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# The Prospect of Solid-State Power Transformers

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**SUMMARY**

Recognizing that future demands on high-voltage transmission systems, imposed by the inevitable shift to renewable generation sources, will likely require that high voltage DC "supergrids" overlay the existing AC grid and, further, that the networking of DC will require the DC equivalent of the AC transformer, researchers in many countries have worked to develop such a device. Several of the options proposed borrow from the solid-state technology inherent in modern AC/DC converter stations, advantages being (1) a wealth of successful operating experience, (2) sold-state technology lends itself to internal redundancy, thus eliminating the need for spare units and (3) the solid state option eliminates the need for external circuit-breakers.

In studying solid-state DC-DC transformation principles, one cannot help but reflect on the prospect that the same or similar transformation principles could one day be used for AC-AC transformation. This paper explores that option using one of several proposed solid-state transformation ideas as a vehicle for doing so while searching for prospective functional advantages… of which there appears to be quite a few, extending to transformation between differing voltage profiles.

The transformation principle describes differs from the continuous system provided by magnetic transformers, depending instead of a series of very short, discrete transfers whose cumulative effect approximates a continuous waveform.

The above search will deliberately set aside the issues of cost and size based on the rational that (1) solid state technology is young, promising future evolution while AC (magnetic) transformer technology is mature and can be expected to continue escalating in cost and (2) A thousand year history of technology substitution showing that shifts from one technology to another in almost any field is never driven by cost but rather by operational advantage or convenience.

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## KEYWORDS

Power Transformers, Power Transmission, AC Systems, HVDC, MMC Submodules, Power Electronics

## BACKGROUND

Early attempts to transmit DC power at utilization voltage, severely limited by transmission distance, gave way to AC with introduction of the first commercially useful magnetic transformer. While subsequent advances in transformer design made possible today's multi-leveled systems with AC voltages as high as 1,000 kV, the transformer technology that made this growth possible is now quite mature with costs escalating yearly.

At the system level, the inevitable shift to wind and solar power generation will require that the transmission system accommodate a major broadening of regional diversity in energy production – one too great to be accommodated by storage alone. Foreseeing this, system planners anticipated the need for far-reaching national and international "supergrids," involving transmission distances and power transfer levels that can best be accommodated by DC. Those DC grids must include *existing* HVDC lines differing in commutation systems and grounding convention. In effect, DC, up to now generally serving point-to-point transmission functions will have to serve as *network*. Recognizing that this will be impossible without the DC equivalent of AC transformers, the past decade has seen a number of development programs directed to that end. It is hard to undertake such a program, selecting options based on modern solid-state technology, without speculation as to whether that same technology might one day displace magnetic technology in AC-to-AC transformation. That speculation gains encouragement from the fact that today's magnetic transformers are based on mature technology while solid state technology will see both functional and cost benefits from ongoing research and higher production levels. For example, capacitors inherent both in in the main column shown in figure 1 and applied to its terminals for wave-form smoothing, represent a significant fraction of the cost of that type of transformer. In both cases capacitance requirements are inversely proportional to switching frequency. While simulations represented in prior work and publications are based on a switching frequency of 2,500 Hz, frequencies from four to eight times higher, based silicon carbide IGBTs, are now being proposed.

Speculation as to solid state technology dominance in the transformer market is also lent credence by a technology evolution theory espoused by two GE scientists in the 1950s, Fisher and Pry [1] ...a theory based on the fact that shifts from one technology to another over many centuries has almost never been based on economic advantage... almost always on convenience and/or functional value.

With that encouragement in hand, the following paragraphs will explore, on a speculative basis, the prospect of solid-state, high power level, AC-to-AC transformation as well as transformation between differing voltage profiles based on one of a number of new DC-to-DC transformer (DCT) ideas...doing so without implying that that the particular DCT solution used as a basis for exploration will lead to the best and most commercially viable transformation structure for that purpose.

