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DC-to-DC Capacitor-Based Power Transformation

PS 1: Planning Study and Future Requirements for DC System

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SUMMARY

DC's role in power system delivery is growing to the point where system planners now envision high voltage dc grids as an overlay to ac systems in Europe and in North America for efficient coordination of loads and generation across wide areas. DC's growth at the end-use level has been even greater; in this case driven by dramatic growth in the use of electronics, new lighting technologies and likely to accelerate with growing vehicle charging load. This growth, both at the power delivery and power utilization level, has been achieved despite the lack of an efficient DC-to-DC transformer; one that would functionally parallel the magnetic transformer that propelled ac to early dominance in both delivery and utilization functions. This paper explores the prospects of capacitor-based transformation of power from one voltage level to another without an intermediate magnetically-based transformer. It considers the advantages and limitations of capacitive circuits widely used for that purpose at the electronics level, but also seeks to take advantage of the capabilities inherent in power-level thyrsitors and IGBT's within the bridge architecture of commonly used MMCs. The paper cites the criteria by which various capacitor-based schemes can be judged as well as means by which relatively smooth dc output and input wave-forms can be achieved within the limitations of what is basically a pulse-based energy transfer mechanism. The practical, multi-modular DC-to-DC capacitive transformer (MMDCT) configuration described is significantly less costly and more efficient than the present DC-to-AC-to-DC scheme and is capable of direct transformation of large levels of dc power from one voltage to another while making use of existing half-bridge IGBT architecture. The system requires no power controller and performs in a manner functionally equivalent to an ac transformer inasmuch as dc power transfer responds to voltage difference between terminals in a manner analogous to that in which an ac transformer responds to phase angle. Detailed PSCAD simulation example shows the proposed transformer's performance interconnecting two major dc

circuits with one another. Approximate cost estimates are included, relating the probably cost in relation to costs associated with conventional MMC bridges.

KEYWORDS

HVDC Transmission, DC-to-DC Conversion, Multi Modular Converter

INTRODUCTION

DC's roles in power delivery and in power consumption has grown significantly over the past several decades; driven by economics, innovation and changes in energy priorities. DC transmission, once used only for long distance point-to-point requirements has become an integral part of large AC networks and now promises to overlie those networks in Europe and North America. Furthermore the dramatic growth in electronic loads, LED lighting, and automobile charging load have suggested to many that at least a share of the power delivered to households and businesses should be DC.

DC's role has grown despite the lack of a DC equivalent to the AC transformer - responsible for AC's early leap to prominence. Transforming between HVDC voltage levels now requires first inversion to AC, magnetic transformation to a new AC voltage, then reconversion to DC. The importance of a more economic DC-to-DC transformation method, analgous in performance within a DC system to that of a magnetic transformer in an AC system, is now well acknowledged by system planners [1]. It is also reflected in an increasing number of publications directed to that goal [2]-[10].

Adapting to HVDC the capacitive transformation methods common at electronic levels is not easy. At very low voltages efficiency demands are more lenient, available switching devices different and insulation requirements less important. The authors' search for a high voltage capacitor-based DC transformer (DCT) suitable for applications, began with attempts to adapt those schemes to high voltage applications. A large number of capacitor-based transformations were first explored with simple energy exchange models; then with PSCAD representation to determine transient behaviour, switching demands, control issues, and compatibility with component architecture commonly used in LCC and VSC converter design. This work led to a design based in capacitor bypassing strategy that satisfied all the requirements felt necessary for a DCT effective for commercial introduction.

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. Potential applications include:

1. Interconnection of HVDC lines of different voltages, grounding systems, or commutation mode (i.e. LLC to VSC).
2. Power flow regulation between HVDC circuits or within a DC grid
3. Voltage boost in long DC transmission lines
4. Wind farm and solar plant interconnection to DC grid
5. Economic taps of moderate power levels from HVDC lines
6. Industrial DC voltage conversion.
7. Residential & commercial load-serving equipment

