PRESENT AND FUTURE OF POWER ELECTRONICS (AND II). MEDIUM AND LOW POWER APPLICATIONS

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Tel +34 944 237 566 – www.revistadyna.com - email: dyna@revistadyna.com

ABSTRACT

In a previous paper, t he general aspect and applications of high power electronics were reviewed. Several applications ranging from industry, transport, construction, communications, informatics, domestics to electromedical instruments were presented. The use of power electronics was only limited to the roll of feeding electronic equipment and setups. The managed power ranged from more than five thousand megawatts; in the high voltage DC electric transmission, to tenths of a watt in micro-power converters for mobile telephones and medical apparatus. In this second (and last) paper, the medium and low power applications, normally restricted in weight and size, are reviewed.

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. INTRODUCTION

In the previous paper [1], the characteristics of *Power Electronics* and its present and future have been reviewed covering the high power applications. In this second and last paper, the medium and low power applications are analyzed.

2. MEDIUM POWER APPLICATIONS

All Power Electronics applications from 1 to 1000 kVA are considered as medium power applications.

2.1. UNINTERRUPTIBLE POWER SYSTEMS (UPS)

Today, the high degree of development that the uninterruptible power systems have reached for the supply of computers and other critical loads and installations, can be verified. The output powers range from 0.5 kVA to several MVAs resorting to paralleling of UPS units for power levels higher than approximately 500 kVA. Above 50 kVA the systems tend to have three phase outputs. The main advantages of these equipment are their capacity to eliminate supply micro-cuts, dips [2] and mains distortion. The *Insulated Gate Bipolar Transistor* IGBT is the power switching device mostly used in both rectifier(much against the thyristor) and inverter modules, using high frequency switching techniques that allow reducing the distortion of the current drawn from the supply in the case of the rectifiers and the output voltage distortion in the case of the inverters. In the case of static switches used for paralleling of units and of mains bypass switches, thyristors are still in use, although for not very high powers IGBTs are beginning to enter due to their ease and speed of commutation. In the field of batteries for UPS there are few changes. The back-up times range between 5 and 30 minutes and the options are nickel-cadmium (for 5 to 10 minute back-up time) or lead (for back-up times 10 minutes and longer). In the over 10 million UPS installed, the most widely used is the lead acid stationary battery (for high powers) and the modular high density, maintenance free sealed battery (for medium and low powers). The trend is to use pure lead designs that offer a better high discharge capability, low maintenance and a good behaviour at high temperatures. High responsibility installations require medium time between failures of 100,000 hours (approximately 8 years).

Regarding the configurations and operation of UPS today, two systems coexist: one with the conventional topology with a rectifier and inverter rated for the full output power and the second based on active filters that interact with the mains and are rated for lower power than the output. There is sometimes great controversy, between sales departments of manufacturers, over the advantages and disadvantages of these topologies and their operation strategies together with other aspects of UPSs and loads, where the end user can be mislead due to the lack of clarity in the specifications. There are papers that can clarify some of these aspects [3]. It is advisable that, in big installations, the end user becomes familiar with the general operation and configuration of the system and analyses advantages and disadvantages of the alternatives proposed before acquiring a new system. It is also of great importance that the supplier of these systems has the technical knowledge and expertise on the one hand and the means and a qualified service team on the other.

In installations where loads and services are important, remote supervision of the UPSs, by the service departments using monitoring modules, connected via commercial telephone wireless or land lines, is increasingly in use. Furthermore, it is possible to remotely, from a centralized service centre, take measurements and carry out switching sequences to prevent faults or mitigate their effects until a service engineer arrives on site.

Fig. 1: Three-phase UPS, model 90-NET, 250 to 800 kVA, high efficiency, LIFE net compatible. By courtesy of CHLORIDE-CENER, Alcobendas, España.

2.2. INDUCTION HEATING

Induction heating acts on ferromagnetic materials subjecting them to a variable electromagnetic induction. The current flowing in the heating inductor generates, by Ampere's law, a field H that, in turn, by Faraday's law induces eddy currents (Foucault currents) in the treated object and heat it up by Joule effect, Fig. 2.

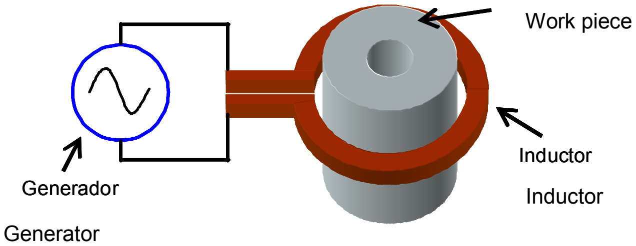

Fig. 2: Induction heating concept.

As the load on the electronic generator is inductive, its power factor is usually compensated by connecting capacitors in series or parallel with the heating inductor, giving rise to the two most common topologies: series and parallel resonant generators [4].