**The MMDCT**

The Multi-Module DCT, an elementary diagram of which is shown in figure 1, among the serious contenders for practical DC-to-DC transformation, is comprised of a column of series-connected capacitive modules, each either within a *half-bridge* as shown in figure 1 which allows any of those capacitors to be isolated from the column and bypassed, or within a slightly more complex *full bridge* which allows a capacitor, once charged from a given bus, to be removed from the series, reversed in its connection polarity, and then re-insertion into the column. The repeating three-step cycle of example DCT of figure 1 is, in its simplest form:

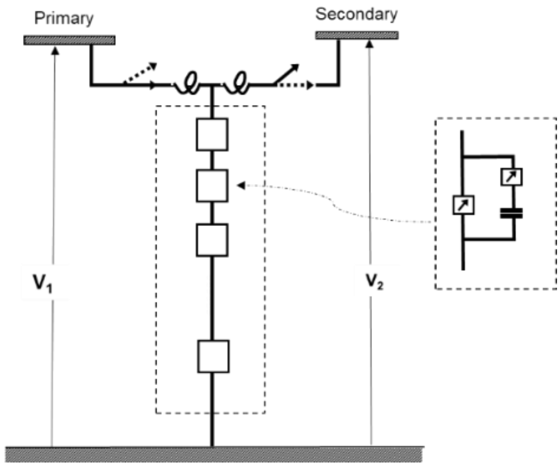


*Figure 1. Basic single-column solid state DC-to-DC transformer*

1. The capacitive column with all capacitors in series is first connected to a primary bus by means of an IGBT or other solid-state switching device through a reactor, thus initiating a resonant exchange of energy with that bus which is interrupted at the first current zero.[1]

2. The primary switch is then opened to isolate the column, during which isolation, a number, m, of the column's n capacitors are bypassed.

3. The remaining series of n capacitors are then switched to resonantly exchange charge with a lower voltage secondary bus, thus affecting DC voltage transformation ratio of n/(n-m).

It is apparent that after charge exchange with the secondary in a cycle that simple, n of the capacitors, would be left with a charge differing from n-m of them. However, the charge among all n capacitors can be equalized by a commonly used process called "sorting" in which participation of the role played by m capacitors is rotated by among all n capacitors equally, leaving all with similar charge after a complete cycle.

While the single column MMDCT shown in figure 1 would produce a pulse-by-pulse primary and secondary DC wave shape unacceptable to most applications, that limitation can be resolved by either connecting a capacitor to ground at each terminal or using three such columns in parallel, each equally offset in time from the other, the latter option tripling MMDCT's MW rating and producing a filterable waveshape. The basic architecture of figure 1 can also be adapted to link DC lines of varied grounding and commutation systems, thus providing a means of coupling both new and existing DC lines to comprise a DC network... one in which flow on individual lines is controlled or allowed to divide in inverse proportion to resistance.

[1] *The column, in an initialization step, is first charged exponentially to the primary bus voltage through a resistor (not shown) which is bypassed during normal operation*.

It has been shown that the basic MMDCT principle can be applied in a number of DC contexts, including one capable of three-way DC-DC-AC transformation [2,3]. Speculation as to its potential in AC-AC transformation, discussed in the following paragraphs suggests not only to a method of doing so, but also suggests a number of important transformation functions difficult or impossible to achieve with a magnetic transformation.

**Adaptability to AC**

The principle cited above would seem directly applicable to AC-AC transformation, voltage input and output varying sinusoidally while the primary-to-secondary voltage ratio is held constant. While there are certain challenges in doing so, that extension affords a number of functional advantages over magnetic transformation.[2] Examples cited in the following paragraphs imply use of a rather sophisticated controller, not shown in the figures; that controller capable of selecting the electrical configurations of capacitive modules within the column shown in figure 1 for charge exchange with the primary bus, as well as reconfiguring the capacitive column between its connection to primary and secondary busses. Such a controller is needed as well to implement the sorting function when called for in equalizing charge exchanges involving fewer than the total number of capacitive modules. Some functional capabilities of the figure 1 configuration, when applied to AC transformation are:

1. *Voltage Ratio Control*

A magnetic transformer, if provided with taps, can change the transformation ratio in a limited number of discrete steps. The example solid state option, an AC extension of figure 1, can achieve a wide range of ratio control by simply adjusting the number of modules bypassed (n-m) during secondary connection.

2. *Taps*

It is apparent from figure 2 that taps in the capacitive column, simultaneously linked resonantly to a number of secondary busses, can, by appropriate subdivision of column modules, be made to match the voltages of those busses. With no load on those secondary busses, the column need only be configured such that the capacitive reactance apportionment is equal to the voltage ratios. It is clear that if one or more taps is loaded disproportionately, the ratio of reactances necessary to maintain the assigned nominal voltages $V_X$, $V_Y$, and $V_Z$ must change. That change will be evident either from measurement of those individual loads or the deviation of each tap voltage from its nominal value. On a cycle-by-cycle basis, the total reactance ratio among legs in figure 2 can be adjusted by a

