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Multilevel converters: review, form, function and motivation

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Abstract: *The paper is devoted to the outlines of converters and more in particular the form and function of multilevel converters. The first commutation principles are recalled towards the switch function today being implemented with solid state devices. Solid state devices combined in various topological combinations enables the connection of various sources and loads of different kinds. The primary energy source can be for instance a battery, solar panel, fuel cell, generator etc while the load can be anything from a motor to the connection with the power system. As will be shown with multilevel converters the number switch functions is increased, while increasing the power ratings with a switching frequency as close to the fundamental frequency. Multilevel converters provide and effective switching frequency increase allowing negligible filter requirements.*

Keywords: commutation, converter, multilevel converter, semiconductor.

1. Introduction

Electricity is a convenient form of energy that can be channeled, simply controlled and distributed to a wide variety of distributed geographically dispersed consumers. There it is converted into other forms. Commonly electricity is controlled by varying parameters such as the voltage, current, frequency, impedance or combinations of these to adapt and control electrical energy, as provided by a primary energy source, to the characteristics of the load.

This paper is about the dc-to-ac power conversion principles performed by so-called *multilevel converters* using solid state switching semiconductor devices.

Recently, advances are made in the topological configurations of these converters by using floating energy sources such as capacitors, being an integral part of the switching process.

This enabled the creation of a new path in the power electronics development for multipurpose power electronic converters connecting dc and/or ac sources and loads for low to very high power ratings.

This paper will start with a short historical review, concerning commutations principles, the function of which is now embedded in solid state devices. Then the paper is mainly devoted by giving an example of topology synthesis starting from a basic commutation cell aiming at reaching higher power ratings and an optimized switching process. The techniques and principles discussed are a prerequisite to transfer the "static" electricity grid into a more dynamic controllable grid and/or loads as being controllable nodes in future grids.

2. Inspiration, admiration and dedication

By the discovery of the electric arc by Sir Humphry Davy in 1800 we might start writing the history of power electronics, though questionable indeed, but everything needs a beginning. It shows however that we cannot destroy energy, rather we can change the character of it, and secondly, it can be considered as an attempt to commutate current. This discovery has led first to the application of arc welding. Research in magnetism and electrical currents continued and in 1820 Jean Baptiste Biot and Felix Savart investigated and reported how a magnetic dipole oscillated on various distances from a current conducting wire; the magnetic force was proportional with the current. The conversion of electrical energy into mechanical energy by electromagnetic means was demonstrated by the British scientist Michael Faraday in 1821. As many need to be credited in the most likely exciting development process, but it was probably William Ritchie to contrive a way to make an electromagnetic to revolve continuously, the first rotary motion of an electromagnet in 1833 [1]. He caused its polarity to reverse twice in each revolution by an arrangement of wires grazing across two semicircular troughs of mercury; mercury commutator [3]. The improvement on Ritchies instrument was attributed to Charles Grafton Page by replacing the mercury commutator with a "pole-changer", the mechanical commutator as we know today [4]. This commutator consisted of two wires soldered and making contact with a pair of insulated half cylinders on the rotating shaft, so that the polarity could be reversed with every half rotation.

3. Commutation

The principle of the commutator by Page is shown in Fig.1, with brush contacts, together with the dc voltage e as two pulsations per rotation, and the induced ac voltage e'. Clearly, the induced ac voltage is by means of commutation 'rectified', the current being commutated, and the character of the electrical energy is changed in a sophisticated way, say arc free. The static commutator beneath in fig.1, as an elementary 3 pole commutation cell, and being a building block for multilevel converters, for instance. This cell, having synergies with and is inspired from the mechanical commutator, first the rectification obviously. This commutation cell will be discussed in the next section probing further on the form and function. But to make it applicable, a device be able to interrupt a current, arc free, is first required.

