer and the application of a multi-terminal HVDC system in the renewable energy industry, compared to the existing HVAC and VSC (voltage source converters) type HVDC systems.

Key words: HVDC, wind, power, offshore, substation, PV (photovoltaic), VSC.

1. 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.). With lower copper and eddy current losses, HVDC (high voltage direct current) power transmission systems potentially give a better efficiency. 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 [1, 2]. The down trend in power semiconductor costs (i.e., £/Watt) and the predicted up trend in copper costs, see Fig. 1, has also stimulated the need for further HVDC power transmission development.

Referring the conceptual information from the TREC UK (Trans Mediterranean Renewable Energy Co-operation); large scale renewable energy generated from CSP (concentrated solar power) plants in the Middle East and North Africa, together with other wind farms along the transmission link, will transmit high levels of green energy back to Europe via super HVDC links across the Mediterranean (DESERTEC) [3]. A number of other SuperGrid concepts have also been proposed by various players and organisations. As a product developed in the pre-DG (distributed generation) era, instead of forming a multi-node complex transmission and distribution network, existing HVDC systems in general are designed to transmit large scale power (i.e., > 1 GW) in a single point to point configuration. Although, in principle, some

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Source: www.infomine.com (12 Nov 2009)

Fig. 1 10-year copper price (1999-2009).

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 as the backbone of the SuperGrid to transmit high power over very long distances (i.e., > 1,000 km). In renewable energy power generation, especially offshore wind, generating farms are formed by multiple small scale power generators (i.e., < 10 MW wind turbines). Outcomes from a recent project funded by the Sixth European Union Framework Programme (FP6), Project "Upwind" concluded that there are benefits in developing next generation, larger offshore wind turbines in the 10-20 MW power range [4]. The investigation concluded that this is feasible and offers an opportunity for a strategically important area. However, existing HVDC configurations are still too bulky and uneconomic, should they be used as the first stage in the farm power collection network. Currently, MV/HV AC systems are generally used to collect power within the farm, and also the transmission network. 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 [5]. In offshore wind, such a substation is and continues to be very costly to build and maintain.

Many (i.e., > 80%) of the existing large scale wind turbines (i.e., > 5 MW) utilise fully rated MV (medium voltage) converters as grid interface. In wind power generation, it is important to maintain both power generation control (e.g., maximum power point tracking and stability control) and grid connection quality (e.g., harmonic distortion, radio frequency interference and reactive power compensation) of each individual wind turbine. Modern MV power converters (e.g., variable speed drives, active rectifiers and inverters) are sophisticated, reliable in many onshore applications and are considered suitable for offshore applications. They have been widely used in the renewable energy industry to achieve these objectives.

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. This paper predominantly focuses on the system concept and its pros and cons compared to existing HVDC systems. Details of the control and results of the simulation are planned to be published separately.

2. Existing HVAC Transmission Systems in Offshore Power Plants

The vast majority of the generation, transmission, distribution and high level consumption of electrical power is in the form of AC. 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.

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 Fig. 2. The most cost effective interconnecting AC cables to date are solid dielectric cables e.g., XLPE (cross linked polyethylene) insulated cable. Most of the recent deployed offshore wind farms transmit power to shore at a higher voltage level, i.e., ≥ 132 kV, compared to the inter-array cabling and turbine export voltage i.e., ≥ 33 kV. However, with the increased generating capacity, use of submarine cables at this voltage level introduces high line losses and excessive voltage drops. As a result, multiple submarine cables would be required. Therefore, there is an intention in the offshore wind industry to increase the substation to substation voltage to a higher level.

Unlike air insulated overhead lines and HVDC cable, the capacitive component in the HVAC cable plays a major role in limiting, both technically and economically, the feasible length of the HVAC power transmission line. The cable capacitive component causes charging current to flow unevenly along the length of the cable. Because the cable must carry the charging current as well as the useful load current, the physical load-carrying capability of the cable will be compromised. 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:

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

C_{cable} (cable capacitance) 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:

$$I_p = \left(I_T^{\ 2} - I_C^{\ 2}\right)^{1/2} \tag{2}$$

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.

