System Impacts of an Efficient DC-DC Transformer

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SUMMARY

DC's growth has been achieved with neither the availability of nor need for an economic DC-to-DC power transformer (DCT). That's changed with the prospect of major DC Grids overlaying systems in Europe and North America. Apart from the anticipation of DC Grids, a more efficient DC-to-DC power transformer could serve a host of other purposes in the rapid growth of dc as a form of energy delivery, utilization, and even generation. For example, dc distribution and transmission provides an efficient, cost effective and reliable alternative to traditional ac systems for offshore wind farm integration. High power DC-DC converters are key components to realize future offshore DC Grids and multi-terminal HVDC systems.

This paper outlines the requirements of a dc transformer capable of functioning, within a dc system, in a manner analogous the manner in which an ac transformer functions within an ac system – in the latter case where flow is driven largely by phase angle and in the former largely by voltage difference. System operation is simplified for most applications if a DCT transfers power according to the requirements of the network without any closed loop power controller. However a DCT should also be able to regulate the power flow within large DC Grids like phase shifting transformers does in ac grids. It should also be able to interconnect dc systems with different grounding conventions and the ability to link older LLC-based systems in which flow reversal is achieved with polarity reversal to modern VSC-based systems of constant polarity and reversible current.

Alternative approaches to DC-DC transformer designs are discussed, as is a novel capacitor-based dc power transformer which meets the functional equivalence criteria cited above.

KEY WORDS

HVDC, DC grids, DC Transformers

1. SYSTEM ROLES FOR AN EFFICIENT DC-DC TRANSFORMER

DC's reintroduction as a means of power transmission in 1954 marked the beginning of a steady progression of HVDC applications, that growth driven by continuing advances in dc technology to the point where terminals are more compact and, once a consumer of reactive power are now a supplier and potential regulator of quadrature power – a principle regulator of power flow within ac systems.

The need for dc transformation first became apparent in the planning of large DC Grids for eventual overlay of ac systems in Europe and North America [1]-[4]. Major existing dc links will often have to be electrically linked to or integrated into the grid, requiring transformation between lines of differing grounding systems and commutation technology. Grid-based dc lines will also impose new flow distribution and voltage boost requirements which, if needed within an ac system would be satisfied by phase-shifting transformers or auto transformers.

In the rapid growth of dc as a form of energy delivery, utilization, and even generation, a more efficient DCT could facilitate the interconnection of wind farms and solar plants to the DC Grid. An economic DCT may expand the role of dc systems themselves by making lower power taps more economic. It is currently extremely expensive, in $/MW, to tap the highest voltage dc lines for relatively modest levels of power. An economic DCT will allow reduction in dc voltage to a level where conversion to ac is economic.

Efficient, bilateral dc transformation may also extend dc's role downward in voltage well below the HVDC transmission level. The case for making micro-grids dc rather than ac is growing in strength as the fraction of dc load in households and businesses approaches the ac fraction and as solar (inherently dc) becomes a larger contributor to the energy mix. Dc energy storage stations, now reaching the hundreds of MW level, may eventually be more efficiently tied to the DC Grid by DCT's.

2. OVERVIEW OF DCT ALTERNATIVES

Buck and boost converters are the most widely used DCTs for low power applications [5]. They transfer energy from input to output with a high frequency PWM technique by means of an inductor, either as voltage step-up or step-down. Since power transfer between dc circuits is discontinuous, input and output require significant filtering. Furthermore components must be rated at maximum instantaneous value of the input and output voltage and current, resulting in higher component ratings and costs. Operation depends on both electromagnetic and electrostatic storage of energy which requires a large number of components as well. Elements can be reduced in size by raising frequency, but at the cost of higher losses. A boost converter can theoretically achieve infinite voltage conversion ratios but in practice the maximum is limited by circuit imperfections, such as parasitic elements and switch commutation times. Moreover, under light loads the output voltage is not a linear function of the input voltage and depends on many other converter parameters.

