PRESENT AND FUTURE OF POWER ELECTRONICS (I). INTRODUCTION AND HIGH POWER APPLICATIONS

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ABSTRACT

Power electronics has applications throughout countless fields of industry, war, transport, public buildings, communications, informatics, domestics and electro-medical equipment. Although normally ignored, as it serves the subsidiary roll of supplying energy to equipments and electrical setups, its applications and implantation are constantly growing. Its power range is very large, covering from more than five thousand megawatts in DC transmission, to tenths of watts in micro-power converters for mobile telephones and personal medical apparatuses. Its multidisciplinary character and universality makes of power electronics a technological synergic vortex where semiconductor physics, electrical engineering, heat transfer thermal management, control theory, industry communications, transport and almost every industrial process are brought together. This paper, first of two, considers the general aspects of power electronics and its applications in the high power range.

Key words: Power electronics, electronic regulators, static converters, power supplies, uninterruptible power supplies, voltage stabilizers, motor speed controllers, line conditioners, static transfer switches, power quality.

1. CONCEPT

Power Electronics modifies, controls or converts electric energy, in its different forms of use (direct current at different voltages and alternating current at different voltages and frequencies), using electronic devices. These devices are mostly semiconductors, although vacuum or gas valves are sometimes used. Although some controllers can use electromechanical devices to achieve their goal, they must nevertheless use electronics in their control circuits. An example of this circumstance are the voltage stabilizers using tap-changers where electromechanical devices are used to connect the required transformer tap to the supply and the power electronics versions that use thyristors or transistors for the same purpose. The functions and power rating of the power electronic converters depend mainly on the topology used and the active electronic devices available. On some occasions, the topologies to carry out definite functions have been invented before the suitable semiconductors for the application were available. Some inverter circuits designed at the time of electronic valves, had to wait until the development of thyristors and power transistors to find a practical application due to the high voltage drops encountered when using valves.Power electronic equipment usually include three main sections as shown in Fig.1, *power circuit* where the electric energy is regulated or converted using valves or semiconductors, *control circuit* in charge of controlling the devices in the *power circuit* and the *surveillance and monitoring circuit* that includes the measuring devices, remote monitoring and sometimes some sequence control. In simple equipment the monitoring and surveillance circuits are not included and the control circuitry is integrated into the power circuit.

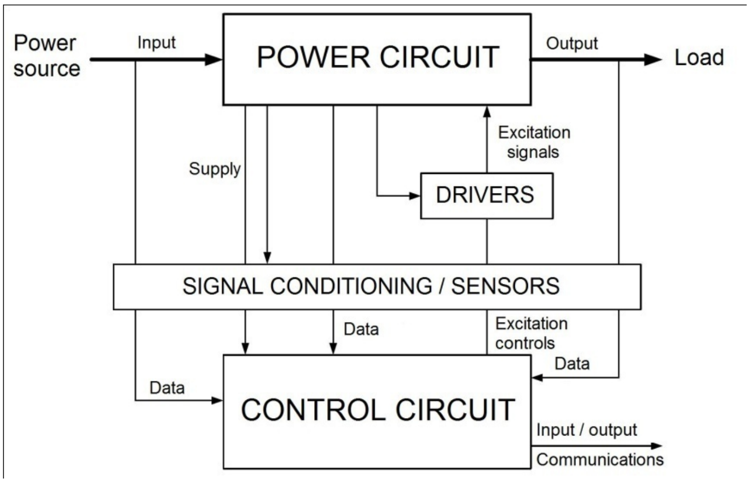

Fig. 1: Block diagram of a generic Power Electronics equipment.

2. DEFINITION

Before presenting a definition for *Power Electronics*, it must be pointed out that this field includes applications that handle only fractions of a watt as the electro-medical devices both implanted and non-implanted. Therefore, the main characteristic of this field of electronics is not handling high powers but converting or controlling energy with the highest efficiency. Similarly, the output amplifiers in transmitters used in TV and radio handle kilowatts and they are not classified within power electronics but rather in the signal electronics field since the main characteristic is amplifying signals with high fidelity whatever the power rating keeping the efficiency, although important, as secondary. Likewise, the electronics used in mobile telephones to regulate the battery voltage, that handle less than 1 watt, must be included within Power Electronics and not in Signal Electronics. Here, efficiency of conversion is the priority, to make the battery charge last as much as possible, whilst the output characteristics, though also of great importance, are secondary. Having clarified these differences, the definition of power electronics which is most commonly accepted by experts [1], p. 4 is presented: *Technology that modifies the way in which conducted electric energy is presented by means of current controllers that act on the flow of electrons with priority on efficiency over fidelity of the desired output waveform.*

3. BREIF HISTORY

Although this paper focuses on the present and future of *Power Electronics,* it is convenient to go back to its origins. Like in any other field of knowledge, the description of its birth and evolution shows, more than any definition, its object, nature and future. *Power Electronics* started with on-off electric current switching devices controlling the flow of electrons (vacuum diodes and valves for low powers and gas filled valves for higher powers, Fig. 2) to convert and control electric energy for several uses (supply of radio transmitters and receivers, welding and in industrial processes). Important breakthroughs were the invention of the mercury arc rectifier valve in 1901 by **P. Cooper**, the vacuum diode in 1904 by **A. Fleming** (applied to the power supplies of radio receivers and transmitters), the thyratron tube between 1914 and 1928 by **I. Langmuir** and **A. Hull** (soon used for controlled rectifying). The anonymous invention of the selenium diode followed in 1930 in its hand crafted form. In 1940 the ingnitron valve was introduced by *Westinghouse* and others (used mainly on controlled rectifiers for welding). With these devices several thousands of amps were controlled at voltages ranging up to 20,000 V with a relatively low voltage drop (18V, approximately 0.1%) in the on state. By reducing the losses relatively this field of electronics became a technology capable of handling high powers efficiently.

Fig. 2: Three-phase mercury arc rectifier valve, 150 A and 150 V made around 1940 by Electric Construction Company LTD, England. By courtesy of Laboratorio Mahedero, EII, Badajoz.

Nevertheless, it was not until the arrival of power semiconductors that power electronics took off due to the simplification in design by the reduction in size, cooling requirements and auxiliary circuitry. Following the invention of the transistor and the junction diode by **W. B. Shockley**, **J. Bardeen** and **W. H. Brattain** in 1950, bipolar transistors, Fig. 3, capable of handling 200 A and 2000 V were developed between 1950 and 1970. In 1951, **S. Darlington** in the *Bell Laboratories* cascaded several of these devices to improve their current gain at the cost of commutation speed. The big step forward came with the advent of four layer semiconductors (thyristors in their different types: SCR or *Silicon Controlled Rectifier*, GTO or *Gate Turn-off Switch*, TRIAC or *Triode AC Semiconductor*) that allowed higher currents as well as voltages. After the introduction of the SCR by *General Electric* in 1957, new semiconductor diodes and controlled devices, capable of handling several thousands of amps and volts, were soon developed. The on-state voltage drop of these devices, 1 V to 2 V, which was much smaller than that of the ignitrons, allowed the use of this technology in the low voltage sector with low losses.

Fig. 3: First germanium bipolar power transistors with TO-3 capsule from Sylvania, 1956. They reached up to several amps and some tens of volts. By courtesy of J. A. Knight.