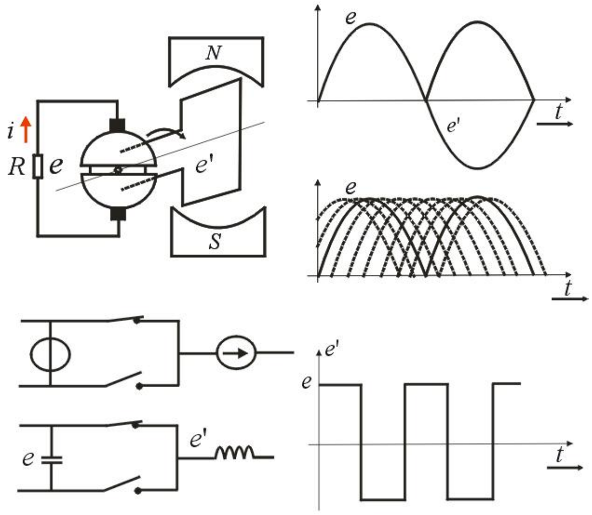

Figure 1: Mechanical commutator and 3-pole commutation (canonical) cell.

Developments continued obviously and in 1882 Jemin and Meneuvrier had recognized the behaviour of unidirectional current flow in a mercury arc with atmospheric pressure. Whereas in 1903 Cooper-Hewitt provided a means to control the arc via a screen between the anode and cathode. Lets speak of a period here when classic power electronics flowered, where for instance Prince builds an inverter with vacuum triodes, Presser designs a selenium rectifier, both in 1925. Voorhoeve builds a voltage control for a dc generator using high-vacuum triodes, and Langmuir and Prince developed the practical realization of a mercury arc rectifier, both in 1928 [2].

The modern power electronics can be considered to take off during 1940-1945 with the development of silicium and germanium diodes, appearance of Ignitron and Excitron. Finally, Schockley came along a theoretical way to the layer transistor in 1948, and around 1953 the PSN diode has been developed. Moll c.s. recognized in 1956 the practical use of the thyristor [2]. This semiconductor is still widely used in high power applications and has no current turn-off capabilities. So called turn-off capability was later implemented in the Gate Turn-off Thyristor (GTO), followed by the hard driven GTO, the so-called Insulated Gate Commutated Thyristor (IGCT).
The first devices that were able to turn-on and turn-off current are the bipolar transistors with

significant power handling capabilities, in 1960s. Metal Oxide semiconductor technology advanced (initially to produce integrated circuits) being available in 1970s, leading to the power MOSFET in 1978. And then the MOSFET structure was combined with the transistor as the Insulated Gate Bipolar Transistor (IGBT) being available in 1980s and the wide acceptation in the 1990s, can now be seen as the working horse in many kinds of power electronic applications. The today's silicon power semiconductor landscape is shown in fig.2

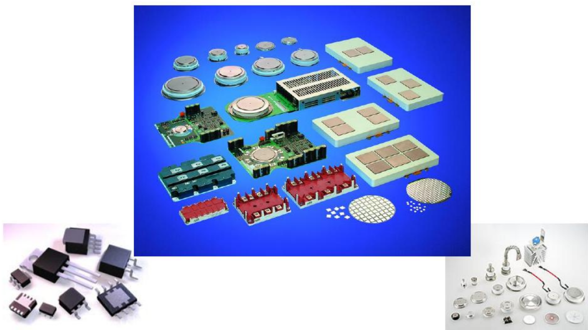

Figure 2: Power semiconductor devices

An indication of the placement of the type of semiconductor along the voltage, current and switching frequency axis is given in fig.3.

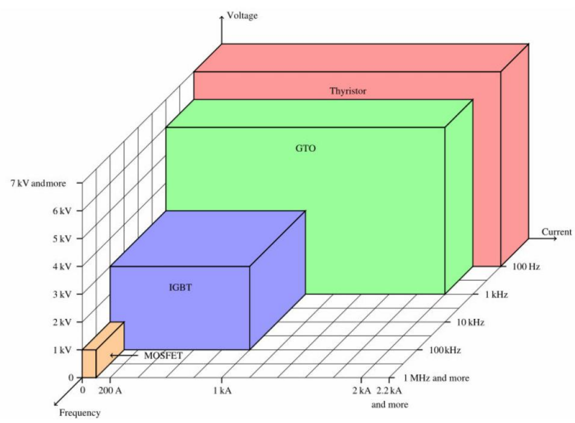

Figure 3: Approximate power semiconductor performance ratings

To use a semiconductor device for an application voltage beyond the voltage rating of the component, one can series connect devices, use different converter associations by means of transformer connections or use a multilevel converter. Some possible converter associations are shown in fig.4, that obviously might have a multilevel converter implementation. Multilevel voltage synthesis is here possible as well by using the transformer connection and or modulation.