The above mentioned factors must be taken into account in the design of the high voltage AC terminal substation equipment; the longer the cable, the more challenging and costly it becomes to obtain satisfactory design solutions that would not significantly disrupt or diminish transmission capacity and reliability of the overland transmission system.

3. Existing HVDC Systems

From a HVDC perspective, the point to point HVDC power transmission method is the only currently available alternative to the HVAC (high voltage AC) systems used to connect offshore wind farms to the grid. 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 at high voltage using "cable only" connections. HVDC transmission systems can be categorised, by the converters used, into three categories:

- LCC (line-commutated converters);

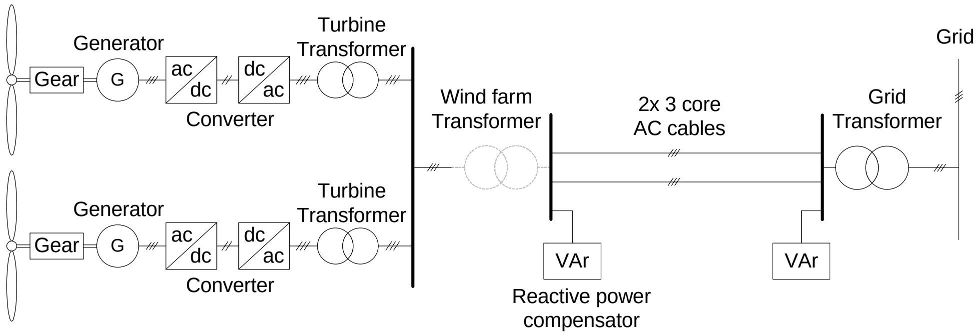

Fig. 2 Typical offshore wind AC grid connection.

- CCC (capacitor commutated converters);
- VSC (voltage source converters);

Line commutated devices (e.g., thyristors) are used in the LCC based HVDC system to control the voltage level and power flow. These types of system were used in the early days (i.e., 1970s, 1980s) when high power self-commutated power devices (e.g., IGBTs, IGCTs, etc.) were not available and they were usually referred to in many articles as “classic HVDC systems”. One of the biggest disadvantages of the LCC based HVDC system is its reactive power requirement, which can be more than 50% of the active power rating; though actual reactive power absorption depends upon the power flow level. Another issue with the LCC-based HVDC system is that, to avoid commutation failure, it is not suitable for connecting to weak AC grids.

The CCC-based HVDC system is an evolved version of the LCC-based HVDC system, with series capacitors coupled between the converter transformer and the thyristor-bridge. The series coupled capacitors compensate the inductive factor of the line commutated converter to reduce the reactive power requirement and lower the risk of commutation failure when compared with the LCC-based HVDC design. However, due to the lack of popularity, there are not many developments using this 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. However, this does come with at an increased converter cost and with potentially higher converter losses. In general, IGBTs (insulated gate bipolar transistors) 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 [6]. 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 Iwamuro [7] shows the technology improvement in power semiconductors over a 20 year period, which matches the above 60% improvement claim. A comparison of LCC-HVDC and VSC-based HVDC systems is given in Table 1 [8].

In general, the core characteristics of the existing VSC based HVDC systems are very similar. Converters used in these systems utilise two-level three-phase bridges with multiple valves, each consisting of series-connected semiconductor switching devices (i.e., IGBTs). Fig. 3 shows the block diagram for the existing VSC-based HVDC systems.

Table 1 Comparison of LCC-based HVDC and VSC-based HVDC systems.