The main disadvantage of thyristors is their inability to revert to the blocking state, except for GTOs, without the use of auxiliary commutation circuits. The

Darlington transistors and later on the *field effect* devices, (FET or *field effect transistor*, and their power versions introduced by *Siliconix*, *International Rectifier* and *Siemens* in the seventies) were capable of controlling the on-off state through the gate with low power but were unable to handle really high currents and voltages. The development, between the 1970 and 1980, of the IGBTs, or *Insulated Gate Bipolar Transistor* (devices combining the bipolar technology for the power structure the FET technology for the control), allowed handling relatively high power with simple controls. These devices can be considered today, in their ability to handle thousands of amps with voltages reaching 6000 V, as the quasi-ideal solid state switch of the future.

From the 1980 onwards, power semiconductor devices have been integrated into the same capsule with auxiliary circuits for protection and switching control. The concept behind, is to obtain an intelligent power switch (*smart power*) that makes applications easier to realize.

The history of *Power Electronics* must mention the development of integrated circuits of high complexity that have allowed the sophistication of control functions and ease to implement them. At first, in the sixties, the control circuits were designed with discrete transistors and diodes. With the introduction of the first integrated circuits, ICs, with gates, flip-flops and operational amplifiers the design work was simplified. In particular, the development of the CMOS range of ICs (seventies) that operated with 15 V supply brought a greater noise immunity and wider use. This technology displaced the other family of ICs, the TTL or *Transistor Transistor Logic*, with zener diodes integrated for protection. In 1971, *Intel* commercialized the 4004 microprocessor, that with its 2300 transistors and 60.000 instructions per second, that started the expansion of programmable devices towards the relatively powerful and cheaper devices (*microprocessors, microcontrollers*, digital signal processing like *DSPs or Digital Processing Devices* and programmable logic like PLDs or *Programmable Logic Devices*) now in use. It must be noticed, that normally, the price of a single power semiconductor of a medium to high power system is more expensive than the control devices. In summary, in power equipment over 100 kVA, the cost proportion between design and components is such that it is worth spending time optimizing the design to gain in reliability and cost. On the contrary, the cost of control devices is so small in comparison with the power section that it is worth spending in development to improve the design and reliability.

4. MULTIDISCIPLINARY CHARACTER

In *Power Electronics* many different disciplines converge: solid state Physics (since most of the active components are semiconductors); electric circuit theory (electronic circuits derive from them), electro-technical disciplines (that cover relays, contactors, power factor correction capacitors, etc.) digital electronics (which is increasingly used in control circuits) and analogue electronics used in monitoring of signals and in analogue control circuits; control theory (applications to control circuits); static magnetic devices (single and multi-winding transformers and chokes) as well as the rotary magnetic machines (electric motors and generators that must be controlled); electrochemistry (batteries and electrolytic capacitors); thermal management (equipment and device cooling); industrial communications (used for remote supervision and control of converters and critical electronic systems); mechanical and industrial construction (electronic equipment handling large powers weigh several thousands of Tons and take up as much space as a soccer pitch, like the high voltage DC transmission systems HVDC); reliability and maintainability theory (it studies the functional association of components and sub-systems to improve the continuity of operation and ease of repair); electromagnetic compatibility (the equipment must not generate interference that affect other systems or its own control circuit and must be robust enough to accept interference generated by others); simulation techniques (as power equipment are costly it is convenient to use well proven simulation techniques at the initial stages of the development to reduce problems).

Power Electronics [2], [3] concentrates fields like electronics, electricity, mechanics and chemistry much the same as *Robotics* does with the fields of automation, software and artificial intelligence. This latter one is established at a more abstract level and combines as subsystems electrical, mechanical and electronic devices. If at the early stages the same designer was able to cover all the different aspects of *Power Electronics*, nowadays specialization in the fields of power or control circuits, mechanical design or thermal management is growing, especially in medium and big enterprises. Nevertheless the power circuit design is still considered the most critical since it defines the system's possibilities and the most important part of the cost. Furthermore, it is easier to move from power circuit design to control design than it is to move from power to control design since power covers more technical and critical aspects.

5. PRESENT AND FUTURE OF COMPONENTS, TOPOLOGIES, CONTROL AND CONSTRUCTION OF EQUIPMENT

Power Electronics systems depend on the availability of the different aspects required by them [4] [5] [6], like components, topologies (where it is becoming increasingly difficult to innovate), available control devices (highly sophisticated today), control methods and construction technology (that in the case of power switches, transformers and chokes have reached a very high reliability, unlike capacitors where reliability is not so high).

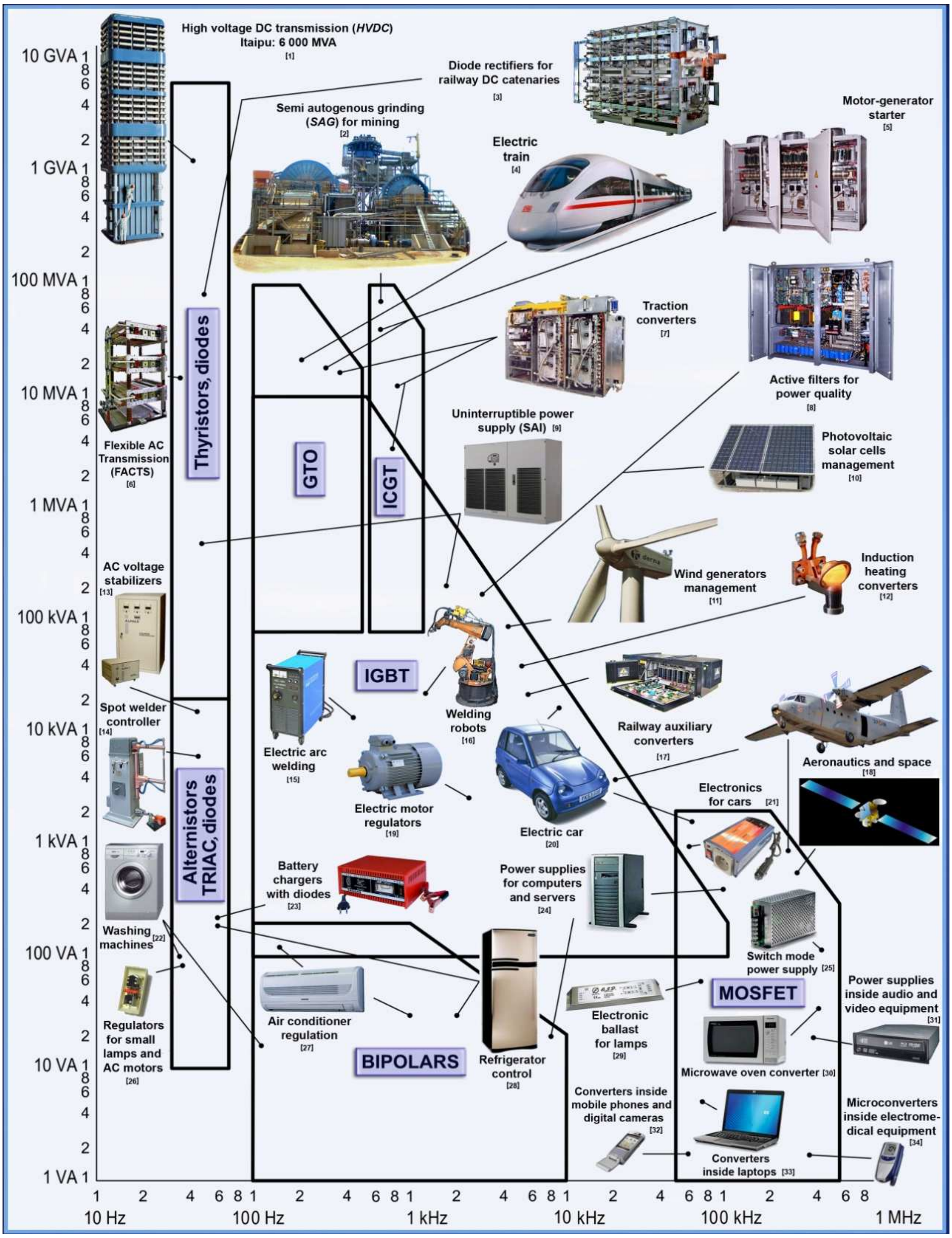

Fig. 4: Power Electronics equipment classified according to output power (vertical axis) and commutating frequency (horizontal axis). By J. C. Campo, S. Martínez and S. Monteso. Available as a high resolution file in www.revistadyna.com.