PERFORMANCE REQUIREMENTS

An optimal DC-to-DC transformer (DCT) will perform within a DC system in a manner functionally equivalent to the way an AC transformer does in an AC system. However rather than a continuous magnetic transfer of energy from primary to secondary busses as possible with AC, a DCT must depend on discrete transfers of charge using capacitors, inductors and solid state switches. In order to be generally useful, it must:

a. Be capable of high MW ratings.
b. Have an efficiency comparable to Voltage Sourced Converters
c. Change power flow in response to changes in relative primary and secondary voltages *without a power control signal*. Need for such a signal would require very complex control interactions between the DCT and converter terminals of the effected DC lines.
d. Be capable of regulating flow by use of external controls just as an AC transformer does through tap changes.
e. Achieve bidirectional flow.
f. Result in relatively smooth input and output current without a large filtering burden.
g. Be modular in structure to reduce cost of manufacture, increase design carry-over from one project to the next, and provide interruption-free redundancy in the event of component failures.
h. Operate such that modules equally divide pole-to-ground voltage to minimize switching and insulation costs.
i. Provide primary and secondary fault isolation and accommodate both internal faults and faults on either terminal.
j. Be comprised of components already part of modern MMC-VSC, e.g. half-bridges or their equivalent. This will save time and cost in prototype prove-in, lower manufacturing cost, and provide reliability carry-over.

FUNDAMENTALS OF CAPACITIVE TRANSFORMATION

Based on the requirements cited above, the authors have explored and evaluated a wide range of capacitive transformation schemes and developed one that meets all of the requirements cited above. The proposed transformer scheme is based on a relatively simple series column of capacitive modules which is charged resonantly through a reactor from a primary bus and discharged resonantly through a different reactor to a secondary bus. Losses are minimized with soft switching by breaking connection with either bus at the first resonant current zero. A brief review of capacitive change principles will help in explanation of the MMDCT's operation and features.

The energy content in Joules of each pulse exchanged between a capacitor and source is:

$$\Delta E = \frac{1}{2} C \cdot (V_2^2 - V_1^2) \qquad (1)$$

Where V_1 and V_2 are the capacitor pre-and post-charge voltages respectively. In this case the pre- and post-charge voltages of the column are $(1-k)\cdot V_{dc}$ and $(1+k)\cdot V_{dc}$. Therefore equation (1) can be expressed as:

$$\Delta E = 2\cdot k\cdot C\cdot V_{dc}^2 \tag{2}$$

The MMDCT achieves transformation by alternately receiving a current pulse from one bus; then delivering a current pulse to another through the line switches (LS) as shown in Fig. 1 which also illustrates input and output current waveforms. The line switches must be bi-directional to allow the current flow both ways. To maximize energy exchange, the frequency characterizing both input and output charge exchange should be as high as practicable. Since the effective total capacitance of the columns differ between charge and discharge cycles, the reactors on each side of the MMDCT must be different if those frequencies are to be the same. If power output is delivered resonantly to or from the MMDCT with frequency of $f = \frac{1}{2\pi\sqrt{LC}}$, where C is the equivalent capacitance of the total capacitive column at the time of charge or discharge, then for a given pre- and post-discharge voltage on C;

$$P \propto k\cdot\sqrt{\frac{C}{L}}V_{dc}^2 \tag{3}$$

The current waveforms represented in Fig. 1 would obviously be challenging to filter to smooth DC. However if three or more MMDCT columns are placed in parallel and caused to generate equally spaced pulses, then in addition to smoothing both output and input waveforms, the compound MMDCT group increases its megawatt transfer capability proportionally. Fig. 2 illustrated this for three parallel MMDCTs each of which contributes overlapping current pulses offset by 120 electrical degrees at the charge or discharge frequency. Smoothing to that extent requires that charging and discharging frequencies be equal. Together they present a waveform with very low sixth harmonic ripple of the switching frequency and at the same time increase the power cited in (7) by a factor of three.