Most of the previously proposed DCTs for HVDC applications, e.g. [4], [6], [7], have been based on a two stage DC-AC-DC conversion topology. This "Front-to Front" configuration has DC-AC-DC converters between which is an ac transformer. For low voltage ratios, such converters can be designed to operate without an ac transformer [4]. Since the ac link in such a scheme is not connected to the ac grid, the operating frequency can be selected freely, trading off between reduced volume of the passive components and higher losses in the semiconductor switches. While the transformer in this scheme provides galvanic separation between the two dc connections, both converters and the transformer must be rated for full dc power, thus resulting in additional losses. The Front-to-Front DCT also requires a large footprint.

To reduce the size of the offshore platforms for wind farm application, a modular front-to-front converter comprising many low-power sub-converters has been proposed [8]. In this scheme the isolated sub-converters are connected in parallel on the low voltage side and in series on high voltage sides. However the proposed scheme requires a complex control system as well as ac transformers rated for the high-side voltage.

One proposed DCT scheme emulates an ac auto transformer [9]. It consists of two series-connected VSC converters where the sum of both dc voltages forms the high level dc voltage and the lower sub-converter forms the low level dc voltage. Both sub-converters are interconnected through an ac link, usually an ac transformer, in order to transfer energy between the upper and the lower converters. The overall sub-converter voltage ratings must be higher than the dc link voltage in order to clear a dc fault. This scheme does not provide galvanic isolation between dc nodes, and it is not capable of connecting LLC to VSC links.

Recent interest has focused on in compact high power DCTs that require no ac transformer. Many use switched capacitor (SC) topologies, commonly used in electronics applications.
Topologies of that kind include a ladder-based resonant SC converter and a Symmetrical Multilevel Modular SC converter (SMMSCC) [10]. The Ladder topology has the lowest individual switch voltage rating, but also has low efficiency. The best topology in terms of component volt-amp requirements and efficiency is the SMMSCC converter. However, it is not capable of having both the converter input and output voltages referenced to ground at the same time. In addition unlike the Ladder circuit, the minimum voltage rating of individual switches is twice the converter input voltage and it requires an external power control signal [10].

Another soft-switched, resonant, transformer-less, step-up DC-DC converter has been proposed in [11] for high power applications. The switches in this converter are thyristors and operate under zero current switching so that switching losses of this converter are relatively low. However, the low voltage side thyristors operate at the same voltage rating as the high voltage side. It also requires a complex control system [12].

3. COORDINATION OF CONTROLS IN DC GRID

DC voltages at various nodes on a dc system fulfil a function analogous to phase angle at busbars in an ac system: When the power input in the DC Grid rises, dc capacitors are charged and the dc voltage will rise. The reverse is true when power input drops. Dc voltage is an indicator of power balance in the dc system just as phase angle is within an ac system. [13].

The objective of power flow control in a DC Grid, as in point-to-point transmission, concerns the dc voltage control in the dc system and the power through each converter, which is the power exchange between ac and dc systems. Indirectly the branch powers are thereby controlled in order to prevent over currents through the valves, lines or cables. Several proposals for this purpose can be found in [14]-[17], all of them presenting various advantages and disadvantages.

VSC dc links provide much greater flexibility than either LCC or ac alternatives. The VSC provides for bidirectional reactive power exchange with the ac system by controlling the phase angle δ and amplitude of the VSC ac output voltage in relation to the voltage of the ac system. However VSC applications require layers of decoupled closed loop voltage and current controllers to control the selected ac operating variable (either ac voltage or reactive power) and one dc operating variable (either dc voltage or dc power) independently at the same time. Fast dc system dynamics and the non-linear behavior of the converters make it complex to acquire a stable system and make the control robust and useful in practice [18].

Thus a great deal of research on hierarchical control topics is needed to assure satisfactory operation of DC Grids, still requiring a lot of research on the topics related to hierarchical control. Coordinating controls among each tie point of a DC Grid to the local ac system will be a challenge in its own right but substantially simpler if dc transformers within or connected to the grid respond to grid voltage rather than signals from grid control. CIGRE study committee B4 has several working groups studying DC Grid systems, each using a hypothetical DC Grid test system [19]. In this system a DC-DC converter connects two dc lines rated 400V and 800 kV respectively. In the CIGRE simulation case the DC-DC converter is modeled as an ideal mathematical transformer that does not have any physical equivalent and requires no power order.