5.1. Power components

The specific components used in *Power Electronics* are the a.c. and d.c. switches based on semiconductors, capacitors, chokes and power transformers. Power resistors are also included for snubbers and filter discharge.

5.1.a. Power switches

The evolution of power switches has been very important from the introduction of the first power transistor and silicon controlled rectifier up to the present direct current switches (transistors and thyristors) and the alternating current (TRIACs and alternistors). The main contributing factors have been, the increase in current and voltage handling capability, the reduction in on-state voltage drop, and the increase in commutation speed. The design of these components focuses mainly on the fields of application, hence the transistors and asymmetric thyristors are developed for use as d.c. switches whilst TRIACs and alternistors for use as a.c. switches. Nevertheless, many transistors and thyristors can be used successfully for d.c. and a.c. applications (for a.c. applications the devices are connected back to back).

The main efforts now, are placed in reducing the on-state voltage drop and the switching times, in bipolar transistors and MOSFETs (*Metal Oxide Silicon Field Effect Transistor*) and IGBTs. This last family can reach currents of 4 kA and voltages of 6.5 kV. Further research is being carried out with silicon carbide (SiC) semiconductors that that are expected to reach voltage ratings higher than 10 kV. Thyristor technology is also pursuing improvements in the GTO, such as the IGCT (*Integrated Gate Commutated Thyristor*), preferred to the GTO in the faster controllers for high power motors. The fields of application of these semiconductors, together with the power ratings and switching frequencies can be seen in the chart presented in Fig. 4 Fields of Application of Power Electronics (this chart can be seen with higher resolution in www.revistadyna.com as additional data to this paper).

The programmability of the dynamic characteristics of power devices, that allows specific adjustment and protection in different applications, and the integration of several semiconductors into programmable bridge configurations, characterise the evolution of power semiconductors. These advances, when designing power converters, allow concentrating more on the load requirements, than on the static switches since their characteristics can be adjusted. Design is further simplified by using the drivers that are usually integrated. Both these lines of development, plus the improvement in the switching characteristics of the devices (that have reduced or even eliminated the need for snubbers or clamping circuits) have contributed to the reduction of the design time dedicated to power semiconductor protection and have improved the reliability. The future of power switches seems associated with wider band operation prohibited to silicon devices. For these, silicon carbide and synthetic diamond are considered adequate materials, especially for high power devices, since they can handle higher voltages and operate at higher temperatures than silicon, thus increasing integration possibilities and efficiency improvement [7].

5.1.b High level integration of power and control devices. Basic “precooked” converters

One of the most dynamic lines of development in power converter design is the integration of power semiconductors, not only with control elements for driving and protecting the power devices (technology that gave rise in the 80s to the so called intelligent power semiconductors or *smart power devices* and in more recent years to the power devices with programmable characteristics) but also to sophisticated control and protection circuits (that include small chokes, capacitors and resistors) and configure complex sub-assemblies (like multiphase inverters that are easily programmed). Fig. 5 shows one of these systems, consisting of a three phase IGBT inverter developed for the automobile industry and that includes protection and high level control circuitry.

Fig. 5: Exploded view of a bridge inverter module with IGBTs for controlling electric motors in cars. The IGBT associated circuitry includes drivers, snubbers and control circuits for basic functions. The upper board shows the very high degree of integration achieved. By courtesy of Semikron.

5.1.c. Transformers and chokes for *Power Electronics*. Integrated magnetic components

The ever increasing switching frequencies in *Power Electronics,* has led to the development of chokes and transformers with special core and winding capable of operating at frequencies above 100 kHz. Cores made from ferrites and other ferric sintered materials, operating at reduced induction to lower core losses, are common in high frequency designs. In components above 1 kVA, multi-conductor windings, like Litz wire, to reduce the skin effect that in turn reduces the effective conductor cross-section are common.

Another important aspect is the integration, where possible, of chokes and transformers into the same core to reduce volume and increase reliability. This is important in equipment rated for several kVA because it reduces size and cost whilst increasing reliability. To achieve this “magnetic integration” designers take advantage of the magnetising characteristics and of the stray inductance to obtain series or parallel integrated chokes used for filtering, Fig. 6. These techniques are used where space is of great importance (as in auxiliary converters for railways and aviation) or where a high reliability is required (as in a.c. and d.c. ferroresonant voltage stabilizers and in *triport* U.P.S. for power stations, chemical industry and railways where they are still much appreciated due to their low maintenance requirements).

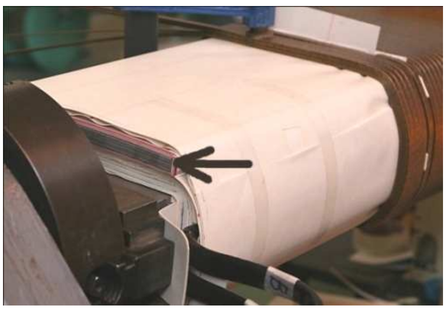

Fig. 6: Auxiliary iron column between primary and secondary in the transformer of an auxiliary converter for railways, 750 V d.c., 90 kVA + 17 kW. It reduces the coupling between windings and behaves as a series choke. By courtesy of SEPSA and Valdepinto S.L., Madrid.

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In equipment under 100 VA and very high switching frequency flat transformers integrated into the printed circuit boards are used thus greatly reducing production and assembly costs. The cores are usually made from very flat ferrites whilst the windings are built from several P.C.B. layers. Via this technology the concept of *embedded circuits*, born with digital circuits and exported to analogue electronics, extends to very low power transformers and chokes.

In the design of magnetic components for *Power Electronics*, finite element theory plays and important role in anticipating current and flux distributions, voltages and losses allowing design optimization by avoiding hot spots.

5.1.d. Capacitors for *Power Electronics*. Commutation capacitors and supercapacitors

Power Electronics increasingly imposes higher requirements on capacitors for commutation of semiconductors, capacitors capable of handling high currents and voltages at high frequency. These requirements impose a very careful construction of the capacitors in order to withstand the electrodynamic forces generated and to reduce the series inductance and resistance, Fig. 7. It is common to use metallized plastic films wound on a former for the construction of the electrodes with a heavy metallization on the edges connected to the terminals with short braids or multi-wire connections to reduce internal resistance and stray inductance. Other applications, such as filtering are covered by the classic dry capacitors. The self-healing characteristic of film capacitors is of importance since it has increased the life of these components.

Fig. 7: Commutation and snubber capacitors for GTO. They withstand high current surges and voltage peaks at a high frequency rates. By courtesy of WIMA and FACTRON.

Within the group of polarized or d.c. capacitors, the advent of very high capacity components has allowed their use in energy storage applications up to 1 minute, where the high discharge current Ni-Cd and lead batteries had difficulties. These enhanced characteristics, giving rise to the supercapacitors or ultracapacitors Fig. 8, have been achieved by greatly reducing the insulation layer using the chemical process called "*electric double-layer*", [1] p. 227. Due to this very thin insulation layer the maximum voltage of each cell is limited to a few volts although series connection is possible if higher operating voltages are required. The supercapacitors find applications, amongst others, in regenerative braking of electric vehicles.