The series resonant generator is supplied from a voltage source and normally commutates with no voltage across the switching devices, *Zero Voltage Switching (ZVS),* to achieve soft switching in the anti-parallel diodes. As the power regulation is carried out by the actual inverter, it is supplied from an uncontrolled rectifier. Power regulation is done by varying the frequency, by varying the pulse density *(Pulse Position Modulation PPM)* or by varying the pulse width *(Pulse Width Modulation PWM)*.

The parallel resonant generator is supplied from current source with a choke between the power supply and the inverter. The parasitic choke, resultant of the connection between the oscillator and the capacitor bank, is used to obtain soft turn-on switching. The power regulation cannot be done by the inverter so the power supply must be regulated and this is usually done with a fully controlled bridge rectifier for the higher powers, or with a chopper for the lower power range.

Thyristors, operating at frequencies up to 3 kHz, are used for power ratings of several MWs, IGBTs, operating at frequencies up to 150 kHz for power ratings up to 3 MW and MOSFETs for power ratings under 1 MW operating at frequencies up to 500 kHz. The power level and frequency are imposed by the application and the production requirements. The higher the frequency the lower the heat penetration into the work piece. Fig. 3 shows an induction heating generator for welding pipes rated at 400 kW / 400 kHz where the power source and the oscillator inverter are separate.

Fig.3: Induction heating generator, 400 kW/400 kHz, for tube welding. By courtesy of GH Electrotermia, Valencia, España.

Certain applications require more advanced topologies that aim to improve the heating characteristics or to expand into new fields of application. This is the case of the dual frequency generators used to supply the inductor, sequentially or simultaneously, with two different frequencies, one in the medium frequency range (3 to 10 kHz) and the other in the high frequency range (200 to 400 kHz). These type of generators are used for hardening work pieces with irregular surface geometry like gears. The topology of a simultaneous dual frequency generator for tempering applications consists basically of two inverters decoupled by a choke as shown in Fig. 4.

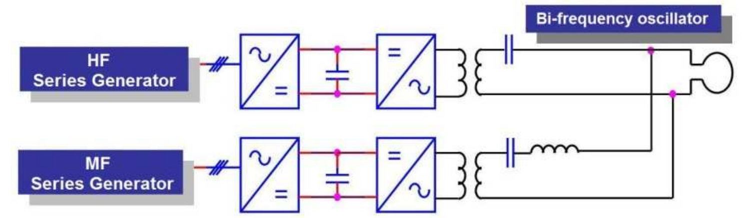

Fig. 4: Dual frequency generator block diagram for hardening metal work pieces with irregular surface geometry

Fig. 5 shows the two operating frequencies of the dual frequency generator and the current that flows in the inductor.

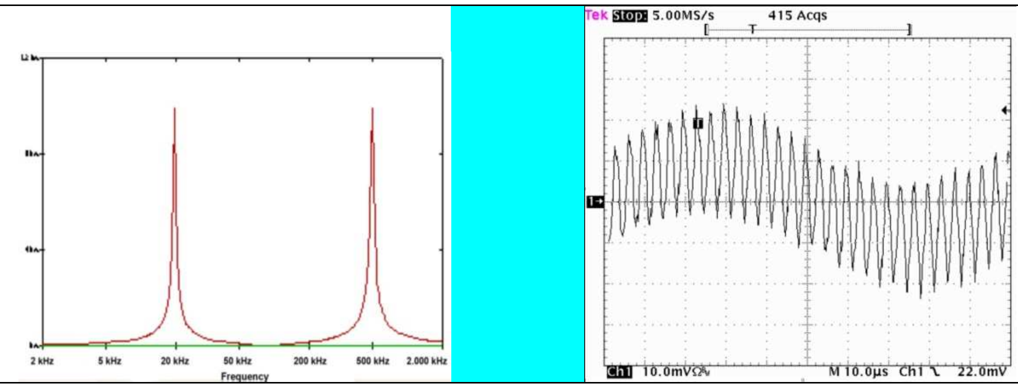

Fig. 5: Left: Frequency response of a dual frequency oscillator. Right: Current in the heating inductor.

The multi-output generators supply several inverters of the series resonant type with independent power ratings and operating frequencies. These are used where two thermal sequential processes like hardening and tempering are required, or where simultaneous production lines are used, like in paper drying and cable heating lines.

Wide-band generators have a wide operating frequency range, between 10 and 150 kHz, selected by changing the configuration of the capacitor bank depending on the specific application. They are ideal for general heat treatments that, depending on the application, require a variety of frequencies to obtain the desired hardening profile.

The control circuit can carry out two functions, regulate the converter and control the process sequence. Both these functions can be integrated into the same control circuit. Nowadays, these circuits are implemented using *Field Programmable Gate Arrays (FPGA)* both for the fast and slow loops of the inverter controller. They also include bus interface connections for industrial communication links like *Profinet, Interbus, Profibus*, etc. On occasions, where a lot of data must be stored, the process is controlled by an industrial personal computer.

Amongst the many application of induction heating the most common are in domestic appliances (for example, induction cookers) and in industry, in sectors as different as steel, automobile, gasoduct, windmill, aircraft, in tube or pipe manufacturing, electric motor and semiconductor. It is used for metal smelting, forging, surface treatment, sealing and welding by induction. The use of induction heating improves the speed of the process, its precision, efficiency and repeatability, that helps automating processes with specific equipment, Fig. 6.