	LCC-based HVDC	VSC-based HVDC
Size range for single convertor	150-1,500 MW	50-550 MW
Convertor/semiconductor technology	Line-commutated, Thyristor	Self-commutated, IGBT
Relative volume	1	1/6-1/4
Type of cable	Mass Impregnated Paper Oil/Paper	XLPE
Control of active power	Yes	Yes
Control of reactive power	No (only switched regulation)	Yes, continuous control
Voltage regulation	Limited	Extensive
Fault ride-through	No	Yes
Black start capability	No	Yes
Minimum short circuit capability in AC grid	> 2.0 × rated power	No requirement
Power reversal without interruption	No	Yes
Backup generator needed on off-shore platform for black start	Yes	No requirement
Minimum DC power flow	5%-10% of rated power	No minimum DC power
Typical losses per convertor	0.8%	1.6%
Operating experience	> 20 years	< 15 years
Operating experience off-shore	No	Yes

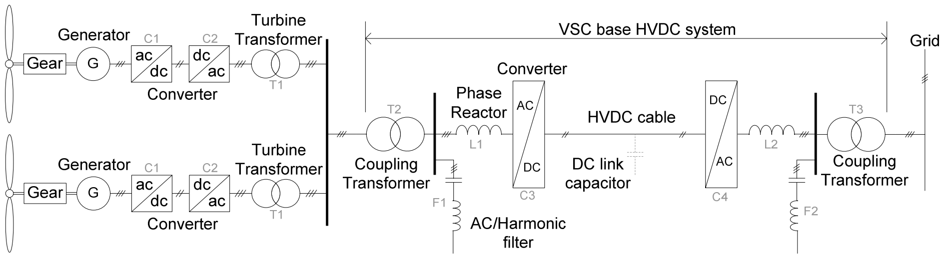

Fig. 3 Existing VSC-HVDC block diagram.

4. Proposed System Compared to the Existing 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 system block diagram for the proposed HVDC system is shown in Fig. 4. It is noted 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).

Fig. 5 demonstrates one of the possible connection options that could complement the above mentioned HVDC Supergrid concept. 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

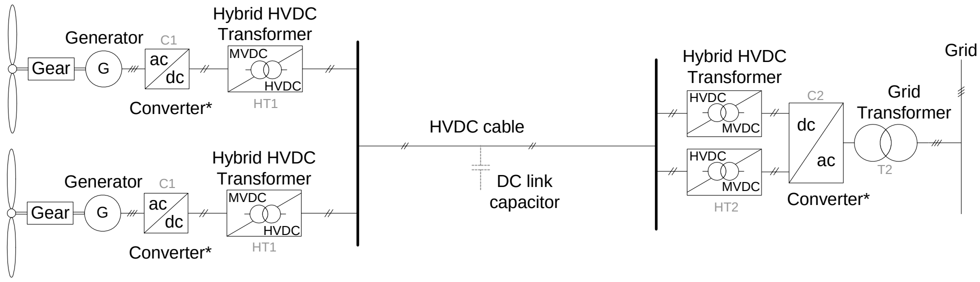

Fig. 4 HVDC grid connection using proposed hybrid HVDC transformer.

