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Importance of DC-DC Transformation in Grids of the Future

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SUMMARY

DC's rapid growth as a medium for power delivery has been driven by economic and functional advantages - both fueled by technical innovations in HVDC conversion technology. DC's role will expand dramatically with the introduction of cost effective HVDC grids, now proposed as overlays to systems both in Europe [1] and by extension into North America. Those grids will improve access to lowest cost and least carbon-intensive energy sources, allow advantages associated with regional diversity in consumption, generation, reliability and frequency control, while simultaneously supporting heavier loading of existing ac lines. But it was recognized at the outset that DC grids will require the dc equivalent of an ac transformer …one that will perform, within a dc system, in a manner analogous the way a magnetic transformer performs within an ac system. Within a DC grid it must:

1. Regulate power flow among lines comprising the grid
2. Boost voltage on long dc segments of the grid
3. Allow economic low-power, bidirectional taps from an HVDC line to underlying ac systems
4. Couple to or integrate within the grid, dc systems of differing grounding and commutation systems

The latter requirement must recognize that line-commutated (LCC) dc systems, which still comprise many of today's installed dc lines, must reverse voltage to reverse load flow while lines comprising a modern VSC-based grid do not. It must also preserve the redundancy characteristic of existing lines as they are coupled to lines of differing grounding and commutation systems.

The need for a dc transformer (DCT) within future HVDC systems has been widely recognized and the subject to numerous recent technical papers. One approach, applications of which are shown in this paper has been validated by detailed simulation to meet all of the demands cited above, to be relatively simple in operation, and to be based on components commonly used in VSC multi-module converter stations.

KEY WORDS

HVDC, HVDC grids, offshore wind farm, DC-to-DC Transformers

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1. DC to DC TRANSFORMATION

Dc-to-dc transformation at high voltage, a requirement which up to now largely limited to industrial uses, has consisted of (1) conversion from dc to ac (2) transformation by an ac transformer and (3) reconversion to a new dc voltage. The need for a simpler, economic, more compact solution became apparent as systems saw the advantages of HVDC grid overlays to ac systems in Europe [1] with North America to follow.

The incentive for an efficient DCT recently become even more apparent (and more immediate) within the off-shore wind farms where, after initial conversion of asynchronous ac to dc, power can be directly transformed to an intermediate dc collector voltage, then to a high dc voltage for transmission to a shore converter station…thus realizing the economics of dc cable transmission and simplifying and reducing the cost of electrical architecture within the wind farm.

The search for an efficient DCT obviously started with attempts to adapt the vast field of experience in direct dc-to-dc transformation within the electronic industry where transformerless dc-to-dc conversion is common but subject to dramatically different constraints. At power levels losses pose a serious 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. Thus began an intense search for a novel power-level DCT which has resulted in a number of proposals, examples of which include:

- Adaptation of series charge – parallel discharge principle [2]
- A "Front-to-Front system in which the classical dc-to-ac-to dc scheme is made to function without an intervening transformer [3]
- A capacitive-based system in which a capacitive column segment is made to act in a manner analogous to the teaser winding on an auto transformer [4]
- Transformation of the ac output of each offshore wind turbine generator to medium voltage ac and rectify to medium voltage dc and aggregate onto feeders that terminate at a dc to ac inverter [5]. This option would need a DCT on a platform when distance from wind farm to inverter with many medium voltage dc cable feeders is uneconomical.
- Capacitive columns with special bypass logic, controlled to transfer charge between dc busses in a non-resonant manner [6]
- A system which injects a series voltage in a dc line to control current flow under study by CIGRE Working Group B4.58: "Devices for Load Flow Control and Methodologies for Direct Voltage Control in a Meshed HVDC Grid."
- A resonant capacitive charge exchange system depending on capacitor bypass actions to achieve transformation (MMDCT) [7].

The latter system will be cited here as a basis for illustrating how direct capacitor-based transformation of dc can be achieved and applied within dc systems, including the transformation between dc systems having differing grounding and commutation systems.