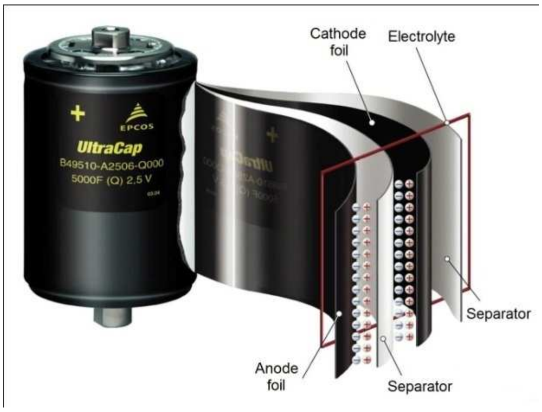

Fig. 8: Electrolytic supercapacitor, or double layer capacitor, with high capacity. It replaces high rate discharge batteries for discharge times under 1 minute. By courtesy of EPCOS.

Manufacturing reliable capacitors has proved a difficult task so the number of manufacturers worldwide has reduced. These are the most critical components in power electronic converters and those that influence reliability most, therefore special attention must be given when selecting a capacitor, generous overrating and use of accredited manufacturers is recommended.

5.1.e. Batteries and other energy storage devices

Some power electronic equipment require energy storage components with autonomies greater than one minute, where supercapacitors cannot be used. The uninterruptible power supplies, electric vehicles, portable electronic devices (all of which will be dealt with in the second paper) and other industrial applications, amongst others, can be included in these field.

Research into batteries has been growing, boosted by the development of portable equipment (such as lap-tops, photography equipment and mobile telephones) and electric vehicles. In this last field the use of the traditional lead and nickel-cadmium batteries live together with the nickel-metal hydride and the lithium-ion whilst efforts are being made to introduce the zinc anode batteries that have a high specific power (energy density). Furthermore, research is on-going in hydrogen fuel cells, for automobiles and other industrial applications, that generate electricity that is then treated by various types of power electronic converters. In applications where long storage times are required, like military applications, silver-zinc batteries are used. In high power high energy storage applications, associated with power quality and uninterruptible power systems (both analysed in the second paper) other storage systems based on compressed air, water pumping, superconductors and flywheels are being developed. Only a few systems are commercially available at the moment.

5.2. Topologies

The electric and electronic components that comprise a power electronic equipment are interconnected to build-up a circuit that accomplishes a predetermined task. When the equipment is complex, as in the universal conditioner shown in Fig. 13 and Fig. 14, the circuit is split-up into partial circuits, each with a different role and name. The “parallel converter” and the “series converter” shown in the figures mentioned above can serve as an example. Complex power electronic equipment are usually called systems as in the case of “uninterruptible power systems” used to supply critical loads.

It is understood by topology of an electronic equipment the organization by function and by circuit of its components. This name derives from the greek word *τόπος*

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that means place, and is used because of the analogy between an electric schematic, showing components and circuits, and a map showing places and regions. "Configuration" can also be used for "topology" with a similar meaning. These terms are also used for transformers and chokes of complex design as those discussed in section 5.1.c relative to integrated magnetic components.

From the topology chosen for a power electronic equipment, its fundamental characteristics can be derived, therefore the correct selection will enable the adaptation of the equipment to the task demanded from it. Research into power electronic equipment topologies requires a broad knowledge of the different circuit possibilities, understanding of the theory that governs electrical transformation [9] [10] and industrial experience in converter manufacturing, in such a way that practical advantages and disadvantages are always under consideration.

If any of the above requirements are not considered, misleading and incomplete results can be obtained when studying different topologies, a problem that occurs frequently. Examples of this are the reports by EPRI (*Electric Power Research Institute*) [11] [12] on the possibility of eliminating the cumbersome periodic maintenance of on-load tap changer voltage stabilizers by substituting the electromechanical switches by static switches with the same topology as the classical system. This configuration although possible, is not practical due to the huge amount of thyristors required for the great number of taps involved multiplied by the requirement to series connect devices due to the high voltages present. On the contrary, if compensating transformer topologies, not considered by EPRI, are used, such as those already applied in low voltage [13] and covered by patent 522.497, the result is technically and economically viable [14]. Furthermore, this topology allows direct installation in any point of the Grid.

It is not possible to describe in this general section the lines of development in topologies in the whole of *Power Electronics*. After presenting some of them here, relevant points regarding some applications will be further discussed.

In general, the development of new topologies has slowed down, except in a few cases [5] [7]. The most important line of innovation in power converters is in the integration (see 5.1.2) of complex circuits based on DSPs and FPGAs (see 5.4) for supervision and self-tuning (see 5.4) and for control and remote parameter monitoring (see 5.7). Nevertheless it is possible to discuss several aspects of the research into topologies that is on-going:

- <u>configurable converters</u> that save components and adapt to different operating conditions like traction and auxiliary converters for railways, described in 6.5, that have to operate with different catenary voltages. Other examples are the off-line uninterruptible power system UPS, that uses the same inverter to supply the critical load or to charge the battery depending on whether the supply voltage is present or not and the *Unified Power Flow Controller* UPFC or universal conditioners that transform into a UPS when the mains are missing, as will be discussed in 6.1.
- <u>multilevel converters</u> that reduce the voltage applied to each switch whilst reducing the harmonic distortion of both voltage and current.
- <u>distributed supply</u> to reduce the voltage drop on supply buses that in some cases go together with research into
- <u>improvements in high frequency modulation techniques</u> to reduce harmonic distortion in voltage and current.
- <u>frequency increase in power transformers</u> to reduce size and cost.

5.3. TOPOLOGY RESEARCH WITH IMMEDIATE COST CONTROL

It is of little use to develop new power electronic circuits if their technical characteristics are worse than those of previous designs or their cost is too high. The vast majority of publications presenting new equipment and circuit configurations lacks a means of auto-evaluation and it is only time that proves the validity of a *few and weaknesses of most. In a rational and ethical research environment, the presentation of a new topology should include an evaluation of it showing that it is as good as any previous topology both technically and economically. To do this, it is advantageous to use in Power Electronics a research method that includes immediate cost control. Below, a method of cost control [15] is summarized. It has been developed with the experience of over thirty years of practical realisations in the industry and the university. More than seventeen patents have seen the light using on this method, amongst others [13] and [18], and the equipment manufactured, according to the manufacturers, have been exported to more than forty five countries.*
The method has five phases.