All the DCT schemes cited in section 2 above depend on power order and internal power controllers which will result in complex control interactions between the dc converter and the converter terminals of the effected dc lines. The operational disadvantage introduced by that controller requirement becomes apparent when, in contemplating DC Grid operation, one realizes that, besides the control of voltage and the current through the converters in DC Grid, the branch powers also need to be measured and controlled. Grid-based dc lines will also impose new flow distribution and voltage boost requirements which, if needed within an ac system would be satisfied by phase-shifting transformers or auto transformers but in a dc grid must also be served by a DCT function.

4. CHALLENGES FOR OFFSHORE WIND FARMS

Worldwide interest in and demand for renewable energy sources has increased dramatically, a demand which has also led to new applications for DCTs. Offshore wind farms benefit from more consistent winds found over the oceans. Locating wind turbines offshore also overcomes the problems of acoustic noise and adverse visual impact. It is now becoming apparent that, for large offshore wind farms dc can offer major cost advantages both within the wind-farm itself and in transmission of power to the land-based network.

Currently the most advanced wind turbine (WT) architecture consists of an ac generator with a back to back AC-DC-AC converter that generates a synchronous ac output waveform. An ac collector system then aggregates power generated by each wind turbine. However to gain the advantage of dc cable transmission to shore for longer distances, ac power must then again be collected and converted to dc for transmission to shore and eventual reconversion to ac for connection to the local ac grid. Consideration must also be given for space, weight, and cost issues related to the converter to which it is connected. Furthermore the AC-DC-AC converters associated with WTs and those used for HVDC transmission are usually designed by different manufacturers – each with its own controller system and harmonic characteristics, the separate and proprietary nature of which makes good overall WT performance difficult to assure. In the case where ac collector-level power is again converted to dc for transmission to shore, reactive power must be supplied to those ac cables. Shunt reactors may be needed to compensate ac cable charging capacitance. Moreover, high levels of capacitance and inductance, coupled with the lack of sufficient damping in the offshore ac collector system may lead to over-voltages caused by resonance phenomena [4], [20].

If the offshore power collector system is *itself* made dc, the difficulties cited above are overcome. The system is more stable, the number of AC-DC-AC conversions, including their losses is reduced, and the cost of WT collector cable interconnection is also lower. But a dc power collecter system requires that wind turbines have dc voltage at their output terminals. Many such configurations have been suggested [10]. Although the dc transformer candidate for this application should achieve a reduction in size, weight, and cost of offshore platforms, it should not add complexity to power flow control in offshore transmission systems [20].

5. Dc GRID PROTECTION

Short circuit faults on an HVDC transmission line or within a substation may be through either low or high fault impedance, between pole and ground, between two poles or between two poles and ground. The protection system must detect and isolate any such fault accurately within the required time frame, protecting both the system and its users against damages while providing maximum continuity in delivered energy.

The protection for DC Grid systems is much more challenging than for ac systems. In ac systems network impedance is highly reactive, thus limiting the rate of the rise of the fault current. Within a DC Grid, all sources and energy storage units, e.g., filters, dc link capacitors, cable and line capacitance and the ac system, contribute to the total fault current. Consequently, there is very little time to prevent high over-currents before completing the protection actions. Moreover, load switches, circuit breakers, and fuses that are used for ac grids operate based on the zero crossing of the AC current and are therefore not suitable for dc current interruption. Fast DC breakers capable of interrupting high dc currents are bulky and very expensive. As a consequence it is important that DCTs not increase exposure to faults and, in the case of offshore wind farms where high speed dc breakers are currently impractical, that faults be accommodated without them.

6. COUPLING LINES DIFFERING IN GROUNDING & COMMUTATION SYSTEMS

While an efficient DCT should emulate the role of a magnetic transformer within an ac system, the latter has an easier job since all ac systems share a common frequency and phase count. DC systems differ in grounding and differ in commutation systems, with LCC systems having to reverse voltage in order to reverse power flow.