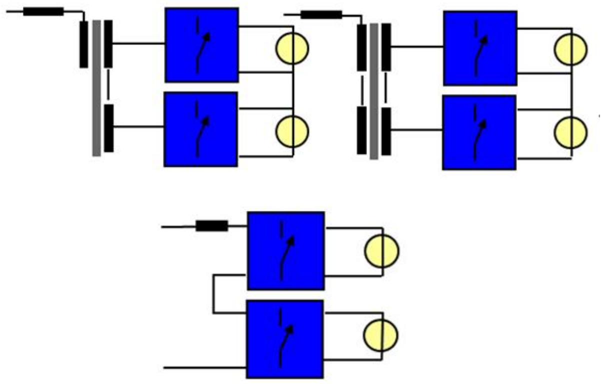

Figure 4: Converter associations in order to reach higher voltages beyond the capabilities of the used semiconductor devices. The third associations without using a transformer could be used for reactive power.

The third association in fig.4 requires isolated dc sources for the conversion of active power, implying a transformer on the dc side, wherein the fundamental problem can be found to avoid this aiming at a modular solution. This important aspect will be discussed in the section multilevel converters.

4. Form and function

Power electronic circuits change the character of electrical energy, from dc to ac, from one voltage level to another, or in some other way. The part of the system that manipulates the flow of energy is the power circuit. Therefore it is the frame for the rest of the system's components such as control parts or the thermal managements parts and so on. The power circuit has a basic topology to which we add the other circuit components as control, filters, protections etc. Although these additional elements are important they do not affect the function of the power circuit. Their purpose is to modify certain aspects of it such as rates of rise of voltages and currents, for instance.
Therefore, the basic form and function need to be considered on forehand starting with for instance the most elementary 3-pole commutation cell as shown in Fig.1, considering forced commutation switching devices. Before discussing the wealth of circuit connections – topologies- that can be created treating in this paper basically the recent dc to ac multilevel converters. Some notes will now be given first, that are so fundamental for

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power electronics and its evolution of development. First, power electronics is there to process electrical energy, nowadays with the usage of semiconductors, by means of a non-dissipative switching process. Apparently, here appears an important driver for the technology as in any other electrical discipline to strive for the lowest possible losses. This does not only imply the semiconductor where new alternatives are now heavily researched worldwide, but also passive components, together with continuously optimizing the switching processes by applying improved control methods.
The function is therefore to adapt and control electrical energy, as provided by a primary energy source, to the characteristics of the load. The network that accomplishes this adaptation is thus called converter (fig.4).

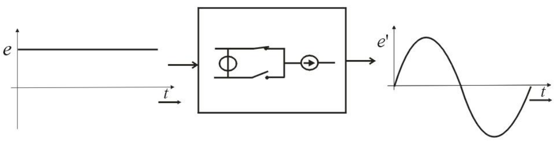

Figure 4: Static dc to ac conversion

The primary energy source can be for instance a battery, solar panel, fuel cell, generator etc while the load can be anything from a motor to the connection with the power system. Not at all in trying to be complete, rather than to focus now more on the 'adaptation' in view of the ideal sinusoidal ac waveform shown in Fig.2. Multilevel converters are the effective answer to accomplish this in synergy with the dc commutator in Fig.1. A multilevel converter is a type of converter that can synthesize from a dc voltage an approached sinusoidal waveform (fig.5).

