Objetivo 1

The application of power electronics to smart grids. Opportunities in Madrid region

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1. EXECUTIVE SUMMARY

This document explains the role of Power Electronic in modern and smarter electric power systems. First of all, the general frame work and main challenges of smart electric power systems are review. It is made clear that electric power system will have to seamlessly integrate distributed generators, increasingly demanding loads and traditional large-scale electric power system. Secondly, the main power electronics application to increase the flexibility of electric power system operation and control are review. The literature survey carried out shows that with the same basic converter topology, many different roles can be implemented with easy changes in software and algorithms. Thirdly, the main obstacles to a widespread of power electronics in electric power system are summarised and two new applications with a promising future are explained. High prices, utilities' lack of confidence and semiconductor limitations are the three main limiting factors which are preventing a widespread implantation of power electronics in electric power systems. Finally, the content of this document is summarised.

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3. DEFINITIONS AND ABBREVIATIONS

Abbreviation	Definition
AC	*Alternating Current*
DC	*Direct Current*
DFIG	*Doubly-fed induction generator*
DG	*Distributed Generator*
DVR	*Dynamic Voltage Restorers*
EPS	*Electric Power Systems*
EU	*European Union*
EV	*Electric Vehicle*
eV	*Electron volt*
FACTS	*Flexible Alternating Current Transmission Systems*
GaN	*Gallium Nitride*
HES	*Hybrid Energy Storage*
HVDC	*High Voltage Direct Current*
IGBT	*Isolated Gated Bi-polar Transistor*
LCC	*Line Commutated Converters*
MOSFET	*Metal-Oxide Semiconductor Field-Effect Transistor*

PCC	*Point of Common Coupling*
PE	*Power Electronics*
PI	*Proportional + Integral*
PV	*Photo-voltaic*
ShAPF	*Shunt active power filters*
Si	*Silicon*
SiC	*Silicon-Carbide*
SST	*Solid State Transformers*
STATCOM	*Static Compensator based on VSC*
UPFC	*Unified Power Flow Controller*
UPQC	*Unified Power Quality Controller*
VSC	*Voltage Source Converters*

4. INTRODUCTION

Present Electric Power Systems (EPS) are among the greatest achievements of the 20th Century and are supporting industry into the 21st Century. However, important technology changes question old uses while open new challenging opportunities. Key issues to be taken into account are: always-increasing demand, reduction of large-scale investments on power stations and new lines, transmission line saturation, the need for flexible and reliable integration of distributed generation with increasing participation of renewable-energy sources, the outcry for optimal use of renewable-energy sources and an the increasing demand for high-quality power at the point of coupling (PCC) of sensitive loads while there is a growth of disturbing and complex loads [1].

The above challenges require “smart” solutions which will only be possible with a versatile dynamically controlled infrastructure [2]. Along these lines, it is envisaged that flexible AC-DC transmission/distribution systems, energy storage systems, distributed generators and smart end-user appliances together with advanced communications systems will be at the heart of the future smart grids [3]. Meanwhile, power electronics technologies have shown a clear potential as providers of advanced solutions to old and new problems in generation (mainly renewable), transmission and distribution because they can achieve:

1. From fast (cycle time scale) to ultra-fast (sub-cycle time scale) response speed.
2. Continuous and controllable smooth output.
3. Reversible operation

Power electronics is ready (with limitations) to provide the actuators required by information and communications technologies for the smart grids of the future in which the customer should be allowed to take an active role in the supply of electricity and ancillary services. Although “Smartness” has to be implemented at the planning stage of newly-developed grids, it must also be taken to existing infrastructures, gradually. It is urgent to understand the requirements from the grid viewpoint and then develop solutions [2].

Power Electronics (PE) must be at the very heart of the flexible interface between renewable energy sources (i.e. wind, sun …) and the grid, and between several forms of energy storage (i.e. kinetic storage resources, batteries, electrical vehicles …) and the grid [4]. PE must also be a key participant in the so-called Flexible Alternating Current Transmission Systems (FATCS) or power flow controllers which can help to improve power-system control and to increase the present power-transfer levels. Finally, PE could also offer solutions for voltage-quality improvement to feed sensitive loads and for active harmonic-current filtering to avoid their side effects [5], [3].

The benefits of power electronics in electric power systems have long been recognised. For example, [6] cites that the value of a reliable and modernised grid in the United States of America can be as high as $638-802 billion over a 20-year horizon, with annualised values of between $51 and 64 billion/year [7]. Nevertheless, power electronics still encounters serious difficulties such as cost, reliability, component packaging and thermal management, cooling methods, efficiency and control.

5. REVIEW OF POWER ELECTRONICS APPLICATIONS

5.1. DISTRIBUTED GENERATION, RENEWABLE ENERGY SOURCES AND ENERGY STORAGE

The development of Photovoltaic (PV) systems is one of the biggest challenges for the 21st century considering their great potential in terms of the solar resource availability. Currently, their presence is still very scarce in comparison to conventional generation systems, due to the low overall efficiency and high cost. Nevertheless, their modularity, scalability and low maintenance requirements are some of the advantages which strongly recommend their integration in future electrical grids.