Fig. 6: Turnkey installation for hardening constant velocity couplings. By courtesy of GH Electrotermia, Valencia, España.

2.3.Electric welding

Electric welding also benefits from *Power Electronics* for the control of spot, arc or laser welding equipment. In the past spot welding, that basically consists in applying a short duration, large alternating current spike to two overlapping sheets of metal fusing a small area to produce the joint, was controlled with thyratrons. These devices were later replaced by thyristors that had a lower on-state voltage. Few developments have taken place in this field except for those related to pliers (mobile, multiple, roller type, etc.) and with the modern integrated circuits that allow a better control. The thyristors available in the market today, both the unidirectional and bidirectional (Triode A.C. semiconductor, TRIAC) types, cover the requirements of spot welding. The transient power rating of these equipment range from 1 to 250 kVA. For higher power ratings medium frequency inverters, up to 400 kVA [5], are sometimes used that operate with real time control loops and feedback from welding sensors.

Arc-welding with coated electrodes is one of the most common forms of welding. Most workshops have equipment of this type of different power ranges. They can also be found on building sites and in most industrial installations. It consists in adding material from an electrode to the fusing material of the pieces to be welded by applying a low voltage to establish a high intensity current between the electrode and the pieces. Initially the equipment were purely electrical devices, based on a step-down transformer with a high leakage inductance to limit the current when the electrode touches the pieces to be welded. The advent of thyristors first and then IGBTs has encouraged the design of equipment with a better control of the current (they include overcurrent, overtemperature together with overvoltage and undervoltage protections). These are used for welding equipment with coated electrodes in inert gas atmospheres with both d.c. and a.c. (sometimes supplied from inverters) that make welding much easier and less dependent on the skill of the welder. Usually the power ranges from 15 to 60 kVA [6]. There is active research on improving the control of the optimum current level and on optimising the general protections of the equipment..

Laser welding is the most precise, because it can concentrate large amounts of power on very small surfaces with a very precise control of the power and time. Combined laser and arc welding are also use to take advantage of the best properties of each welding methods. *Power Electronics* permits building power supplies to control the laser emitter and thus offer precision and repeatability to the process. The power supplies for the laser lamps, based on high frequency modulated IGBTs, apply to the laser lamps and initial high voltage pulse for triggering and then control the current at reduced voltage. The power levels range from a few watts in medical and jewellery equipment to several hundreds or thousands of watts in industry. Very high powerlaser find application in military applications outside welding.

2.4. AUXILIARY CONVERTERS FOR RAILWAYS

The main function of the auxiliary converters is to provide the low voltage – both a.c. and d.c. – to supply the different auxiliary equipment on trains (brakes, air conditioning, lighting, etc.). Electrical isolation of the output voltages from the catenary is usually required in these equipment that are supplied by it.

The power levels vary depending on the application. For a.c. equipment the power ranges from a few kVA to several hundreds. The output voltages are usually three phase 220 V / 60 Hz for some English speaking countries or 400 V / 50Hz in Europe, Fig.7. Three phase bridge inverters with IGBTs operating with high frequency modulation.

The d.c. converters are used for charging the train's battery and for the supply of all the on-board electronic equipment. The typical d.c. output voltages used are 24, 38, 72 and 110 V. The power levels range from a few kilowatts to several tens of kilowatts. These converters can have different configurations and whilst the low frequency equipment use thyristors, the high frequency ones use IGBTs. Both a.c. and d.c. types are controlled with microprocessors of varying complexity.

As with traction equipment, some trains must be supplied from catenaries with different voltages (sometimes even a.c. and d.c.), therefore the auxiliary converters must be designed to accept these supply voltages. These requirement makes necessary, in order to achieve a high efficiency and a reduced size, the development of really complex reconfigurable topologies in the power circuit. There are some converters designed to operate from five different catenary voltages, a.c. and d.c. (15 000 V 16 2/3 Hz, 25 000 V 50 Hz and d.c. voltages of 750, 1 500 and 3 000 V).

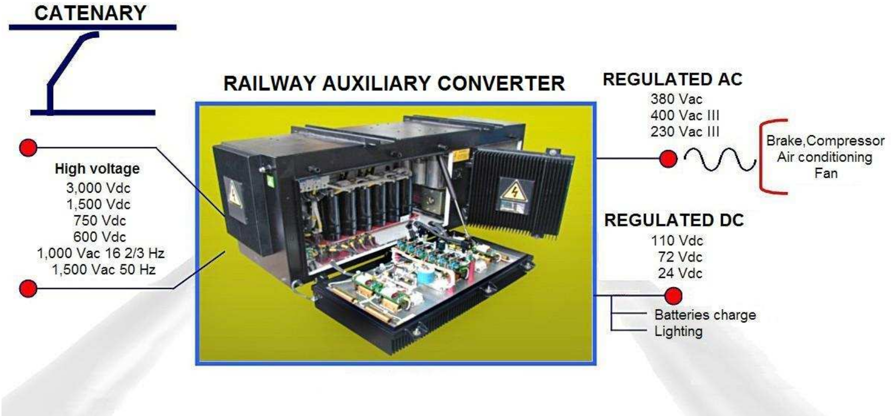

Fig. 7: Railway auxiliary converter. Input and output voltages. By courtesy of SEPSA, Pinto, Madrid.