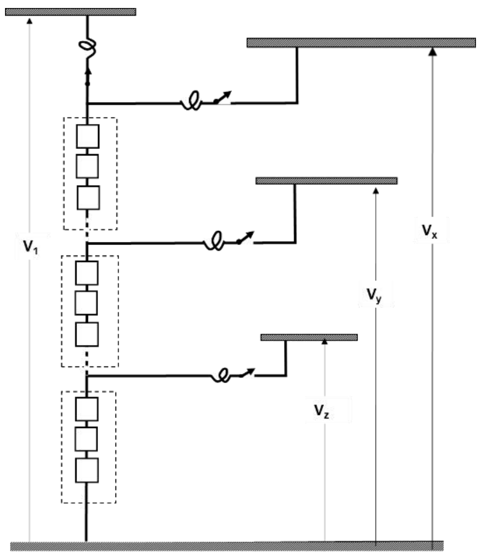


*Figure 2. Prospective single-column transformer with taps*

[2] *Patents pending*

controller to maintain, from each leg to ground, nominal tap voltage.

Figure 2 and other subsequent examples presume, for simplicity, that the various busses served are strong enough electrically to accept or contribute charge to the column without significant change in bus voltage. If that is not the case, it's apparent that a capacitor to ground on such busses will allow the operation as described.

3. *Phase-Shifting*

The energy resonantly transferred to the capacitive column during any one of its connections to the primary bus as the first of the three-step energy exchange cycle, can be controlled within each switching cycle independent of prior of future charge exchanges and/or the point on an AC primary waveform at which the charge exchange takes place. If, during that primary connection, the column is configured to present to the primary bus a voltage lower than the primary voltage, energy will be delivered to the column. If it is exactly equal to the primary voltage, no energy will be delivered. If it is greater than the primary bus voltage, energy will be absorbed by the primary system from the column. Thus with power frequency AC voltage applied to the primary, the time profile of sequential energy exchanges from the primary source *need not be in phase with the primary voltage* and, further, if the column's energy output is kept equal to its energy input, a phase change can be achieved on one or more of the secondary busses in figure 2. However, depending on the complexity that phase change the number of capacitive modules required times the voltage rating of each can be well in excess of the primary voltage. Furthermore, if primary and secondary wave shape(s) are not the same, the column will either be required to store energy within itself or within a capacitor connected to a secondary bus provided for short-term energy storage.

4. Addition of DC busses

Since (1) for a given input voltage the output voltage can be adjusted from one switching cycle to the next to any desired output voltage and (2) with full bridge modules the secondary output voltage can be of the same polarity as the primary voltage or of opposite polarity, one or more output voltages can be DC as shown in figure 3...with the same energy storage limitation as cited above.

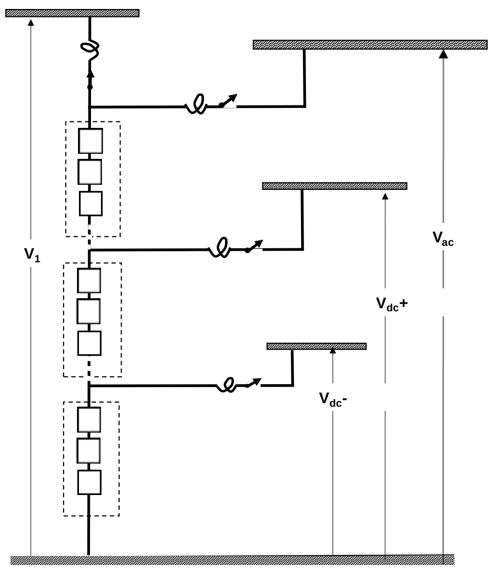


*Figure 3. DC Secondaries*

5. Three-Phase Transformation

It is apparent from the above phase shift argument that, with three columns the nature of that shown in figure 1, single phase-to-three phase transformation could be achieved. However, that transformation can also be achieved with a single capacitive column. In theory the configuration of figure 2 could do so, making $V_x$, $V_y$, and $V_z$ corresponded to $V_A$, $V_B$, and $V_C$ of a three-phase system. However, that extension would require a number of modules whose aggregate voltage ratings would be well in excess of line-to-ground primary voltage.

A simpler method is shown in figure 4 where the single-phase primary also serves as phase A of the three-phase secondary, the capacitive column being subdivided into just two sections. After initial charge exchange with the single-phase input in figure 4, the column is isolated and configured to produce two voltages. The lower column is made equal to the instantaneous voltage corresponding to phase B of the three-phase system wherein phase A is the same as the primary voltage $V_a$. The upper column section is configured to produce the corresponding instantaneous voltage, $V_b - V_c$, thus providing a three-phase secondary with the correct instantaneous voltages corresponding to the A phase input voltage.