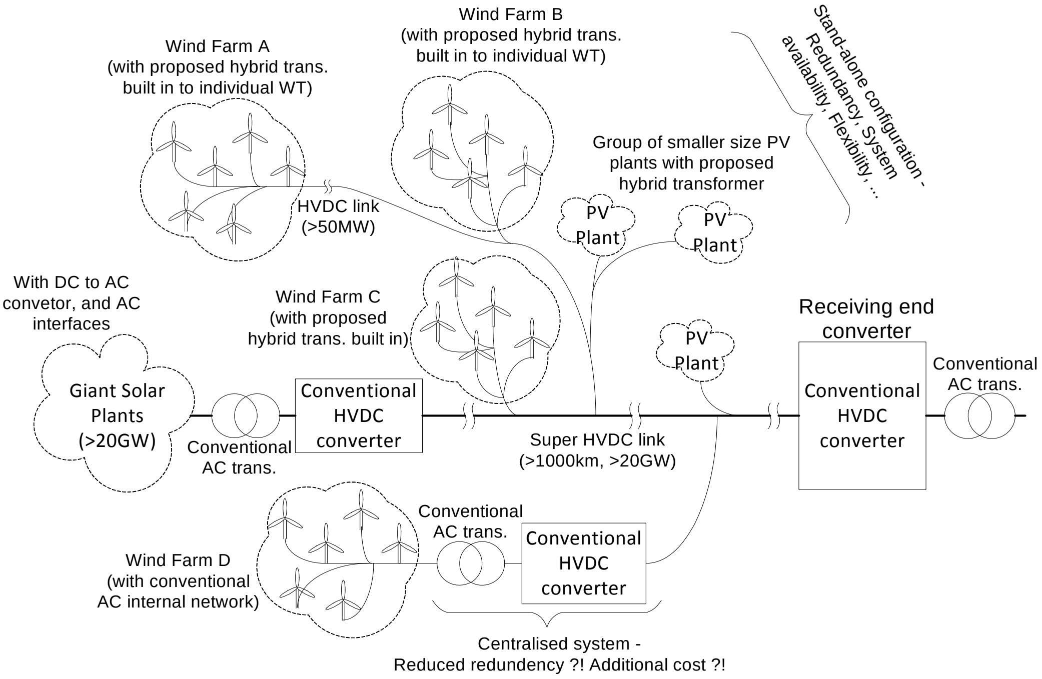

Fig. 5 Proposed HVDC hybrid transformer incorporated into a supergrid link.

down the HVDC to a suitable MVDC level. This MVDC can then be connected to a commercially available grid connection MV inverter. Unlike the NPC (neutral-point clamp) 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 AC and DC systems:

Advantages over AC (including HVAC) systems:

- higher efficiency power transmission system;
- lower cabling cost;
- minimum electromagnetic interference;
- low/minimum reactive power compensation;
- minimum visual impact (with underground cable power transmission);
- cost distribution weighted towards semiconductor, versus copper, gives potential future savings.

Advantages over 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.

Fig. 6 shows the simplified schematic for the proposed hybrid transformer. Maximum voltage level in this case, with $n = 4$, will be lower than 24 kV. 150 kV 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 two series cascaded switching devices will be sufficient to withstand the MV voltage stress (e.g., ≤ 6 kV dc) on one side of the bridge. For example, more than 30-off 6.5 kV rated switching devices ($n > 30$) will be required to be connected in series to withstand a 150 kV dc voltage. Therefore, for systems using 6.5 kV switching devices, to achieve 150 kV dc, 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. Fig. 7 shows the power semiconductor component count comparisons between the existing VSC-based HVDC system and the proposed hybrid HVDC transformer at different voltage levels.