Most HVDC transmission systems are comprised either of monopoles or bipoles, each having specific advantages and disadvantages. The bipole configuration, for example, requires a metallic return to retain fifty percent of its capacity during a line-to-ground fault. Redundancy can be achieved with the monopole only if it's comprised of two independent monopoles using four conductors [21]. The VSC symmetrical monopole on the other hand needs only two conductors but loses full capacity under the same fault condition. It is possible for the VSC symmetrical monopole to be grounded though a very high resistance, so that a line-to-ground fault produces almost no fault current. It is anticipated that some non-permanent faults, such as lightning, may clear themselves when fault current through the arc is very low. In that case load current and pole-to-pole voltage remains unchanged and little or no power transfer is lost. During such faults on high impedance grounded symmetrical monopole transmission, voltage on the un-faulted pole rises to twice rated unless a novel dc side voltage reduction method is used [22]. A dc-to-dc transformation system interconnecting symmetrical monopole and bipole HVDC lines should ideally allow each to retain its inherent advantages as cited above.

7. A PROPOSED DC TRANSFORMER CONFIGURATION

The authors' search for a DCT functionally analogous within a dc system to the ac magnetic transformer in an ac system, began with review of the vast field of technology within the electronic industry where transformer-less dc-to-dc conversion is common but subject to dramatically different constraints. At power levels losses are an economic penalty rather than a heating limitation. Insulation, a minor issue at electronic voltages, is critical at high voltages. Even the availability of components differs.

The elementary configuration of a multi-module DCT (MMDCT) [1] based on resonant transfer of energy between capacitors is shown in fig. 1. Thyristor soft line switches LS1 and LS2 alternate their close-open state, the capacitive column being alternately charged by one bus, and then discharged to the other. Between charging and discharging cycles, some of the capacitors in the column are bypassed so that the voltage presented to the two busses differs. A system for equalizing charge among capacitors during the bypass cycle prevents build-up of imbalance within the column. By using three columns (fig. 2) rather than one, power transfer is tripled while both input and output pulse trains are relatively smooth, usually capable of being adequately filtered by the reactance of attached lines; perhaps with a low-rated line capacitor added [23].

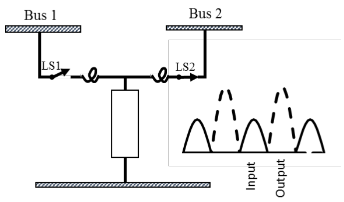

Figure 1. Single Column MMDCT

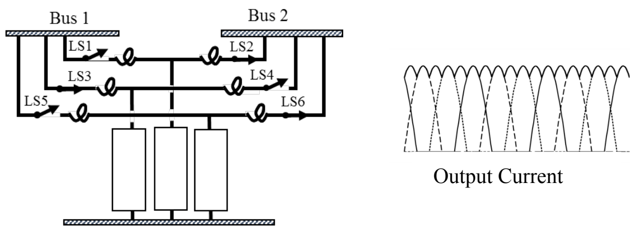

Figure 2. Three Columns MMDCT

Details of operation of the MMDCT, as verified by extensive PSCAD simulations, have shown it to:

1. Transform energy bilaterally
2. Be capable of step-up or step-down operation
3. Be capable of high MW ratings
4. Have efficiency comparable to VSC converters
5. Be capable of regulating flow within a DC Grid by adjusting the voltage ratio as a phase shifting transformer adjusts phase angle within an ac network
6. Operate (without a power control signal) in response to ΔV just as an ac transformer responds to Δθ.
7. Provide primary-to-secondary fault isolation

[1] *International Patents Pending*

8. Be modular in structure, using existing, commonly applied components and logic.
9. Be capable of interconnected two systems with differing commutation principles and differing grounding systems.

A dc-to-dc transformation system interconnecting symmetrical monopole and bipole HVDC lines should ideally allow each to retain its inherent advantages as cited above. The MMDCT system does so.

During a non-permanent pole-to-earth fault on the symmetrical monopole side, if the pole to pole voltage remains unchanged, there is no effect on the charging or discharging process when the capacitive column is connected to that side. Moreover, the line switches in each MMDCT operate in a complementary manner, i.e. when one is closed the other will always be open. Thus there is always galvanic isolation between the two HVDC lines. Thus the MMDCT does not interrupt power transfer during a temporary pole-to-earth fault on the symmetrical monopole side.

8. CONCLUSIONS

The development of an economic and control-free dc-to-dc transformer will accelerate the change in structure, operation, and modelling challenge for future power delivery systems. Such a transformer must transfer energy between dc systems which differ in grounding systems and/or commutation technology while retaining the intrinsic advantages of the coupled systems. Extensive simulation shows it is possible to meet that challenge.

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