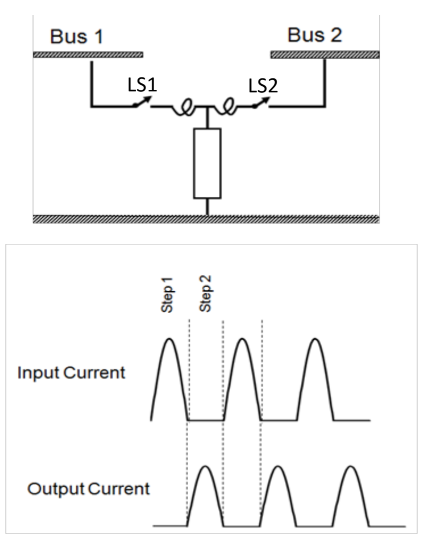


Figure 1 – MMDCT transfer principles

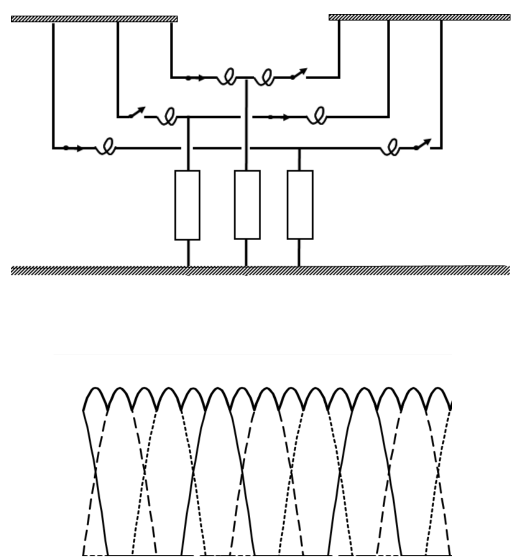


Figure 2 Parallel MMDCT's to smooth input and output waveforms

In practice, the line switches in each MMDCT operate in a complementary manner, i.e. when one is closed the other will always be open, thus always providing galvanic isolation between the two high voltage DC nodes. Since line switching occurs at current zero, a back-to-back thyristor may be a used to achieve higher ratings and lower losses.

A MULTIMODULE DCT (MMDCT)

Equation (1) illustrates that the *direction* of the energy transfer into or out of a capacitive column depends on the difference between the voltage to which it's previously charged and the voltage to which it is connected. Thus to affect transformation, a capacitive column must be configured to present to an input bus, through the complimentary inter-bus switches shown in Fig. 1 and 2, a voltage *lower* than the voltage of that bus and then, by reconfiguration, present to the output bus, a voltage *higher* than the voltage of that bus.

Suppose that the capacitive columns of Fig. 3 are comprised of n half- or full-bridge modules, as shown in that figure. Each such module contains a capacitor (C_{SM}) which can be electrically inserted into a column or bypassed and electrically removed from it. Thus at any given time capacitors in a column associated with m of the n modules can be bypassed while $n-m$ are electrically part of the series column. Assume further that $V_1 < V_2$ and n and m are selected such that the ratio $(n-m)/n$ is exactly equal to a voltage ratio V_1/V_2 and, further, that when connecting to higher voltage bus, all capacitors are in the circuit but when next connecting to lower voltage bus, m capacitors are bypassed. Therefore, the equivalent capacitance of the series column connected to low voltage and high voltage busses are $C_{SM}/(n-m)$ and C_{SM}/n respectively. A capacitive column is rated slightly higher than V_2 due to the voltage variations of the capacitors. The current flow amount and direction depends on the voltage and charge variations of the capacitors in each cycle.

Although the actual number of the bypassed capacitors must remain equal to m for a given voltage ratio, the bypass role must be rotated among the submodules in the column to balance charge and voltage variations. This is a commonly used charge equalization process called "sorting". Sorting in one half cycle of charging or discharging is well adapted to high voltage ratios. For low voltage ratios the bypass role can be rotated among capacitors from one cycle to the next so that, despite some variations in voltage, the voltage of all capacitors remains within reasonable and stable bounds.

Several characteristics of the MMDCT described above will be apparent:

- The MMDCT operates without a need for a power control signal.

- MMDCT has high eficiency. Basically the losses consist of the submodules and line switches conduction losses during the operation and the rotational submodule switching losses while the capacitive column is connected to the lower voltage bus. The line switching occurs at current zero, and no submodule switching occurs while the capacitive column is connected to the high voltage bus.

- Varying m during operation will allow the MMDCT to serve either as a means of flow control or of voltage boosting.

- Where an MMDCT is used to tie an LCC system to an VSC based system the MMDCT modules would simply make use of full bridge modules rather than half-bridges modules shown in Fig. 3.

- The number of capacitive modules provided in the column may exceed the number used in the process described above in order to be inserted to replace failed modules; thus increasing reliability.