2. MMDCT SYSTEM

The elementary configuration of a multi-module DCT (MMDCT) [1] based on resonant transfer of energy between capacitors is shown in Fig. 1. Line switches alternate close-open position, the capacitive column being alternately charged by one bus, then discharged to the other. Between charging and discharging cycles, some of the capacitors in the column are bypassed so that the voltage

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[1] *International Patent Pending*

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 adequately filtered by the reactance of attached lines.

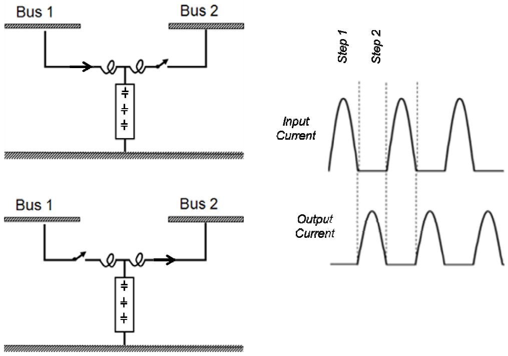


Figure 1 – MMDCT Transfer principles

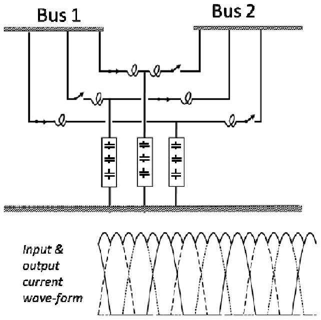


Figure 2 – triple-Column MMDCT

Details of operation of the MMDCT, as verified by extensive PSCAD simulation, 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 converter bridges
5. Be capable of regulating flow within a dc grid as a phase shifting transformer does 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
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.

3. APPLICATIONS

In development of the MMDCT, initial Excel models capable of simulating inter-capacitor and bus-capacitor energy exchange were followed by PSCAD simulation for a wide variety of applications with various MW ratings ranging up to at least 1,000 MW. The latter have shown this DCT to meet the nine requirements cited above. Examples include:

3.1 HVDC Grid interconnection

Several CIGRE SC B4 working groups studying dc grid systems, use the hypothetical dc grid test system of Fig. 3 in which a DCT connects two dc lines rated 400V and 800 kV respectively [8]. In the CIGRE simulation case the dc-dc converter is modeled as an ideal mathematical transformer without any physical equivalent [8]. Voltage and current profiles resulting from PSCAD simulation of

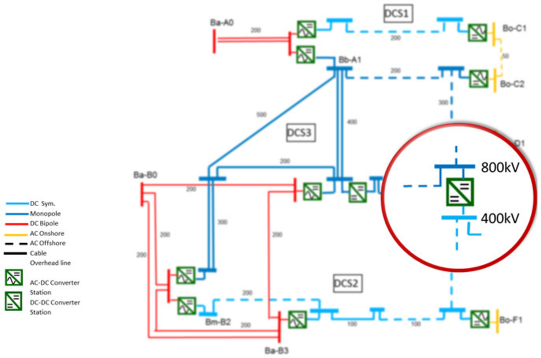


Figure 3 CIGRE B4 DC grid test model

the MMDCT are identical to those developed using the CIGRE Model. A number of other Grid applications have also been successfully simulated include those achieving flow control and/or voltage boosting within a dc grid.

The complexity of power control within a dc grid, a daunting challenge in its own right, is exacerbated if each transformer within that grid must also be provided a control signal. Such a signal is not required with the MMDCT which responds to ΔV in a manner analogous to Δθ within an ac system.