2.5. CAR INDUSTRY

The role to be played by electronics and Power Electronics, in the car industry, in the coming years will be fundamental. It has been estimated that, by 2012, 40% of the cost of a vehicle will be in electronic equipment. Search for new energy sources, reduction of energy use, increase in comfort and safety will be the factors contributing towards this figure.

As a main factor, the search for new energy sources as alternative to fossil fuels will contribute to the expected drastic change in the concept of automobile industry in the near future, through the development of electric and fuel cell driven cars. In the configuration of the traction section of a pure electric car (illustrated in Fig. 8), Power Electronics takes care of the control of the flow of energy (battery bank and supercapacitor bank) between the energy source and the traction motor, with d.c. converters (voltage adaptation) and inverters (supply of a.c. electric motors) [7].

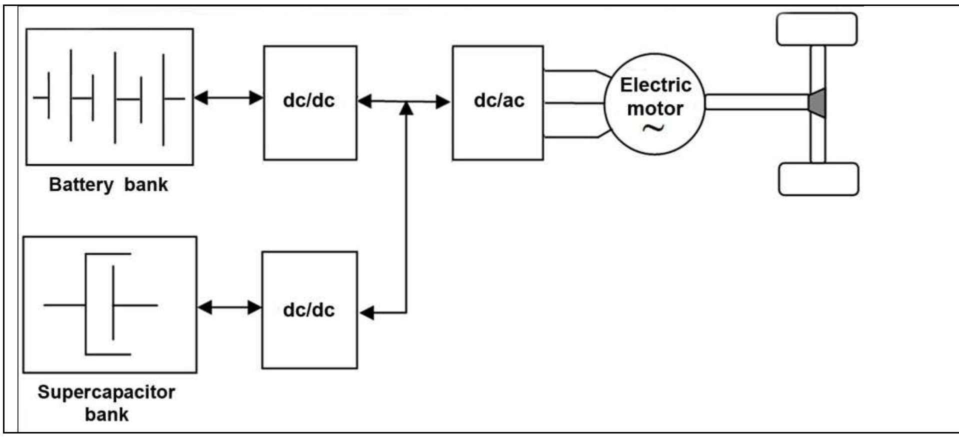

Fig. 8: Block diagram of the traction system for an electric vehicle.

The battery bank supplies the average power requirements whilst the supercapacitors take care of the transients. This system is bidirectional to recover the braking energy. The fuel cell systems, the cell is used to supply the average power and operates in parallel with either supercapacitors, a battery or a combination of both (supercapacitor and battery).

These systems are still under study, since their economical feasibility has not yet been proved. At present, manufacturers are concentrating their efforts on the hybrid vehicles, Fig.9, that include an internal combustion engine with lower power rating and reduced fuel consumption than conventional systems operating in parallel with the electric equipment previously described.

Power Electronics has not only contributed to development of more efficient and environmentally friendly traction systems, but also to the replacement of hydraulic and electromechanical systems (following the same strategy as previously started in aeronautical systems, see 2.7). This has achieved, not only a lower power consumption (the systems are connected only when required and are not continuously in operation), but also an optimal control of the loads with the corresponding increase in comfort and safety. The examples of these applications are varied and amongst others the following can be presented: control of d.c. motors (for fan control in air conditioning, window, door and seat controls) with d.c. / d.c. converters (series regulators or the more efficient PWM controllers); control of brushless d.c. motors with inverters for the same applications; or the combination of electromechanical or electromagnetic actuators with a brushless motor (electric compressor, valve control instead of the camshaft, electric braking, electric steering and suspension …) or the replacement of halogen and incandescent lamps for the more efficient Xenon or LED lamps. For the first type, electronic systems constituted by a step-up converter (with output voltages of about 1 kV) plus a PWM inverter, whilst for LEDs, current control is used, preferably with switching converters to maximize efficiency.

All these developments imply an increase in the demand of electric power that bring a change to electrical architecture of the vehicle. The present configuration, consisting on a 12 V battery and an alternator, will be replaced by a system similar to that presented in Fig. 10, constituted by a high voltage d.c. bus (*supply* bus or *power* bus) to supply the higher power loads and a low voltage bus to supply the low power conventional loads.