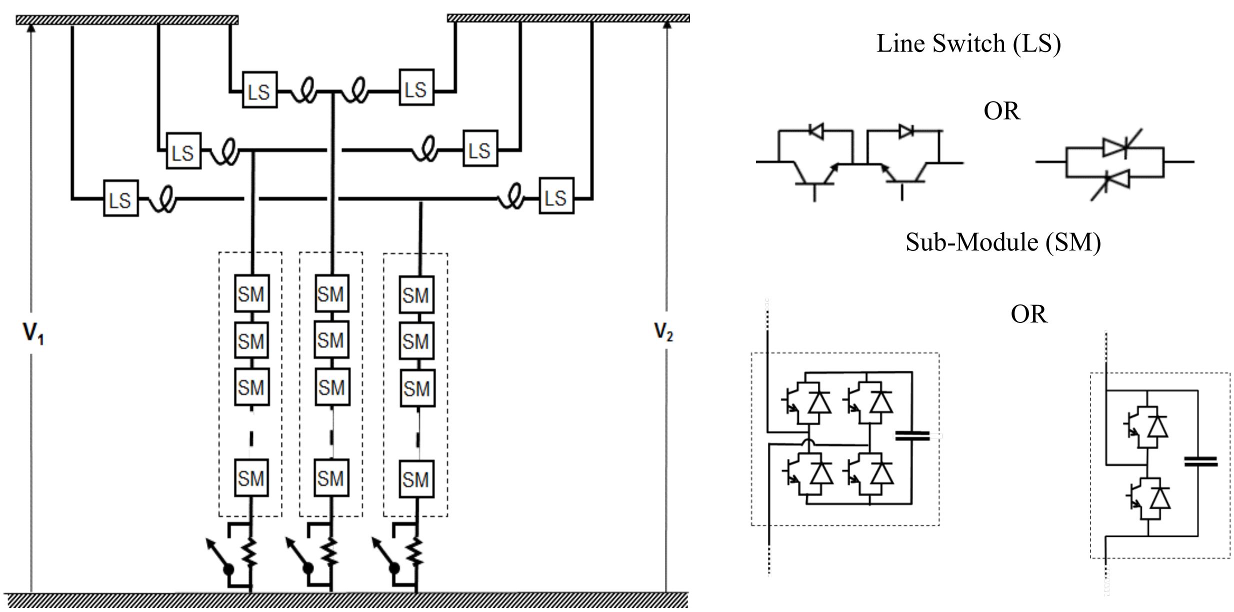


Figure 3 – Circuit diagram of the MMDCT. Options for line switches (LS) and sub-modules (SM) in capacitor column are shown

The capacitive filters at the terminals of MMDCT will effectively decouple the impact of the line impedance on the resonance frequency and it will also reduce the voltage and current ripples. Moreover if MMDCT connects two high voltage DC lines, the small current ripples generated by MMDCT will be filtered at the converter side by transmission line inductance.

MMDCT Performance Start-up and Power Changes

Assume that the MMDCT connects two DC lines with different voltages; each in VSC HVDC applications. Assume further DC voltage is controlled by the converter on the low voltage side of the MMDCT and the power is controlled by the converter on the high voltage side. Power flow in a DC line depends on the voltage difference between ends of the line and the line resistance. When the converter power order is changing, its voltage changes accordingly and thus controlling DC current flow.

During start-up the MMDCT column is charged by V_2 through a resistor temporarily in the circuit at the base of the column, to prevent an initial resonant over-shoot of capacitor voltage. Thus with all capacitors in the circuit at startup, each is charged to V_2/n. The resistor is then bypassed for normal operation. When power flow in both the lines linked by the MMDCT is zero, line voltage is equal to rated DC voltage over the length of each. Suppose that within the MMDCT column, m and n have been chosen with respect to the two nominal line voltages V_1 and V_2 such that at those voltages no power is transformed from one line to the other. Suppose however that the voltage on high voltage bus drops to *less* than V_2. Now connection of the column to that bus will cause a resonant charge transfer from the column to that bus reducing each capacitor's voltage to *less* than V_2/n . Then when $n-m$ capacitors are connected to the low voltage bus, charge will be transferred from that bus to the capacitor column. Since DC voltage is controlled to be constant by the low voltage side converter, current flow through the MMDCT will cause the low-side voltage to decrease too, thus keeping the ratio of voltages constant. With this process power is transferred from the low voltage bus to the high voltage bus. It is apparent that if the voltage on high voltage bus becomes *greater* than V_2, power will flow from the high voltage bus to the low voltage bus. Thus transformation of power between two high voltage nodes responds to variations in DC voltage of primary and secondary nodes based on system requirements without the need for a power controller.

MW TRANSFER CAPABILITY

According to (3) it is apparent that, for a given frequency and capacitor discharge ratio within a feasible range, power is maximized when the equivalent discharge capacitance is high and the discharge inductance is low, suggesting use of air-core reactors such as are used in wave-traps, the latter having inductance in the range of 200 mH. To minimize the capacitor size, the operating frequency has to be as high as possible. Once L and C are fixed, power flow is changed by rate of change of energy stored in the capacitors.