1. *<u>Circuit analysis</u>: The operation of the new topology is studied establishing the equations of the evolution versus time of the electrical variables to further solve them with the existing methods: differential and integral calculus, Laplace transform, etc.*
2. *<u>Calculation of the stress levels on components</u>: Preparation of equations to define the main parameters and stress levels of the circuit components as a function of the converter specifications. These equations allow determining instantaneously if a topology is adequate for an application. This phase requires effort and discipline, but its application will show the practical interest of the new configuration (showing in many cases its lack of practical interest) thus simplifying further design.*
3. *<u>Component standardization and cost calculation</u>: After defining the components and stress levels, it is necessary to evaluate their cost. This task is simplified by transforming them into equivalent standard components of known cost, to obtain instantly an updated price list. For example, for each transformer and choke used, the power of an equivalent 50 Hz standard transformer with the same quantity of iron and copper must be deduced (concept of equivalent 50 Hz power, effective power [17] [18]) so that its cost can be obtained directly from a price list of standard double wound 50 Hz transformers, for which there are several manufacturers. Similarly, all other components must be converted to their equivalents of known price.*
4. *<u>Transformation of topological variants:</u> A power electronic circuit, normally has several topological variants, that although their circuit diagrams and applications are apparently different, are governed by similar equations that can be deduced from those corresponding to other topologies. Some of the proposed new topologies ignore that they are variants of previous ones, leading to the unnecessary repetition of research work. The thyristor inverter topologies proposed in the sixties and seventies are examples of this. Exceptions apart [19], many of the proposed new circuits later revealed to be close variants of known topologies [8] [9] [20]. Special methodologies have been proposed for this analysis [24]. For each topology variant the stress calculation and the component standardization steps must be followed.*

5. *<u>Technical and economical comparative study of solutions:</u> In the development of Power Electronic equipment, the circuit analysis, stress calculation and standardization of components must be carried out for a sufficient number of topologies, whether variants or not. Building a table to compare the technical and economical characteristics of the solutions proposed is very helpful for the comparative study. See examples in [22] [23] [14].*

5.4. CONTROL DEVICES AND FUNCTIONS

The control subsystem of a power electronic equipment is constituted by elements that establish the regulation mechanisms of the relevant variables, like voltage or output current, by the elements that drive the switches, that trigger the protections, that carry out functions on the power switches following special criteria and that inform or establish the interface with humans or other subsystems.

Regulation is carried out generally with analogue technology in electronic systems rated several hundreds of watts. Circuits that integrate several functions like pulse width generation, switch drivers, converter soft-start or error comparators for control purposes. The UC1525 is an example of these type of integrated circuits used in d.c. / d.c. converters. Nevertheless, there is an increasing tendency towards using digital technology in parts or in the total control circuit because of the increased flexibility at lower and lower costs [24].

To implement digital controls programmable devices like microprocessors, microcontrollers, *digital signal processors (DSPs)* or field programmable gate arrays *(FPGAs).* As digital control requires high speed calculations for some functions, the boundary between microcontrollers and DSPs has disappeared and each device has incorporated instructions or functions of the other. Consequently, *digital signal controllers* (*DSCs*), such as the 56800 family from *Freescale* and the C2000 from *Texas Instruments*, have appeared on the market that are adequate for medium power converters.

FPGAs have entered recently in strength the field of control in direct competition with digital processors and digital signal controllers. This component sector of the market is presently one of the most dynamic and its therefore foreseeable a increasing importance of these components in the field of control. The greatest advantage of these elements is the possibility to implement “custom devices” adapted to the application, very quickly and with great processing capacity, with the possibility of implementing any function or digital device even digital signal processors. Some families recently presented, such as *Actel Fusion*, include analogue functions.

The digital control circuits allow implementing classical functions, as protections, more efficiently by acting on the power system in an specific manner depending on the characteristics of the fault. The self-diagnosis functions included are gaining importance by monitoring critical signals and power supplies together with the ability to establish communications with other subsystems within the power equipment or other external systems. The possibility of including excellent and cost effective voltage and current references allows the implementation in control circuits of self-adjusting functions of the principal variables, such as output voltage in d.c. and a.c. power supplies, uninterruptible power systems (UPS) as well as power line conditioners. Fig. 9 shows a modern IGBT driver from *Semikron* that incorporates a FPGA.

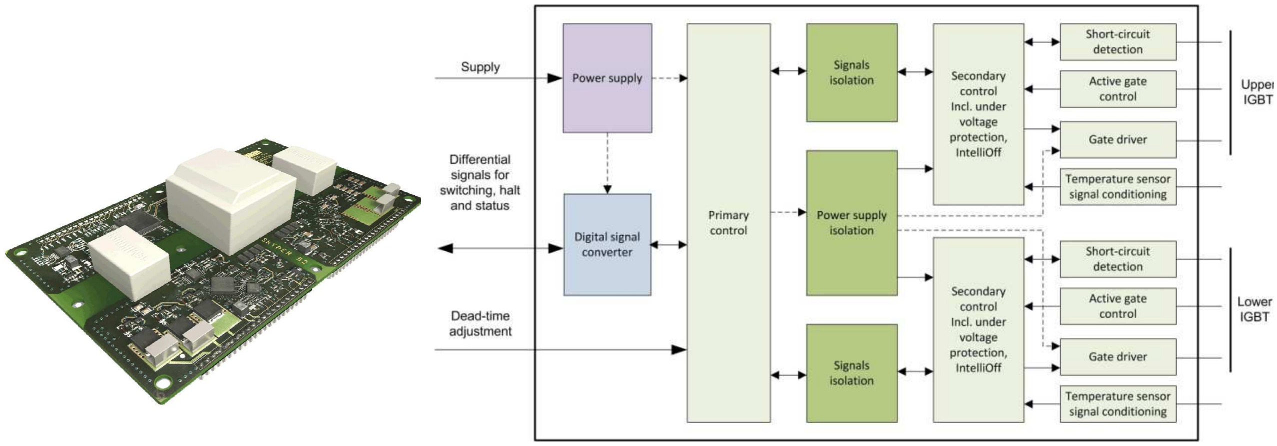

Fig. 9: Photograph and-block diagram of the digital driver for IGBT Skyper 52, from Semikron, with a FPGA core. It integrates a communications bus LVDS, several protection functions, adjustable dead times and input circuitry for temperature sensors, self-diagnosis and others. By courtesy of Semikron.

5.5. MECHANICAL CONSTRUCTION

In power electronic equipment and systems, especially in the in the higher power range, several construction problems converge such as cooling, insulation, electromagnetic compatibility, reliability and maintainability that impose a careful mechanical design. On occasions, as is the case with high voltage converters, Fig. 10, and with some equipment for aviation and space applications, mechanical design is as costly or more than electronic design and both specialists must cooperate closely throughout the development and construction phases. In these examples, as in many other with a high added value, the mechanical support is specific to each equipment or family of equipment.

Fig. 10: Reversible a.c./d.c. electronic converter for high d.c. voltage transmission of electric energy. By courtesy of ABB.

On the contrary, in equipment where demand is low and costs must be reduced, it is sometimes preferred to use universal prefabricated construction systems called “meccano type assemblies”, available as racks, cubicles and enclosures for electronic use. These standardised elements have experimented an important development and there are, today, specific modules for power electronics such as supports for power semiconductors, cooling units, cases with fins, Fig. 11, etc. Although their use is limited, the availability of modules, enclosures and accessories is ever increasing.

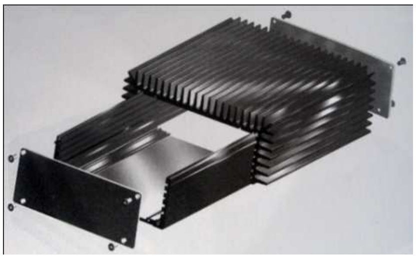

Fig. 11: Meccano type case with heat-sinks for small-power electronic converters. By courtesy of Fischer elektronik.