Figure 5 shows the sum of absolute values required of the column in order to provide the instantaneous voltage of phase B plus the instantaneous voltage $V_b - V_c$, the maximum *sum* of absolute values being approximately 1.7 times greater than the crest of the A phase input voltage. This demands that, during the step 1 charge exchange the column with the phase A input bus, sorting must insure that, while the sum of *connected* modules at any given instant must always equals the source voltage, the sum of charges on all modules must exceed that voltage by a factor of 1.7.

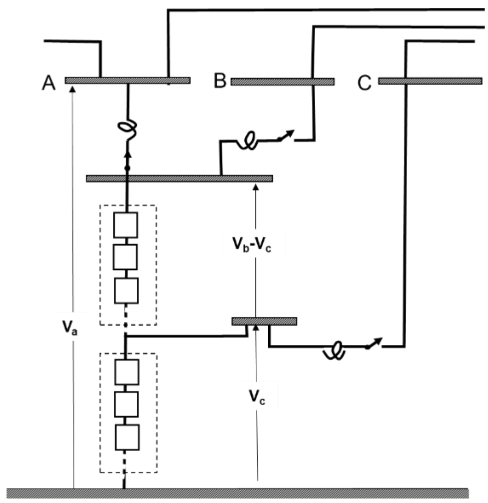


*Figure 4. Single Column, Single-phase to Three-Phase transformer*

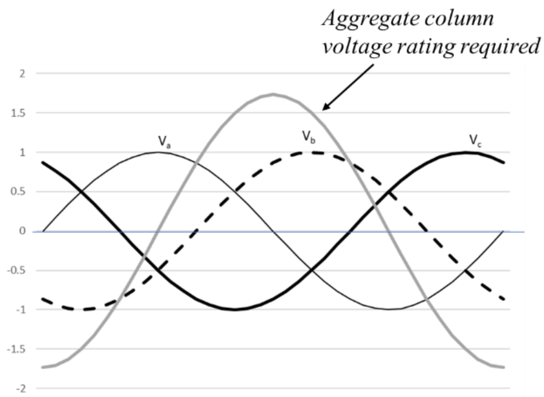


*Figure 5. Total column voltage rating requirement of figure 4 transformer*

**Functional Comparison of Solid State vs. Magnetic Transformers**

Among the functional advantages potentially afforded by solid-state transformation are:

1. Fault isolation

It is clear from the charge exchange process that a fault on any one of the busses can be isolated from other busses.

2. VAR generation/absorption

A capacitance connected to any of the secondary busses, could be made to appear to the primary as either a consumer or generator of reactive power since the profile of energy transfer to that capacitor could be made to lead or lag the primary voltage.

3. Two phase operation of three-phase lines.

In theory at least, a three-phase transmission line coupled to both its terminals by a group of three transformer columns of the general configuration shown in figure 3, one for each phase, could operate at two-thirds of its MW rating with one phase out of service, doing mischief to the N-1 rating convention.

4. AC primary, AC + DC Secondaries

It also appears possible, with the transformation system explored, to transform from AC to AC while simultaneously supplying a bipolar DC secondary...an interesting prospect as the DC fraction of household end-use load becomes comparable to or greater than the AC load.

5. 50 Hz to 60 Hz Transformation

It is apparent from fact that the energy transfer profile of a solid-state transformer need not match the profile of the primary voltage, that transformation between 50 Hz and 60 Hz busses would also be possible. Doing so would require energy inter-cycle energy storage a discussed above.

6. No Circuit Breakers

The basic capacitor column configuration shown in figure 1 periodically and alternately interrupts connection first with the primary, and then with the secondary. It therefor eliminates the need for circuit breakers needed to isolate magnetic transformers.

7. No Spares

The column structure of figure 1 is obviously very easy to provide with redundant capacitive modules, which, with the already demonstrated reliability of modern DC terminals, eliminates the need for a spare transformer or the long delivery time inherent in getting a replacement.

8. No oil.

Even transformer oils without PCBs are toxic and considered an environmental hazard, often requiring provisions for containment in the event of oil leaks. That is not the case with solid state options.

**CONCLUSIONS**

Even though solid-state transformers are now technically possible, both cost and space requirements currently make that option impractical. Yet developments in solid state technology and in DC-DC transformation based on that technology should be carefully watched, as should the cost escalation of magnetic transformers ...watched with the realization that, as with other technology switches, any move to solid state transformers in high voltage systems will not be driven by economic competitiveness but rather by functional advantage.

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