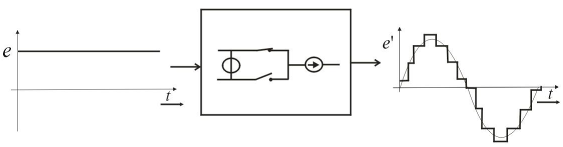

Figure 5: Static dc to ac conversion (voltage synthesis) using multilevel converter

In an attempt to be abundant mentioning the synergies with multilevel converters, the number of windings in the machine is increased to achieve a more constant dc voltage (Fig.1), or divided in several branches instance with several windings in series in each to increase the voltage. The spatial distribution of the windings (i.e. pole placement) to achieve the required 'current-coverage' (Ampere/meter) in order to approach as said that the radial component of the magnetic induction approaches an sinusoidal shape. As will be shown next, with an example of basic commutation cells, multilevel converters show some similarities.

5. Multilevel converters

Many publication exist on multilevel converters, the concept as such, modulation, control etc. Let's consider here the voltage sourced once, since they are the most dominant in application. Multilevel gained industrial interest with the appearance of the Neutral Pointed Clamped converter [5]. Followed by the flying capacitor circuit [6], and recently followed by the modular multilevel converter [7]. To get a grasp of different stages of development of the multilevel concept, the variety in possible solutions, and the evolution over decades its recommended to read [8]. Not to confuse, the cascading of converter cells, say as in [9], and see also fig.4, was definitely of interest due to the modularity and other aspects that will be mentioned later, but for active power transfer separated isolated dc sources were required provided by means of a transformer and a rectification stage. This fundamental problem has been addressed in [7] actually, opening a complete new fertile field of possible new solutions. That because, as introduced and proposed in [6], by having a intermediated voltage source, such as a capacitor, floating with respect to ground potential in the converter circuit, actively balanced by means of the switching process of the converter, took some time for wide acceptance. There are other so-called flying capacitor concepts, for instance, as in the Ćuk dc-dc converter. The usage of the flying capacitor as intermediate voltage sources for the ac voltage synthesis in power converters initiated many to study the fascinating natural balancing effect of the floating capacitor voltage, and recently, new insights on this phenomena can be found in [10], were this effect also has been studied for interleaved converters. The evolution of the flying capacitor continued into the stacked flying capacitor circuit, as will be shown in the next section or into so-called cross connected cells in [11].

6. Parseval

Parseval as applied to the Fourier analysis is about quantities that are in proportion to power or electrical energies. Parsevals theorem can be written in its general form as,

$$\frac{1}{T}\int_{-T/2}^{+T/2} f(t).\,g(t)\,dt = \sum_n F_n.\bar{G}_n, \qquad (1)$$

where $f(t)$ is the voltage for instance, $g(t)$ the current, and obviously the product of these two gives the power, which according to (1) equals the sum of the product of the Fourier coefficients of voltage and current. Consider now a voltage $u(t) = \hat{u}\cos(\omega t + \varphi)$ and a corresponding current $i(t) = \hat{\imath}\cos(\omega t + \gamma)$, using (1) gives then

$$\frac{1}{T}\int_{-\frac{T}{2}}^{+\frac{T}{2}} u(t).\,i(t)\,dt \qquad (2)$$

$$= U_1 I_{-1} + U_{-1} I_1 = \frac{\hat{u}\,\hat{\imath}}{2}\cos(\varphi - \gamma)$$

the average power over a fundamental period of a sinusoidal voltage and current.
Applying Parseval on periodical non-sinusoidal voltages and/or currents, could be a square wave for instance. The current could be a square wave even in case of a resistive load or a periodical sum of exponential functions in case of an inductive load for instance,

$$\frac{1}{T}\int_{-T/2}^{+T/2} u(t).\,i(t)\,dt = \sum_n U_n.I_{-n} \qquad (3)$$

$$= \cdots U_0 I_0 + (U_1 I_{-1} + U_{-1} I_1) + (U_2 I_{-2} + U_{-2} I_2) + \cdots$$

were the total average power is equal to the dc power plus the power of all harmonics separately.
With the aim, and recalling the adaptation, multilevel converters provide an effective means for power conversion, approaching providing fundamental power with minimum or no filter requirements. It should be emphasized though, that multilevel converters are most suited for high power applications since for medium, for sure for low power low voltage applications the adaptation can be reached by using high frequency Pulse Width Modulation while moving the harmonic products up into the frequency band where they are easier to filter [12,14]. High frequency operation of the semiconductor switching devices causes however losses, while multilevel converters have great potential with its reliability, surge power capacity and efficiency.