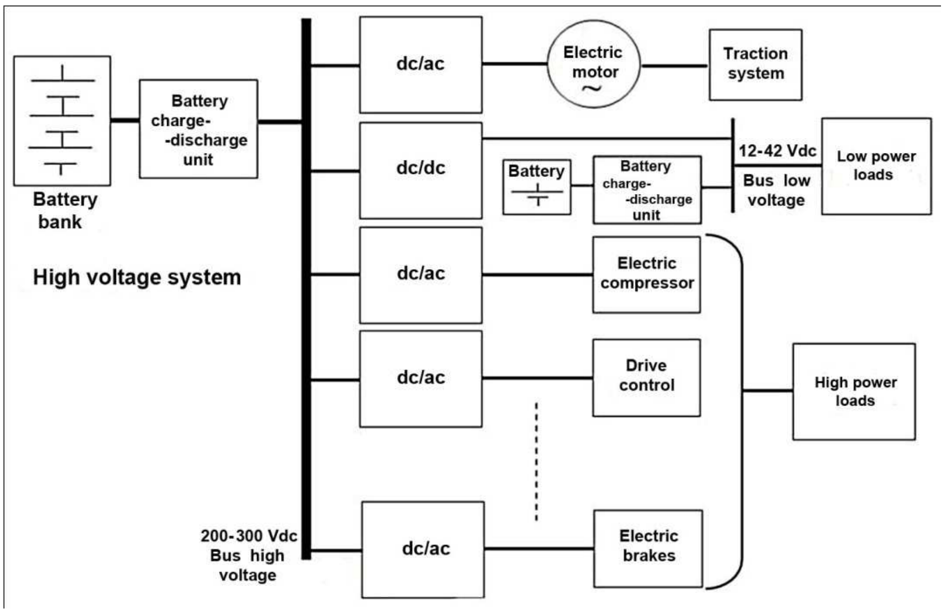

Fig. 10: Block diagram of an electric vehicle with massive use of electronic controllers.

In the commercial hybrid vehicles, the high power bus is usually between 200 and 300 V, whilst the traction system, after the d.c. converter, operates with voltages that range from 500 V to 650 V (Toyota Prius and Toyota RX400h) [9]. The low voltage bus in use today is 12 V. Due to the increasing number of loads connected and to improve the system efficiency, new configurations operating at higher voltages, like 42 V, are being studied.

The converters not only take care of adapting the voltage levels, but also to transmit energy, both in d.c. or in a.c. form. The active component most widely used in these converters is the MOSFET transistor. For traction applications, at higher voltages, the IGBT is used.

2.6. MEDIUM AND LOW POWER ELECTRIC MOTOR CONTROL

Power Electronics is not only present in the control of high power industrial motors (see section 6.3 in the first paper), but also in the low and medium power ranges (10VA to 100 kVA) for the control of electric motors for a wide variety of systems and devices for industry, building, laboratory and domestic use. It has been estimated that about 60 % of the total energy generated is used in electric motors [10] in applications such as ventilation, lifts, pumps and many home appliances. It is becoming increasingly difficult to find any device without an electric motor in it, like vacuum cleaners, washing machines, fridges, shavers…., even in DVD players have motors for the drive and insert / eject mechanism.

Most of the motors mentioned are a.c. motors except in the very low power devices that are d.c.. In many cases, the control is just on / off control or starting and stopping in different position, but in some speed control in different speed ranges is required. In big motors it is normal to used delta-star starters to reduce the starting current. Many of these motor starters, were made with contactors, but nowadays, it is common to use soft-starters with thyristors that in some cases improve the results by temporarily chopping the supply voltage.

Full speed control of a.c. motors, synchronous and induction (the most common), is carried out with IGBT inverters that apply a variable pulse width modulated voltage at a variable frequency to the motor, Fig. 11. The inverter, in turn, is supplied from the mains via a rectifier. For power ratings above several kilowatts, the rectifiers use high frequency techniques (active front ends) to improve the power factor and distortion of the current drawn by the supply. A limited range speed control of small a.c. motors is sometimes realized by chopping the supply voltage with thyristors to increase the slip.

Fig. 11: Circulation pump for domestic and industrial heating systems. Moved by an electric motor regulated by an electronic inverter. By courtesy of Grundfos.

2.7. AVIATION

Aircraft include several types of power electronic converters to, amongst other applications, light up the cockpit instrument panel (*cockpit converters*, from 30 to 400 W), control the lighting (*dimming regulators*) and to generate 50, 60 or 400 Hz alternating current at 115 or 230 V, from14, 28 or 48 V batteries, to supply different loads (*avionic inverters*, from 20 to 50,000 VA). The greater part of these converters and inverters use single stage topologies with MOSFETs due to their low on-state voltage. In the high power range nevertheless, the tendency is to use an intermediate d.c. / d.c. converter with MOSFETs switching at very high frequency to boost the battery voltage followed by a pulse width modulated inverter and a filter, implemented with IGBTs since their on-state voltage is now relatively smaller. Note that the voltage and current ranges of IGBTs are continuously expanding, surpassing those of the MOSFETs. The search for topologies, in avionics, is mainly guided towards the reduction in size and weight. An example of the search for topologies, for 1 kVA 400 Hz inverters, following the method presented in section 5.3 [1] and in [11].

Power Electronics is also present in supply systems for cabin lights, external strobe lights, electromechanical actuators and electric motors. For some decades, the trend in aviation has been to build aircraft controlled by electromechanical devices (*fly-by-wire*)
instead of mechanical or hydraulic devices, because they offer a greater versatility, a reduced in the weight of control piping and more adapted to centralized computer control. This therefore increases, especially in big aircraft, the need for power electronic equipment.