5.6. AVAILABILITY, RELIABILITY, MAINTENANCE AND STANDARIZATION

The availability requirements of power electronic equipment depend on the equipment they supply or control. Reliability is defined by the mean time between failures (MTBF) that can vary between 1 and 8 years (12,000 to 100,000 h) and maintainability by the mean time to repair (MTTR) which greatly differs on the type of equipment and varies between 1 and 5 h. High equipment availability is related to a careful electronic design that limits failures and a good mechanical design that makes repairs easy. The most critical electronic components are the power semiconductors and the capacitors (whether commutation or electrolytic for storage or filtering). To increase their reliability overrating of components both in voltage and current is a normal design practice. Power semiconductors, like IGBTs, are overrated by a factor of 2.5 to 3 times both in voltage and current [25]. Strategies to reduce the MTTR are based on the use of standard well proven components and subassemblies easily available in the market as well as a modular construction that eases the substitution of faulty subassemblies. In critical applications it is desirable to use modules in parallel that offer some redundancy and that can be substituted with the equipment in operation. This is the case with high power uninterruptible power systems or UPSs (above 300 kVA).

5.7 REMOTE CONTROL AND SUPERVISION OF POWER ELECTRONIC EQUIPMENT

The increasing complexity and responsibility of power electronic systems has led to the implementation of remote control, supervisory and diagnostic systems that are presently under development. Under the general name of *connectivity products*, manufacturers offer a range of auxiliary components for their equipment that through land lines or radio links allow control and monitoring from remote control rooms. In uninterruptible power systems remote monitoring is widespread due to the criticality of the equipment supplied. Remote control also reduces maintenance costs. Fig. 12 shows a concept diagram of a remote control system.

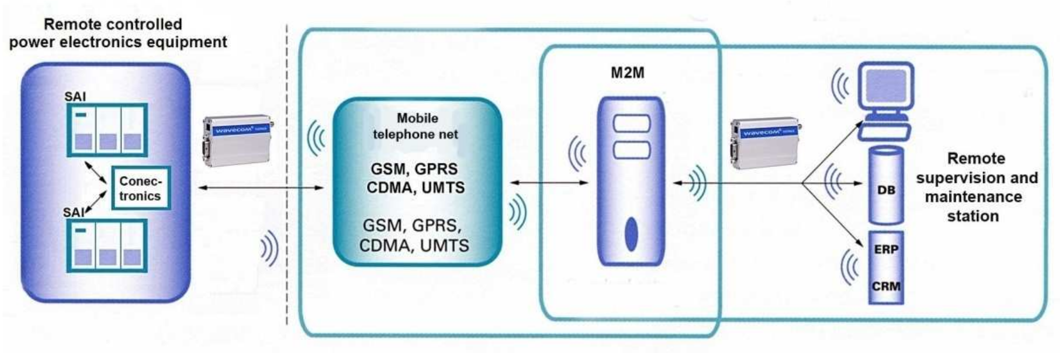

Fig. 12: The concept of remote control and maintenance of an Uninterruptible Power Supply (UPS) through wireless communications. Similar systems are also possible via cable or optical fiber telephone networks. Adapted from figures by Wavecom and Diode.

6.- PRESENT AND FUTURE OF HIGH POWER APPLICATIONS

In this section the numerous applications of *Power Electronics* are presented. These have been subdivided into groups attending to power handling levels and commutation frequency of the internal switches as shown in Fig. 4 (this chart can be seen with high resolution in www.revistadyna.com). All applications above 1 MVA, although not exclusively, have been grouped as high power applications. The medium and low power applications will be dealt with in the second paper.

6.1. FACTS AND HVDC TRANSMISSION

The limitations encountered in the a.c. transmission of electric energy due to distance, stability and power flow control, have led to search for new solutions based on Power Electronics. These have been grouped into a family known as *“Flexible AC Transmission Systems”* or FACTS [26]. This denomination appeared in the eighties when converters to increase the power handling capacity of distribution lines and to control the power flow through defined routes were studied. These converters can, in turn, be classified into two main types according to their topology: those constituted by capacitive or inductive impedances or multi-tap transformers with thyristor switches and those that use forced commutated converters as a controlled voltage source.

In the first group the reactive compensator *Static Var Compensator (SVC)*, the *Thyristor Controlled Series Capacitor* (*TCSC*) and the *Phase Shifter* can be found. Each of these systems acts mainly on one of the three parameters that control the transmission of power, i.e. the voltage, the line impedance or the transmission angle.

The equipment included in the static converter group offer better efficiency and the possibility of exchanging active power with the system, besides controlling the reactive power. This second group includes the *Static Synchronous Compensator* (*STATCOM*), the *Static Synchronous Series Compensator (SSSC)*, the *Unified Power Flow Controller (UPFC)* or universal conditioner, Fig. 13 and the *Interline Power Flow Controller (IPFC)*. Each type of converter controls a different parameter: voltage by parallel reactive compensation, line impedance by series compensation, the three parameters simultaneously (voltage, impedance and angle) or the transfer of power between two systems, respectively. The static switches used are normally IGBTs and the power rating range from a few tens of MVAs to several hundreds of MVAs.

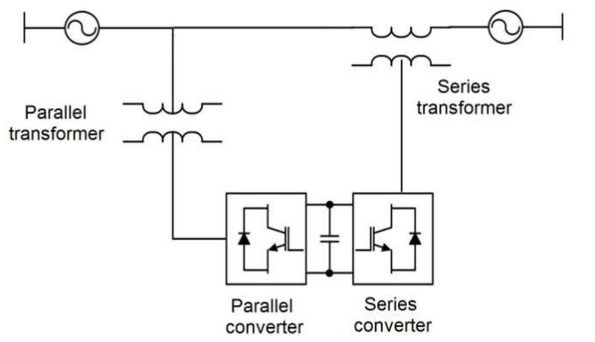

Fig. 13: Basic scheme of a unified power flow controller (UPFC) or universal power conditioner, the most versatile FACTS equipment.

In the unified power flow controllers there has been a great deal of research into topologies, obtaining systems that not only condition the output voltage and control the current taken from the supply, but also, in the case of brown-outs or voltage dips it reconfigures into a UPS supplying power, from the d.c. link capacitors, to the critical loads during 500ms (maximum time estimated necessary to clear a fault). See the first UPFC reconfigurable into UPS [16] [18] in Fig.14.

Fig. 14: Unified power flow controller (UPFC), or universal conditioner, with active filters in series (to control the voltage) and in parallel (to control the current) for a 400 kVA load. First UPFC reconfigurable to a UPS [16] [18] in the case of a total failure of the supply voltage by means of circuit configuration changes with no input, or output, static switches. By courtesy of IBERDROLA.

The *High Voltage DC Transmission Systems (HVDC)* [27] can be included in this last group. The transmission of power over large distances poses problems like phase shift and voltage drop due to the inductance of the power line. In d.c. transmission there is no voltage drop due to the line inductance and the cost of the line is reduced. The system consists on rectifying the three phase a.c., transmitting the resulting d.c. via one cable and ground or two cables to reconvert it back to a.c. with a rectifier operating in inverter mode. The classical solutions used thyristors associated in series and in parallel, but more recent configurations with enhanced performance, based on IGBTs, can control the active and reactive power independently. Whilst the first have power ratings up to 6000 MW, the second type reach 1200 MW.

Apart from the previously mentioned groups, there are the *Static Transfer Switches (STS)* that control the no-break supply of critical loads like hospitals, airports and industry with continuous processes by switching from one medium voltage supply to another. They are constituted by gate controlled thyristors (GTOs) or by thyristors with auxiliary forced commutation circuits. The main problem of these systems is the series connection of devices to cope with the high line voltages. The expected commercialization of high voltage silicon carbide semiconductors will greatly simplify these systems.

6.2. SOLAR FARMS

In solar electricity generating plants *Power Electronics* takes care of extracting the maximum possible energy from the solar panels to then convert it into voltages used in domestic installations or into the mains supply a.c. in higher power solar plants [28]. The d.c. adaptation is usually carried out by conventional dc / dc converters with transistors, usually with galvanic isolation between input and output to reduce personal safety and protection problems. Although IGBTs are increasingly used, MOSFETs are preferred when reduction of conduction losses is the priority. Research work is presently going on to reduce these losses by using semiconductors with especially low on-state voltage.