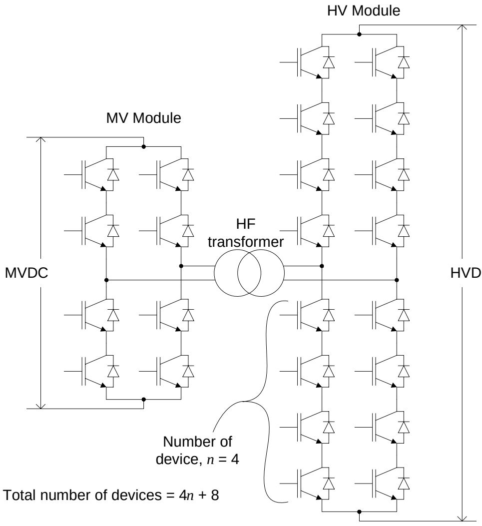

Fig. 6 **Simplified hybrid HVDC transformer schematic.**

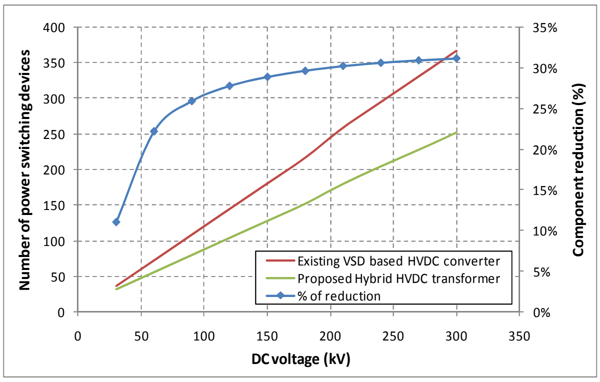

Fig. 7 **Component count comparisons.**

The hybrid transformer based on dual active bridge topology is shown in Fig. 8, 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 6.5 kV voltage and 750 A 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. The gatting sequence is illustrated in Fig. 9, but the focus of this paper is the overall system concept. It is planned to publish the results of the simulation in separate publications.

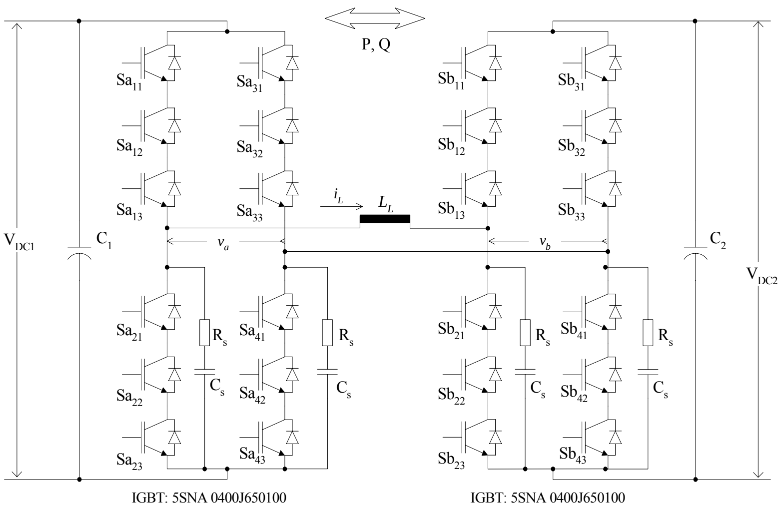

Fig. 8 Schematic for the modelled hybrid HVDC transformer.

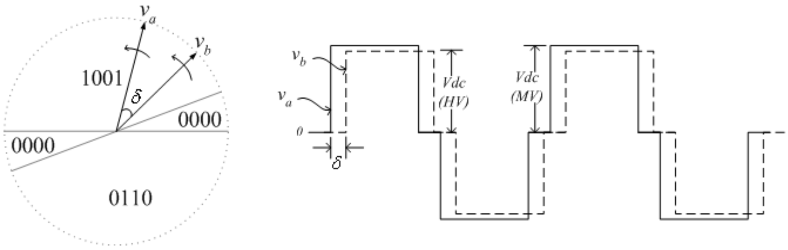

Fig. 9 Suggested operating principle of the proposed hybrid transformer (both bridges).

Table 2 Conventional VSC HVDC system compared to the proposed system.

Item	Conventional VSC HVDC	Proposed HVDC
Offshore substation requirement	100%	0%-25%
Power semiconductor device requirement	100%	70%
Magnetic transformer size (m^3/MW)	100%	22%
AC filters requirement	100%	0%
AC reactor requirement	100%	0%
Multipoint power distribution	No/Maybe	Yes
Flexibility (overall system configuration)	No	Yes
Redundancy	Low	Very high
Overall system availability	High	Very high
Efficiency	94%*	95% ± 1.5% (est)**
PV site direct connection	No	Yes

*Efficiency of the ABB's Murraylink project in Australia.

**Assumes part of the power losses can be used to power the auxiliary circuits and turbine utilities.

5. Conclusions

Conclusions in several aspects of the proposed concept have been made from the above system and component level studies. A summary table, Table 2, is included at the end of this paper to show the comparisons between existing HVDC systems and the proposed concept.

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 100 MW power block in conventional VSC-based systems and 20 × 5 MW 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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