Like all on board electronic equipment, these converters must go through very rigorous vibration and electromagnetic compatibility testing, therefore mechanical design and reliability are fundamental design aspects. Other important aspects of design, characteristic of avionics, are the requirements to build specific test benches and to prepare extensive installation and maintenance manuals for all on board equipment, including power electronic converters; jobs that are very long and time consuming for the design teams.

3. LOW POWER APPLICATIONS

Applications with power ranging up to approximately 1 kVA are considered as low power applications of *Power Electronics*.

3.1. HOME APPLIANCES

Apart from controlling small motors, *Power Electronics* is present in many home appliances: for temperature regulation in cookers, ovens and electric heating, for dimming control of incandescent lights or for opening and closing electro-valves in washing machines and other applications. In most applications the control and regulation is carried out with thyristors either for “on / off” control (electro-valves) or for firing angle control (heating with resistors and incandescent lamp dimming). There is an increasing offer of dedicated integrated circuits for the control of the different functions, that makes design and manufacturing of the end product easier.

3.2. SPACE APPLICATIONS

Power Electronics is present in practically all on board space equipment, from subsystem power regulation to d.c. / d.c. converters, also including motor controllers, travelling wave tube amplifiers and the power sources for electric propulsion. Due to limitations in the length of this paper, only the present and near future applications will be discussed. The longer term or more general views on the matter can be found in [12] and [13].

In general terms, the main objective of the satellite power subsystems is to supply electric energy to all the on board equipment during all the phases of the mission for which they have been designed with the smallest mass and highest efficiency possible. Nevertheless, depending on the type of mission (communications, interplanetary or low orbit satellites) other objectives, like production cost reduction, tolerance to radiation or others, will have priority [12].

Fig. 12: Power control and distribution unit for the GOCE ESA satellite. Made in Crisa, Spain.

For geostationary communications satellites, the concept of a totally regulated subsystem, capable of delivering a d.c. voltage of 50 or 100 V (depending on the satellite power requirements) with a tolerance of ± 2 %, has been implanted and it is not expected to change in the medium term. Nevertheless, the high cost of solar panels, the long deliveries and, above all, the increase in the parasitic capacitance may prompt changes to the concept of regulation of the solar panels. If today this regulation is done using *Sequential Switching Shunt Regulators (S3R)*, in the near future it can change to the *Maximum Power Point Trackers (MPPT)* controlling buck-boost converters, that will allow standardizing the solar panels independently of the satellite power requirements.

In low orbit satellites, the use of a battery bus, with voltages between 24 and 36 V, has been established over the past years. The MPPTs, that optimize the operation of the panel, are being progressively introduced to the detriment of solar panel regulation systems using direct energy transfer techniques (such as S2R, S3R, S4R). In this case, the introduction of digital algorithms and the segregation of the regulators from the solar panels seem better options when offering more flexible solutions, that reduce development costs when changing from one mission to another.

Finally, in interplanetary missions (for example, Rosetta, Mars Express, Venus Express, BepiColombo…), the use of a regulated supply bus with MPPT, is fully introduced. As these require a better tracking of the point of maximum power than that offered by digital algorithms, they use analogue techniques. Regarding the regulation of MPPTs for low orbit satellites and for interplanetary missions, the configurations based on buck converters have reached an adequate degree of maturity whilst the boost converter configurations have still margin to improve, especially in dynamic response.

3.3. D.C. POWER SUPPLIES

The most common direct current power supplies have power ratings between some tens to a few hundreds of watts and are used to supply constant low voltage [14] [15]. The majority use conventional input / output isolated configurations with pulse width modulation and analogue regulation to control the power switches. The typical switching frequencies range from 100 to 500 kHz and the most widely used power switch is the MOSFET due to its low on-state voltage. Resonant topologies are used only for special applications, such as electromedical equipment where magnetic coupling is very poor. In power supplies connected to the a.c. supply, regulations on electromagnetic compatibility have forced designers to pay special attention to the power factor of the current drawn from the supply and use mainly boost converter configurations.

As digital circuits are continuously demanding lower voltages to increase their properties and speed, the 5 V systems are becoming obsolete and are being substituted by 3.3 V, 1 V and even smaller voltage systems. This implies an increase in the current demanded from the power supplies for digital systems, that not only affects the topologies used but also encourages the development of new semiconductors and control systems, since the higher currents are more difficult to control. Thus, the improvement of the MOSFETs in the past fifteen years has been important. For example, the on-state voltage drop has been reduced by a factor of 10.

Fig. 13: Power supply prototype, 208 W - 6 outputs, for computers, also operating as a d.c. UPS with 7 min. back-up time when the mains is out of service [16]. By courtesy of the Grupo de Conversión Eficiente de Energía, Electrónica Industrial e Iluminación, Universidad de Oviedo.