Conversion into a.c. is done with mains commutated thyristor inverters when power injected into the supply is small. For higher powers, self commutated high frequency inverters with IGBTs are used. They reduce current harmonics and allow the control of amplitude and phase angle thus regulating power factor.

In installations above 500 kW peak power, paralleling of inverters is used to make manufacturing easier and to increase availability. The d.c. link voltage supplied by the solar panels to these converters depends on the installed power and varies between 200 V and 1000 V. Coupling to the supply is done at medium voltage level when the installed power is higher than 500 kW. In some cases transformers are eliminated in order to increase plant efficiency using converters with multi-level IGBT topologies to reach the line voltage level (between 15 and 21 kV), Fig. 15.

Fig. 15: Sunny Central HE, 1250 kW. Inverter system for connecting photovoltaic solar plants to medium voltage lines. By courtesy of SMA Ibérica Tecnología Solar.

6.3. WIND FARMS

Electric energy generated by windmills is increasing continuously. In some countries, like Denmark, it reaches 20% of the total energy generated, which probably represents the maximum reasonable proportion of power to be generated by these means due to its availability characteristics. The power levels range from some hundreds or a few thousands of watts in d.c. applications for domestic or small industry use, to 500 kW in mills that inject energy back into the supply. There are experimental windmills that reach 5 MW. Wind farms reach installed powers of hundreds of megawatts, so the interaction with the network can generate important problems. In the smaller d.c. generators *Power Electronics* is used to regulate the output voltage and current delivered, normally batteries and other loads.

In the larger a.c. wind generators, *Power Electronics* is used to improve the behaviour of the generators that are subject to important changes in speed that make a direct coupling to the fixed frequency supply (50 or 60 Hz) very problematic. Synchronous generators would suffer from oscillations, mechanical stress and risk of over-speed, whilst induction generators that can damp the torque oscillations, present an inductive power factor and a high starting torque. In practice, four types of alternating current generators are used: the *Permanent Magnet Synchronous Generator (PMSG)* in the kilowatt range, the *Doubly Fed Induction Generator (DFIG)*, the *Induction Generator (IG)* and the *Synchronous Generator (SG)* for the kilowatt to megawatt range. The generator is used in conjunction with a power electronic converter that controls the voltage and current and consequently the power injected into the supply. For each of the systems in use there are several possible topologies. For the first two types, conventional thyristor inverters and IGBT inverters switching at high frequency are used. For the second, matrix converters can be used although "one of the disadvantages it presents is that it requires 18 static switches that increase the cost" ([29] page 2378 translated by the authors). Although research is on-going to improve matrix converters with multi-level topologies ([30] Fig. 2-6) the problem of the number of static switches worsens, since the number of IGBTs required by for the configuration in Fig. 2-6 [30], Fig.16 is 72.

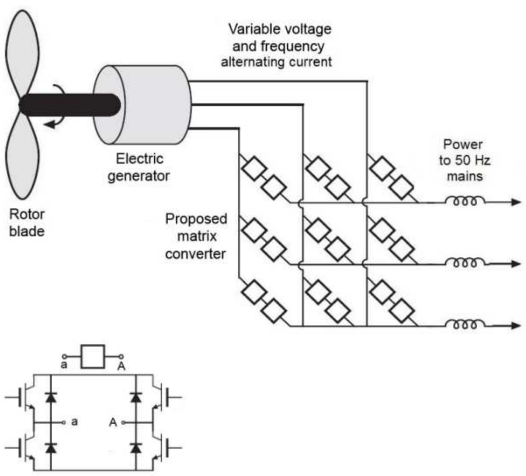

Fig. 16: Top: Multi-level matrix converter for controlling variable speed wind generators proposed by the *National Renewable Energy Laboratory*, Colorado, USA; modified from [30], fig. 2-6. Bottom: Every static switch represented in the upper figure by a small square has four power diodes and four IGBTs. The converter has 72 power diodes, 72 IGBTs and associated drivers with floating power supplies ([30], fig. 2-2).

Matrix converters are very attractive from a mathematical point of view and their possibilities in motor speed control amongst others are obvious, but their complexity in a practical implementation was made clear from the beginning [31], not only for the great number of semiconductors required, but also for the need to use floating drivers that generated undesired capacitive couplings. To obtain all the theoretical benefits from these topologies is seems necessary to wait until fast bidirectional switches with simplified optically coupled drivers are available.

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6.4. CONTROL OF HIGH POWER ELECTRIC MOTORS IN INDUSTRY

High power motors are those ranging from 1 to 100 MW that operate from medium voltage supplies. They are mainly used for pumps, fans and compressors but also in mining and cement industry for grinding as is the case with *Semi-Autogenous Grinding* (SAG) mills and Ball mills that use steel balls to improve the grinding, Figs. 17 and 18. Squirrel cage induction motors are used up to 15 MW in the high and medium speed ranges, wound rotor induction motors up to 15 MW in the medium speed range and synchronous motors from 10 MW to 100 MW in the low and medium speed ranges.

Squirrel cage motors use frequency converters with flux vector control. The main topologies for these converters are:

- Converters constituted by a double wound transformer with a 12 pulse diode bridge rectifier and a three level inverter with asymmetric or reverse conducting *Integrated Gate-Commutated Thyristors (IGCTs)* or high voltage IGBTs operating up to 4.16 kV.
- Converters with a multi-winding transformer where each winding supplies a low voltage module including a diode rectifier with its corresponding single phase IGBT inverter. These modules are then series connected in star configuration to generate a three phase voltage normally operating at 6 kV.
- Converters constituted by double wound transformers with a 12 pulse thyristor controlled rectifier and a current source PWM inverter equipped with reverse blocking IGCTs and output capacitors that supply the motors with sinusoidal waveform in the 6 kV range.

Wound rotor motors use the D*oubly Fed* systems with two PWM inverters, equipped with IGCTs or IGBTs, one connected to the rotor and the second connected to the supply via a transformer. They can be used with supplies up to 15 kV since they operate with the reduced rotor voltage. Using this control system the motors can be made to operate above synchronous speed and with a controlled power factor of 1 or even capacitive.

The synchronous motors also use frequency converters but the topologies used are mainly the *Load Commutated Inverters (LCIs)* which are constituted by a transformer and a 12 pulse thyristor controlled rectifier together with a thyristor current source inverter that is commutated by the motor. It uses the motor characteristic where by, when the motor is over-excited it behaves like a capacitor shifting the voltage phase and naturally commutating the thyristors. In some low speed applications, like in the mining and cement industries, thyristor cycloconverters commutated by the supply are used. For higher power levels (9 MW upwards) parallel connected inverters or motors with double stator windings supplied by inverters are used.

Matrix a.c. / a.c. converters or *Unrestricted Frequency Changers* with bidirectional static switches can theoretically be used in high power low speed applications or with wound rotor motors in the mining industry. Factors, like series connection of IGBTs or IGCTs with diodes to obtain reverse blocking capacity and the high voltage requirements, make their practical use complex and therefore, not advisable. Manufacturers, whilst awaiting for new higher voltage devices with simpler drivers, prefer using the conventional thyristor or IGBT cycloconverters as can be seen in recent reviews [32].

Fig. 17: SAG (*Semi Autogenous Grinding*) mill 12 MW (left) and ball mill 6 MW (right) for mining moved by wound rotor induction motors in Kansanshi Mine, Zambia. By courtesy of International Electronics, Alcorcón, Madrid.