3.2 Simplification of Offshore Wind Farm electrical architecture

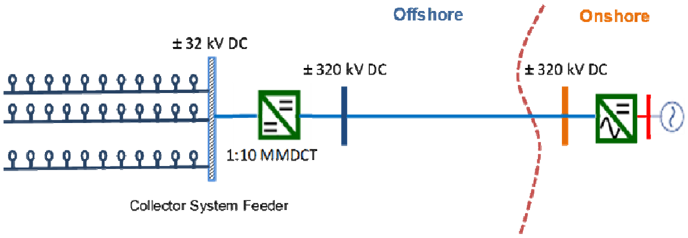


Figure 4 DC architecture for wind-farms

It is now common to rectify to dc the asynchronous ac output of variable speed wind turbines – then reconverted that dc to ac to achieve a synchronous profile. The MMDCT allows direct step-up of the initial dc voltage to a higher voltage (32 kV in the example of Fig. 4) without using an ac transformer and ultimately to a dc transmission voltage appropriate to delivery of energy to a shore station. This eliminates the weight, footprint and cost of reactive power compensation equipment and magnetic ac transformers both within wind turbines and the offshore platforms. Large offshore wind farms usually cover a wide geographical area. Dc cables are substantially less expensive than similarly rated ac cables for inter-array collection systems. Moreover, the MMDCT's inherent fault isolation capability eliminates the need for DC breakers in the medium voltage DC collector system - currently impractical for this application.

3.3 Microgrids

Microgrids, now likely to become a fundamental future power system building block, will provide a flexible energy resource to further broaden the market for generation, storage, and consumption of electric power while reducing vulnerability to power outages. Originally thought of as an ac entity, growth in the percentage of ultimate load that requires dc, growth in dc point-of-load dc generation, and growth in local storage strongly argues that those microgrids be dc. The coordination between dc microgrids and the overlying system to maximize benefits will create new challenges to grid operators [9]. Regardless of their structure, dc microgrids will create an additional need for efficient DCTs.

3.4. Coupling dc links differing in grounding and commutation

Many of today's operating dc links use line-commutated converters which require that polarity be reversed to change the direction of power flow. Some are grounded bipoles; some symmetrical monopoles. As dc grows in usefulness and geographic spread, the economic and operational incentives for transforming energy from one to another, either within or fed from an HVDC grid, will also grow. Disparate grounding and commutation conventions between one system and another pose a challenge to DCT's not faced by ac transformers. That challenge is even greater if the DCT used is to preserve to each system its particular operational advantages, e.g. the ability of the grounded-neutral dc system to operate at half-power, and the ability of a symmetrical monopole to sustain momentary line-to-ground faults.

Figure 5 shows an MMDCT coupling two grounded bipole systems. Unlike an ac transformer, this DC isolates a fault on one bus from the other since line switches S1 through S6 operate in a complimentary manner, i.e. at no time is there a metallic connection between the two systems. A fault on either positive or negative poles, allows the other pole to function normally. Adaptation of the same scheme to coupling two monopole systems is obvious.

Fig. 6 shows the same MMDCT adapted to interconnect two symmetrical monopole systems. Since the symmetrical bipole may be constructed either to be ungrounded or grounded though a very high resistance, a line-to-ground fault produces almost no fault current so that some non-permanent faults, such as lightning, may clear themselves. In that case load current and pole-to-pole voltage remaining unchanged and little or no power transfer is lost.[2] However during a pole-to-earth fault on one pole of a symmetrical monopole, voltage on the un-faulted pole will rise to a higher voltage.