In general terms, the better established topologies today will carry on being the predominant configurations of the near future, although an increase in the resonant configurations is expected. Although in the past the developments in power supplies have come through the evolution of semiconductors and topologies, the present and future in this field will be governed by semiconductor packaging, thermal management and the integration of components and subsystems. There is a tendency, today, towards modular design, that will allow a module based design of power supplies without a deep knowledge of the internal characteristics of the modules. Another possibility in the configuration of the power supplies, after the introduction of the a.c. / a.c. UPS for supply of computers is to integrate an emergency battery that guarantees continuity of supply via d.c. / d.c. converters in the event of a mains failure, Fig. 13. This solution is more reasonable than the UPS but has been ignored probably due to interests of the big computer companies. From time to time, these topologies [16] are studied but they are never finally introduced.

3.4. LIGTHING BALLASTS

Efficiency is increasingly conditioning lighting systems since approximately 20% of all the energy generated worldwide is used in lighting. For this reason, the lighting efficiency (ratio between luminous flux and absorbed power) of the light source is one of the most important parameters when selecting a lamp apart from the life and the quality of the chromatic spectrum generated.

The lighting efficiency of incandescent and halogen lamps is small, approximately 15 lm/W, therefore they have gone into disuse. Apart from the fluorescent tubes, the compact lamps are a good alternative since they offer efficiencies of approximately 60 lm/W with a good generated colour spectrum and a life of 10.000 hours. The ballast consists basically of a resonant a.c. / a.c. converter, with MOSFETs as switches, that include a discrete or functional stage to improve the power factor on the mains.

The high intensity discharge, the sodium vapour and the low pressure lamps present efficiencies of 100, 120 and 180 lm/W respectively and life times of 18 000 hours but the colour rendering is relatively poor especially in the second one. These are widely used in public lighting, especially the high pressure types. The lamps that are being introduced mostly at present are the metal halide discharge types due to their high light efficiency (80 to 100 lm/W) and their chromatic spectrum generated. It is mainly used for lighting of public places, sport centre flood lights and shopping malls. The ballasts used for high intensity discharge lamps are usually electromagnetic whilst the electronic types are rarely used.

In the last decade, the light source that has evolved the most, has been the *Light Emitting Diode (LED)*. Their life exceeds 50,000 hours and their lighting efficiencies are increasing continuously. The white light emitting LEDs, available today, with efficiencies between 50 and 100 lm/W (improvements up to 150 lm/W are expected in the medium term) and a good colour rendering with continuing improvements has made this type of lamp the reference for the future. Thanks to its clear advantages, the LED has quickly found its place in applications where colour filtered incandescent lamps were being used, like in traffic lights and cars [17] [18]. The ballasts used in this case are d.c. output converters with MOSFETs and pulse width modulation using current feedback to control the luminous flux. They use power factor correction stages when supplied from the mains, Fig. 14.

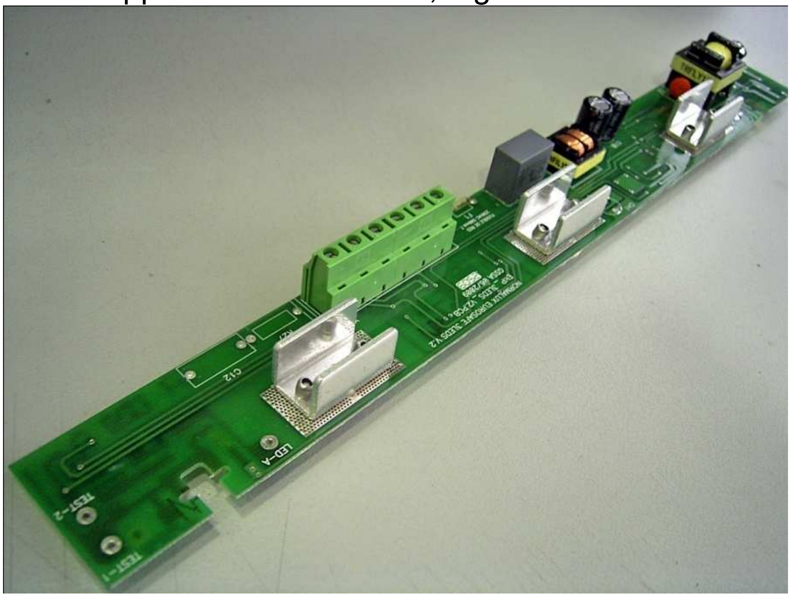

Fig. 14: Emergency lighting unit with LED made by Normalux, model Eurosafe 3LED Vo.2. It uses LEDs type XRE WHT-L1 from CREE which ensure 50,000 hours life. By courtesy of the Grupo de Conversión Eficiente de Energía, Electrónica Industrial e Iluminación, University of Oviedo, and NormaLux, Asturias, Spain.