Fig. 18: Speed controller with IGCT for a 6.5 MW ball mill. By courtesy of International Electronics, Alcorcón, Madrid.

6.5. TRACTION AND RAILWAYS

The traction converters are those that control the motors that drive a train. These have undergone a huge evolution in the last few years. Originally, the motors used were direct current motors supplied directly from the catenary. Speed was controlled by connecting resistors in series and by series / parallel connection of motors. Energy produced during braking was dissipated in the braking resistors. Later, with the advent and improvement of power semiconductors, the d.c. motors were controlled by chopper topologies based on thyristor technology that controlled the value of the voltage applied to the motors. The topologies then started including braking energy recovery systems that improved overall efficiency [33]-[36].

Nowadays, traction systems are based on three phase squirrel cage motors supplied from GTO or IGBT inverters controlled by powerful microprocessors. Normally the power semiconductors are assembled in modules that include drivers and protections or *Intelligent Power Modules (IPM)*. GTO current source inverters have been very widely used in the past. New topologies with multi-level inverters and control techniques (like vector control) have optimized motor driving and recovery of braking energy thus reducing the amount of energy burnt in resistors.

The inverter circuits use complex high frequency modulation strategies that control the amplitude and frequency of the fundamental of the output voltage, controlling the response of the traction motor whilst maintaining a low distortion in the output voltage. With respect to power semiconductors for traction applications the tendency today is to use IGBTs with their associated diodes, as these devices increase their voltage and current handling capacity and reduce the commutation losses.

The topology of the circuit used for the connection of the inverter to the catenary greatly depends on its characteristics. In direct current catenaries the inverter can be connected directly or via a chopper to increase the voltage operating range of the inverter. In alternating current catenaries the high voltage used is stepped down with a transformer that is then converted with a chopper-rectifier that in turn supplies the three phase inverter. In some cases, it is possible to eliminate the chopper-rectifier configuration using modern matrix a.c. / a.c. converters and high frequency modulation techniques. Some trains can operate from different catenary voltages by the reconfiguration of the topology of the converter, Fig. 19. Traction converters include important input filters to reduce harmonic injection together with other protections.

The total maximum traction power in trains today ranges from some 500 kW for some subway and transit vehicles to the 10 MW with a.c. catenaries in some high speed trains. The number of motors and converters in a traction unit depends on the application the reliability requirements and service availability.

Fig. 19: The TALGO S-130 train can change from European to Russian gauge at low speed without stopping . The locomotive develops 4800 kW at 25 kV a.c. and 4000 kW at 3000 V d.c.; maximum speed 250 km/h. Possibility of circulation by winding layouts. The double feeding voltage is accomplished by means of a reconfigurable topology in the power converter. By courtesy of Patentes TALGO, Madrid.

6.6. CATENARY SUPPLY

Power Electronics is present in the supply of catenaries for railways both surface and subway. Catenaries can be split into two main groups: alternating current and direct current. Alternating current catenaries are mainly used in high speed trains or for long distances. 25 or 50 kV / 50 Hz voltages are common, being supplied by substations with transformers operating off power lines ranging from 132 kV and 400 kV. Amongst others, the reduction of Joule effect losses, that allows a greater spacing of substations, must be highlighted as well as the reliability due to the system simplicity. In the list of disadvantages, the inductive voltage drops must be considered. *Power Electronics* is barely present in these systems, based on conventional electrical technology, except in voltage regulation.

On the other part, the d.c. catenaries are used in suburban railways, light rail and regional for medium distance railways, where the most popular voltages are 600, 750, 900, 1200, 1500 and 3000 V, although in English speaking countries a third pick-up rail (600 or 750 V), instead of the catenary is common. Direct current systems are inherently more complex than their a.c. counterparts, mainly due to the use of a rectifier module that usually consists of a Graetz bridge with 12. 18 or 32 diodes, Fig. 20. At first, mercury vapour valves were used, with a much smaller efficiency due to the on-state voltage drop, some 18 V versus the 1 V drop across diodes. Present day efficiency is excellent due to the small on-state voltage drop of silicon diodes together with their high blocking voltage (it can exceed 6000 V) and which avoids the need of series connection. The high current handling capacity of modern diodes (greater than 6000 A, Fig.21) also reduces the need for paralleling devices and makes assembly easier. The input to the rectifier is connected to a step down transformer and, in turn, its primary is usually connected to power lines between 15 and 40 kV. In both a.c. and d.c. catenary supplies, protections and filters are required for correct operation.

Fig. 20: Three-phase 6 MW rectifier for 3000 V catenaries containing 96 diodes arranged in double bridge, with 8 paralleled diodes per cellule. By courtesy of ADIF and CUADRELEC, Madrid.

Fig. 21: Silicon diodes, standard recovery, power range up to 5500 V, 4700 A, or 2800 V, 7385 A, in packages with 140 mm external diameter By courtesy of de ABB.

7. CONCLUSIONS

For quite some time *Power Electronics* has expanded its applications into practically every field of technology. Its growth can also be seen in the power ranges in use, that now reach power levels close to 7000 MVA (a power range that in the past was exclusive to electrical systems) in high voltage d.c. interconnections between large systems. The great contribution towards this expansion has been the development of the components in use, especially the solid state switches, that have seen an important increase in power handling capacity and switching speed. The control circuits and strategies are constantly being renewed, mostly in the field of digital technology. Converter topologies are also being renewed although not at the same pace.

The continuous development of *Power Electronics* has favoured the frequent publication of reviews on the present and future of the speciality [2]-[6]. In these pages, with the aim to offer the reader a less general view on the subject than is usually presented in other publications, but that covers the actual situation and the relevant applications in the present and future of *Power Electronics* we have gathered together

a group of authors that are in direct contact with the latest developments of many of the fields reviewed.

We would like to thank C. Piedehierro for putting together, reviewing and unifying the writing style of all the contributions received in the original Spanish language version, and P. Bradley for the translation into English.

8. ANEX: ACRONYMS AND ABBREVIATIONS

Acronym	Meaning
a.c.	Alternating Current
d.c.	Direct Current
CMOS	Complementary Metal-Oxide Semiconductor
DFIG	Doubly Fed Induction Generator
DSC	Digital Signal Controller
DSP	Digital Signal Processor
FACTS	Flexible A.C. Transmission Systems
FET	Field Effect Transistor
FPGA	Field Programmable Gate Array
HVDC	High Voltage D.C. transmission
IG	Induction Generator
IGBT	Isolated Gate Bipolar Transistor
IGCT	Integrated Gate Commutated Thyristor
IPFC	Interline Power Flow Controller
IPM	Intelligent Power Module
GTO	Gate Turn-Off thyristor
LCI	Load Commutated Inverter
LVDS	Low Voltage Differential Signal
MOSFET	Metal Oxide Silicon Field Effect Transistor
PLD	Programmable Logic Device
PMSG	Permanent Magnet Synchronous Generator
PWM	Pulse Width Modulation
UPS	Uninterruptible Power System
SAG	Semi Autogenous Grinding mill
SCR	Silicon Controlled Rectifier
SG	Synchronous Generator
SSSC	Static Synchronous Series Compensator
STATCOM	STATic synchronous COMpensator
STS	Static Transfer Switch
SVC	Static Var Compensator
TCSC	Thyristor Controlled Series Capacitor
TRIAC	TRIode A.C. semiconductor
TTL	Transistor-Transistor Logic
UPFC	Unified Power Flow Controller

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