7. Multilevel topology synthesis

As already mentioned, capacitors are now in the new field of possible solutions, usually used lately, as intermediate voltage sources that take part in the voltage synthesis in multilevel converters. Starting again with the fundamental commutation cell as shown in fig.1. Around a forced elementary commutated cell, always a 3-pole can be recognized. This cell is at least required to let operate together sources and/or loads that has the character of a 'current source' or 'voltage source'. In terms of operating quadrants this cell can be operated in 2 quadrants. To demonstrate that this cell is the building element towards other configurations two well know examples are shown in fig.6 as the neutral point clamped and flying capacitor circuit, respectively.

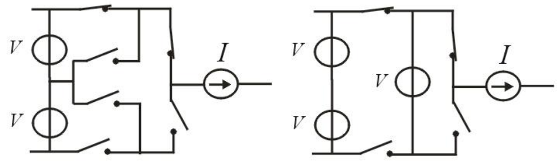

Figure 6: Left: NPC, Right: Flying capacitor 3 level cells

Copying the cell in fig.1 with itself we get a double cell as shown in fig.7. This cell can since duplicated operate in 4 quadrants.

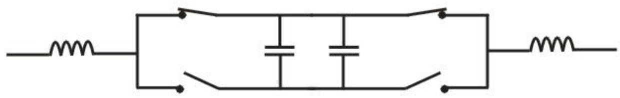

Figure 7: Double commutation cell

This double commutation cell can be series connected to get a chain of cells that resembles a dynamic controllable ac voltage source as shown in fig. 8.

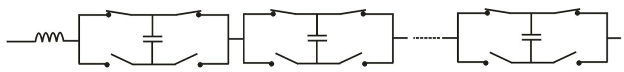

Figure 8: Series connection of double commutation cells

Commutation cells can also be stacked in a way as shown in fig.9. This method is known from the stacked flying cell topology [18].

Compared to the double cell in fig.7, that is able to generate 3 voltage levels including zero, the stack commutation cell in fig.9 is able to generate multiple voltage levels. Also, the stacked examples at the bottom of fig.9 with reduced number of switch functions is able to so and eventually the cell capacitor voltages can differ, and when binary switched even more combinations can be found.
It would be even possible to series connect stacked commutation cells but let's constrain us here considering a trade-off between number of switch functions used and complexity of control.

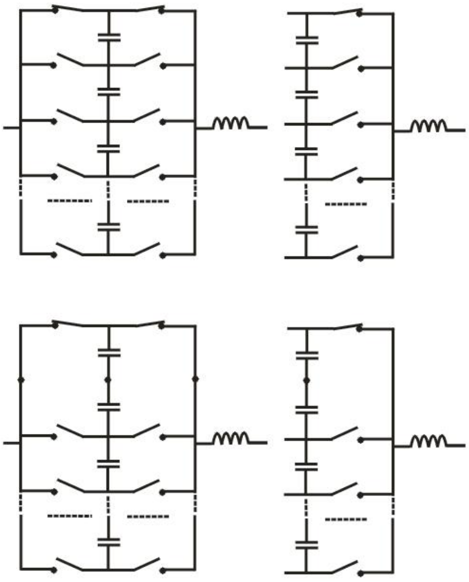

Figure 9: Stacking of commutation cells (top), with reduced switch functions (bottom)

Considering again the commutation cell in fig.1, and to emphasize that it can be used as a building block to develop further circuit topologies, 2 examples will be shown by imbricating the cells that lead to the concept in [7] as shown in fig.10, and using the double commutation cell the topology as shown in fig.11.