3.5. POWER SUPPLIES FOR LAP-TOPS, CARS AND MOBILE PHONES

The use of devices for personal computing (lap-top computers, PDAs), digital imaging (cameras and video) and communications (mobile phones) has spread in the last five years. Their electronic circuits operate with low d.c. voltages supplied from a common battery. Power Electronics is present in these devices to adapt the battery voltage to the voltage levels required by the different circuits (processors, displays, sensors, flash lights, etc.). D.c. / d.c. converters, with ratings between 1 and 50 W, are used. They operate at frequencies above 100 kHz to reduce the size and weight of transformers and chokes and meet this primary requirement. The converters can be assembled on specific boards, Fig. 15, or be integrated with other circuits. The trend is towards increasing the switching frequency as much as possible at the rate faster diodes and switches, mostly Schottky and MOSFET technology, are introduced.

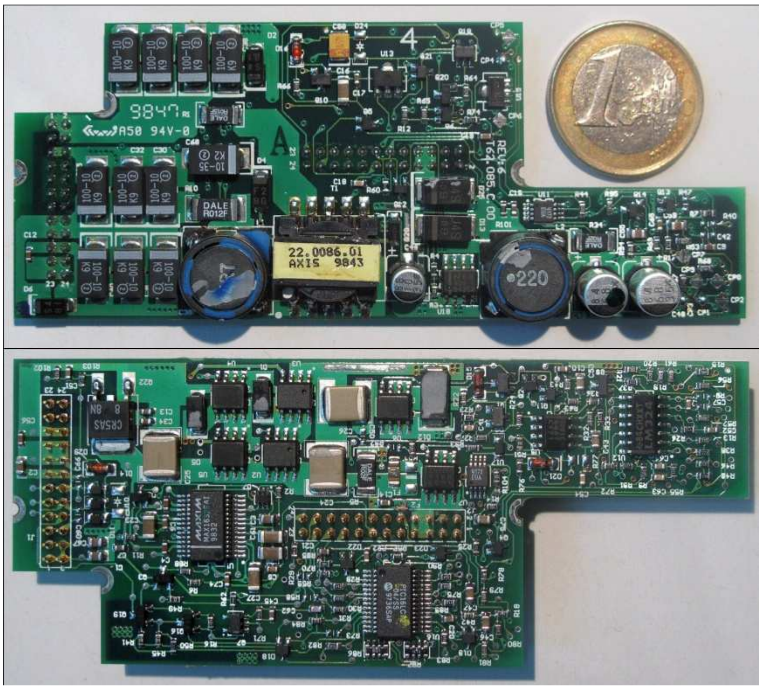

Fig. 15: Power supply with MOSFET d.c./d.c. converter for the ACER lap-top Travel Mate 721 TX.
Top: Power components.
Bottom: Control components and capacitors. By courtesy of J. A. Barba, DIEEC, ETSII, UNED.

3.6. POWER SUPPLIES FOR PERSONAL ELECTROMEDICAL APPARATUS

Very small electromedical apparatus for personal use (hearing aids, pacemakers, etc.) and for medical exploration tools (several types of probes) can require some electronic control of the electrical energy supply. This is carried out with very high frequency d.c. / d.c. converters using FETs where the priority is size together with high efficiency when powered by batteries. Research is on-going to reduced on-state voltage drop in diodes and transistors.

3.7. THE NANOTECHNOLOGY CHALLENGE

The trend towards smaller circuits, presented in the previous sections, reaches a maximum in the recent developments of quasi-microscopic devices for a wide variety of applications. Although the main advances today, in the so called nanotechnology, are being carried out in the mechanics, development in the electrical and electronic circuitry is also foreseen. Therefore, Power Electronics will have to concentrate on the efficient conversion of energy at very low power levels and extremely small sizes. In these converters it is advisable to simplify the control and reduce its size to a minimum since a complex control section can exceed the size of the power section. Research into high integration digital circuits is being carried out, today, to emulate the behaviour of analogue circuits that include capacitors and other big components [19].

4. CONCLUSIONS

Power Electronics is also expanding its applications in the low power ranges, from 1,000 kVA to a few tenths of a watt. In the low end of the range there is continuing development of techniques to reduce size and weight by increasing the switching frequency, sometimes exceeding the MHz boundary [20]. In this field also, new techniques for miniaturizing transformers and chokes are being studied together with research into semiconductors to reduce on-state voltage drop. The spectacular on-

state voltage drop already achieved in the MOSFETs has been of great help to maintain adequate efficiencies in this field.
As in the first part of this review, reserved to the general aspects of Power Electronics and the high power applications, in this second and last part, an effort has been made to present the special aspects of each field by going to authors that are in direct contact with the latest developments in it.

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

5. ANNEX: ACRONYMS AND ABBREVIATIONS

The names and acronyms appeared along this second paper are shown together with those appeared in the first paper.

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
LED	Light Emitting Diode
LVDS	Low Voltage Differential Signal
MOSFET	Metal Oxide Silicon Field Effect Transistor
MPPT	Maximum Power Point Tracker
PLD	Programmable Logic Device
PMSG	Permanent Magnet Synchronous Generator
PWM	Pulse Width Modulation
S3R	Sequential Switching Shunt Regulator
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
Acronym	Meaning

TRIAC	TRIode A.C. semiconductor
TTL	Transistor-Transistor Logic
UPFC	Unified Power Flow Controller
ZVS	Zero Voltage Switching

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