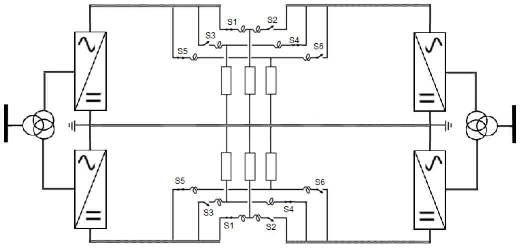


Figure 5. Interconnection of two bipole configurations by the MMDCT

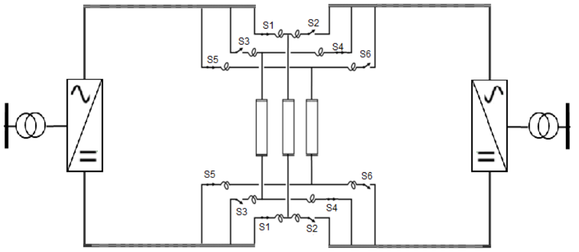
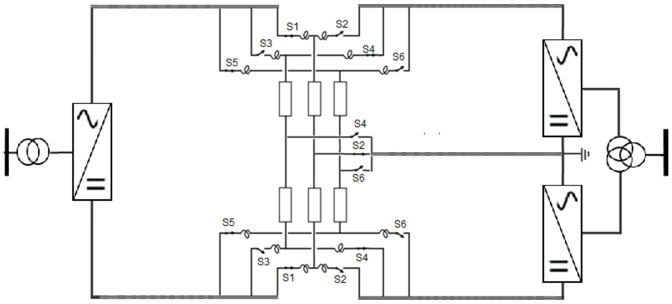


Figure 6. Interconnection of two symmetrical monopole configurations by the MMDCT

A DCT interconnection between a symmetrical monopole system and a bipole system should allow each to retain its inherent advantages; possible ground fault immunity in the first case and 50% redundancy in second. The bipole system has an earth connection while the symmetrical monopole is grounded through a high resistance. Thus the MMDCT's capacitive column, should *not* be grounded when connected to the monopole to receive or deliver charge, but should when connected to the bipole side for that purpose. This is achieved by earth switches shown in Fig 7. During normal operation pole-to-pole voltage appears across the two capacitive columns in series. However charge/discharge actions with the symmetrical monopole are pole-to-pole while with the bipole they are from each pole to ground. Current and voltage seen by the earth switches are almost zero.

Figure 7 MMDCT for interconnection of monopolar and bipolar configurations



During a non-permanent pole-to-earth fault on the symmetrical monopole side, the pole to pole voltage may remain the same, thus having no effect on the converter charging or discharging process when the capacitive column is connected to that side. Moreover, 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.

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[2] *An advantage in operational continuity but not necessarily in allowable loading governed by n-1 nor system insulation constraints*

When two bipole links, as shown in Fig5, are connected by an MMDCT, one set of capacitive columns is associated with the positive pole and another with the negative pole. With a pole to earth fault, power transmission through the faulted pole goes to zero and the capacitive columns associated with that pole no longer transfer power but fifty percent of the power will be transmitted on the un-faulted pole through the capacitive columns associate with that pole.

A pole-to-earth fault on the bipole side in Fig. 7 no longer allows the capacitive column between that pole and the earth to participate in power transmission, while columns associated with the un-faulted pole are still able to transfer fifty percent power from the monopole side to the un-faulted pole of the bipole side. Therefore, the sub-modules of the upper and lower capacitive columns should be rated for at least pole to pole voltage of the monopole side. When the MMDCT is connected to bipole side, the line switches associated with the faulted pole remain open to isolate the fault current from one side to the other, while the sub-modules associated with the un-faulted pole transmit power to that pole.

In an example simulated by the authors using PSCAD software, an MMDCT interconnected a monopole to a bipole HVDC link rated ±320 kV and ±500 kV respectively with a rated power of 1,000 MW. Upper and lower capacitive columns of the DCT were rated 640 kV. After a pole to earth fault occurs on the negative pole of the bipole link, power drops from 1 pu to 0.5 pu. The simulation results confirm retention of the fifty percent redundancy of the bipole configuration despite its transformer tie to a symmetrical bipole system with acceptable system response.

4. CONCLUSIONS

Development of economic and control-free dc-to-dc transformers, functioning within a dc system in a manner analogous to an ac transformer's role in an ac system is a critical step in further expansion of dc's role in electric power delivery. 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 that one such transformer system, based on sequential resonant charge exchange between primary and secondary systems and a series capacitor column meets those requirements.

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