CASE STUDY: INTERCONNECTION OF TWO LARGE HVDC LINES

The foregoing MMDCT characteristics were modeled in detail using PSCAD software to assure operation in accordance with the principles and equations cited above. Fig. 4 illustrates MMDCT connection of two VSC HVDC systems, each using a symmetrical monopole configuration [11]-[13] . DC voltage is controlled by the LV converter, rated at ±320kV and real power is controlled by the HV converter, rated at ±400kV. The DC lines connecting the converters to the MMDCT are 200km on each side. MMDCT parameters for this case are listed in Table 1.

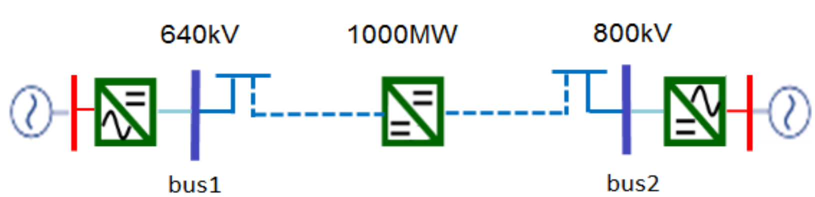


Figure 4 – Interconnection of two large HVDC lines via MMDCT

Table 1 MMDCT parameters

Rated power	1000 [MW]	HV inductor	0.024[H]
Primary voltage	640 [kV]	LV inductor	0.015[H]
Secondary voltage	800 [kV]	Maximum voltage deviation	10%
Sub-module capacitance	2600 [µF]	Cycle frequency	400 [Hz]
Number of sub-modules per column	400	Rated voltage of sub-modules	2 [kV]

Fig. 5 shows dc currents, voltages and power at bus1 and bus2. The figures illustrate a power exchange ranging from +1000MW to -1000MW. Note that the ripples that might otherwise appear on input and output currents of the MMDCT are effectively filtered by the line inductances and that the converter-side currents, shown in fig. 5, are smooth. Figures 6 and 7 show input and output currents as well as the capacitor column voltage of each branch during power changes and steady state respectively. Fig. 8 shows a sub-module's capacitor voltage in one branch of the MMDCT. The capacitor voltage variation at full power transfer is 10%.