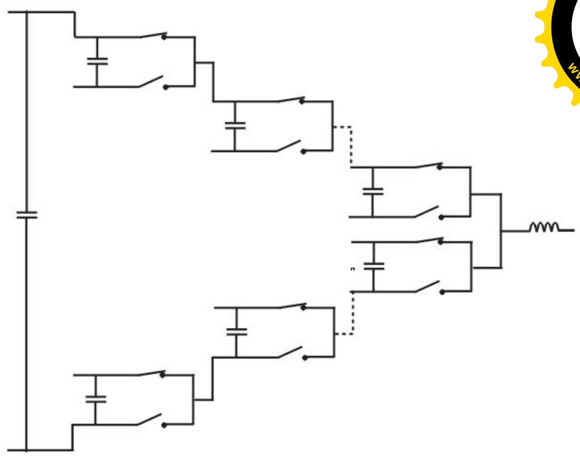

Figure 10: Imbrication of commutation cells

The topology in fig.10 is the modular multilevel using many intermediate floating voltage sources, such as capacitors or batteries.

This topology addresses,

- Low losses, low switching frequency slightly above the fundamental frequency
- Voltage scalability due to the simple cascading of identical cells
- AC filters nearly eliminated, due to the pure synthesized sine wave voltage (say above 20 cells per arm)
- Mechanical simplicity

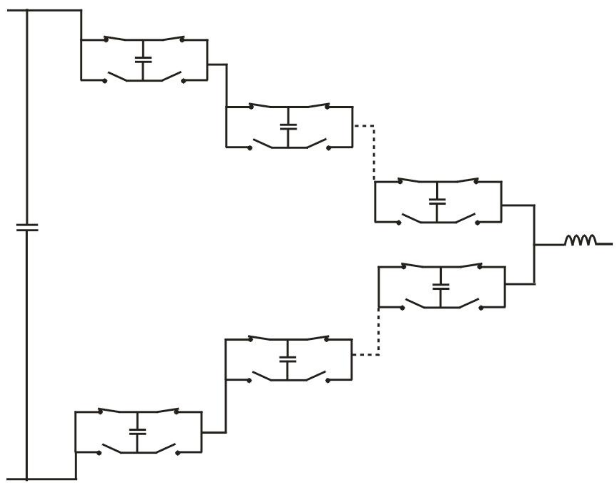

Figure 11: Imbrication of double commutation cells

In view of fig.8, chaining the commutation cells either with single of double commutation cells the constant dc capacitor voltage can be replaced by a string of these cells as proposed in [16,17]. That principle can be used in one of the converter associations of fig.4 for instance as shown in fig.12.

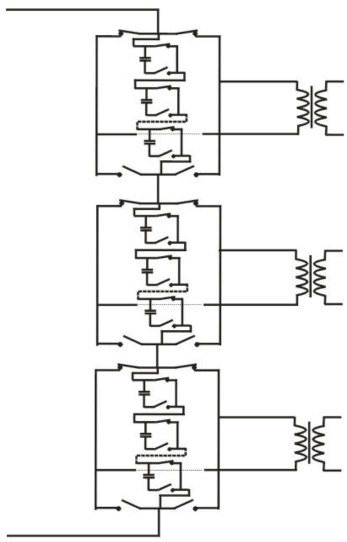

Figure 12: Stacked converter with dynamic capacitor

The principle is here that the dynamic capacitors consisting of a string of cells pre-modulates fundamental sinusoidal voltages that in turn are directed to the ac side.

8. Conclusions

From the very first commutation principles to the wide spread use of solid state switching devices conversion principles for dc to ac have been and are still mainly based on two level converters. As mentioned, the advances in improved efficiency, compactness etc are driven by semiconductor development , better controls, cooling, new materials and what can be considered more. Generally the switching frequency is magnitudes higher than the fundamental frequency. With multilevel converters the number of switch functions is increased, power ratings can be increased, and lately with the modular approach using strings of commutation cells the switching frequency can be adjusted slight above the fundamental frequency, while synthesizing almost a sinusoidal voltage waveform with little or no filter requirements. As multilevel converters provide redundancy and has a high reliability, low losses, while the component cost reduce even further, while steel and copper prices increase, power electronics converters might take over some tasks of transformers as being fast dynamic controllable nodes in future grids and connecting renewable generation. Also, increase use in Variable Speed Drives (VSDs) or Uninterruptable Power Supplies (UPS) and many other applications, even in low voltage applications. Applicability of modular multilevel converters using MOSFETS into for instance the low power area seems to be feasible, but trade- offs need to be found with the current state-of-the art two-level converters.

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