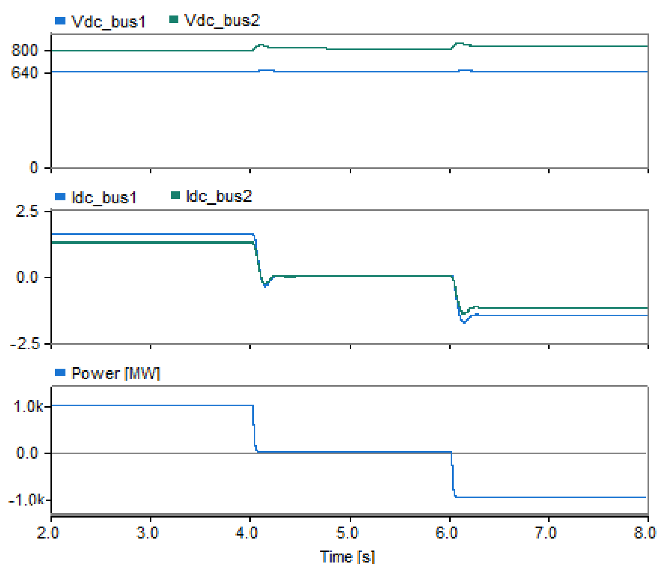


Figure 5 – Dc voltage, current, and transmitted dc power at bus 1 and

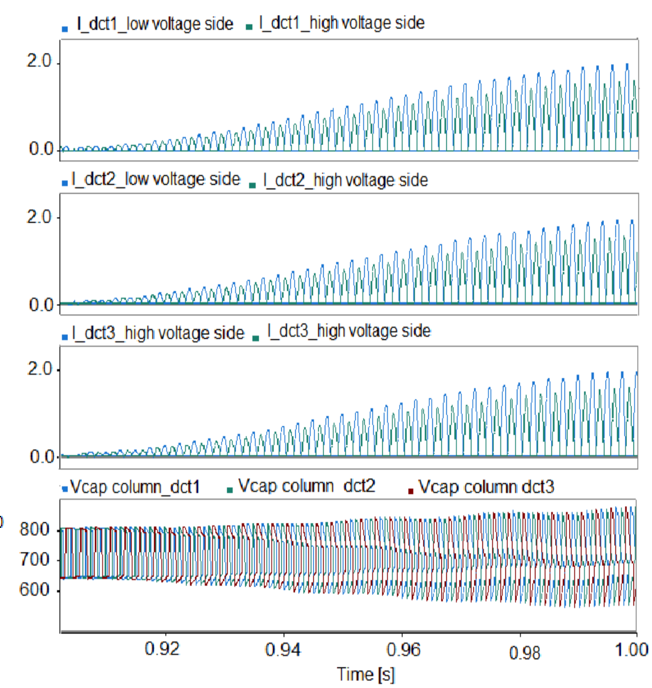
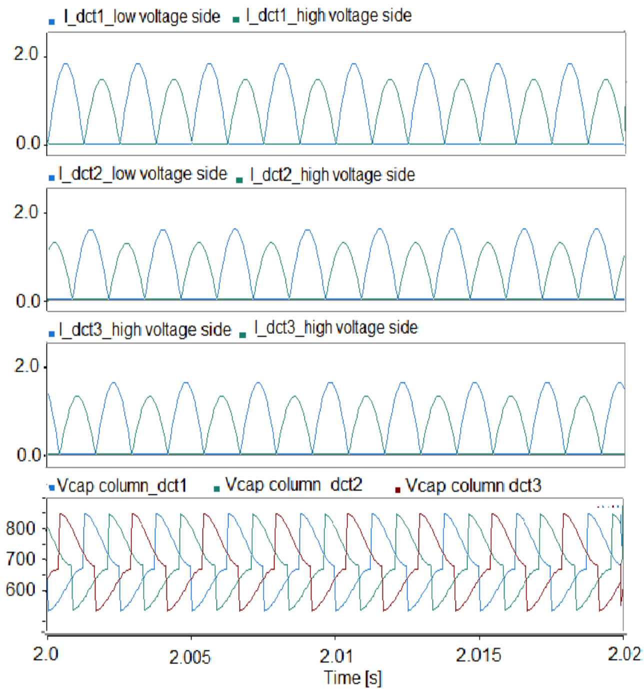


Figure 6 Input and output currents and capacitor column voltage of each branch during power changing from 0 to 1 pu



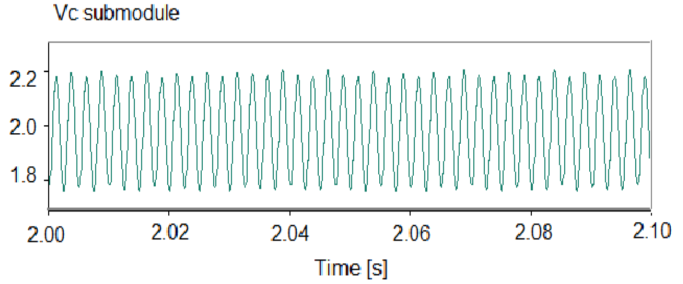


Figure 7 Steady state Input and output currents and capacitor column voltage of each branch at 1 pu power transfer.

Figu

COST CALBRATION

Estimated costs of an MMDCT can be derived by comparison with the components of a single MMC Converter of similar rating [4]. Cost benefits of the MMDCT accrue over a similar rated MMC converter. Important points of comparison are:

1. No transformer
2. Smaller capacitor size due to higher operational frequency
3. Half the number of valve arms but with a similar number of sub-modules in each of three column compare to the number of submodules in each of six valve arms in an MMC converter
4. No ac switchyard but possible minimal dc filtering
5. No external control for power flow
6. The additional equipments needed in an MMDCT compared with an MMC converter are:
    a. Six air core reactors
    b. Six bidirectional solid state switches which can be constructed of bidirectional thyristors
    c. Three resistors and by-pass switches for start-up which can be mechanical switches

Similar facilities an MMDCT will have compared to an MMC converter include a valve hall, sub-module cooling, auxiliary power, control and protection, civil works, project engineering and administration, small rated dc filters (one each side of the MMDCT).

CONCLUSION

The ability to economically transform energy between dc voltages will accelerate the development and usefulness of HVDC Grids and may expand dc's role in wind-energy and potentially in distribution to points of energy use. This paper shows that it is possible to build a capacitor-based dc-to-dc transformer that performs, within a dc system, exactly as a magnetically-based transformer does within an ac system except responding to voltage difference rather than phase angle difference. That transformation can, as with ac, be bidirectional and respond to system demands without a power control signal. In this scheme, existing, commonly-used components and substructures can support ratings in excess of 1,000 MW at an efficiency of approximately 98%.

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