Future research lines are pointed out by the EU PV Technology Platform [8] suggesting the integration of power quality functionalities, grid support and short term energy storage during the next decade. In the long term, [8] suggests the investigation of grids based on Voltage Source Converters (VSC-based grids), long-term energy storage systems and control algorithms for VSC-based distribution networks. Moreover, improved islanding detection and Maximum Power Point Tracking (MPPT) methods will be required with the increasing presence of distributed generators (DGs) and micro-grids. The combination of PV systems with energy storage will certainly provide high-performance smarter energy systems (such as a PV system combined with a Hybrid Energy Storage –HES- system) leading to enhanced stability and reliability, smoother power profile, and improved dispatchability, power quality characteristics and response to grid disturbances. All of these aspects look like potential improvements with respect to the current situation but will require a much larger deployment of power electronics. Some examples already seeking for a major revolution in the application of power electronics based PV systems can be found in [9] with the application of Li-ion batteries and flywheels, [10] with the application of ultra-capacitors, [11] with the application of high-frequency transformers and soft-switching converters and in [12] where the use of transformers with several primary windings is explored to integrate several voltage sources.

Electricity generation using wind turbines is already a mature technology ([13], [14] and [15]). Clearly, efficient wind energy integration to have smarter grids also relies on power electronics, strongly. Medium- and large-size turbines are still largely based on doubly-fed induction generators (DFIG) [14], but this situation may change gradually as full-converter-based turbines are improving. This change is been driven, mainly, by the need to comply with more and more restrictive and demanding grid codes but it is been held back by the prices of rare earth materials, the losses in the full-power converter and the still-high demand of doubly-fed systems led by the huge Chinese market [16].

Nowadays, power electronics is used to interface high-frequency AC or DC generated by fuel cells, solar cells, wind turbines, etc. into the electrical power grid (constant voltage, constant 50 or 60Hz frequency). However, power electronics also offers significant potential to improve the local voltage regulation, help with the supply of reactive power and to compensate for voltage and current disturbances.

5.2. POWER QUALITY AND POWER FLOW CONTROL

The use of power electronics to tackle power-quality problems and to control power flow in electric power systems is a long-standing topic in the scientific literature [17], [18], [19] and [20]. FACTS devices are considered for high-voltage application (transmission) while the so-called custom power devices are considered for low-voltage applications (distribution) [21]. “FACTS and custom power devices are engineered systems of advanced power semiconductor-based converters, information and control technologies (software) and interconnecting conventional equipment that builds intelligence into the grid by providing enhanced power system performance, optimization and control" [22]. Compared with the construction of new transmission line, these devices require minimal (but very expensive) infrastructure, minimal environmental impact and implementation time [6]. FACTS devices are concerned with the control of the path of power flows throughout the network in an adaptive and smart fashion while enhancing the security of the system. Custom power devices are a response to reports of poor power quality and reliability of supply to factories, offices and households. The latter are tailored to protect loads from voltage sags and swells, supply-voltage distortion, power interruptions, etc. while preventing non-linear loads from injecting harmonic currents into the system.

Steady-state performance of FACTS and custom power devices is described in [23] for each device considered separately, while transient performance is demonstrated by simulation. A prototype of a Unified Power Flow Controller (UPFC), which is the most comprehensive FACTS device, was built and tested in [24]. Since the concern of a UPFC was active- and reactive-power flows, simple Proportional+Integral (PI) controllers were sufficient to achieve very good performance.

Since custom power devices deal with quality problems, they required more sophisticated control systems. For example Dynamic Voltage Restorers (DVR's) have to protect loads when voltage sags occur. First of all, this function requires algorithms for sag detection [25]. Secondly, a fast transient response of the DVR is also necessary and state-feedback control plus a feedforward component is proposed and tested in [26]. Finally, a DVR can simultaneously protect sensitive loads from supply voltage distortion and unbalance using selective-harmonic closed-loop control or repetitive controllers such as in [27] and [28], respectively. The comprehensive approach in the latter reference was first tested in the laboratory in [29] and [30].

Shunt active power filters (ShAPF) are also custom power devices and they are concerned with the protection of the electric power system from harmonic currents injected by non-linear loads. A ShAPF always poses a problem of accurately tracking periodic signals (current references) with a number of frequency components (fundamental and harmonics). Novel selective-harmonic current control algorithms were proposed in [31] and [32], the former being a more comprehensive reference than the latter. Non-linear selective filters together with closed-loop control were proposed in [33] and, finally, a compact repetitive controller dealing with all harmonics simultaneously was proposed in [34]. Many references report experimental results of complex current control algorithms applied to active power filters ([35] and [36]) while the development of these applications has been parallel to current-control advances in DGs based on power electronics [37].

Putting a series compensator device (similar to a DVR) together with a ShAPF one obtains a Unified Power Quality Controller (UPQC) as described in [18]. The topology shown there is identical to the one in a UPFC shown in [24]. A comprehensive control algorithm for a UPQC is described in [38]. This control algorithm is able to deal seamlessly with power-flow control and harmonics and was first tested in a DVR in [39] and in a STATCOM/ShAPF in [40].

Therefore, it has been demonstrated that a comprehensive approach to power electronics in electric power systems is possible and that multi-purpose devices are viable. Furthermore, the distinction between FACTS devices (power-flow controllers) and custom power devices (power-quality controllers) cannot be sustained any more in future smart grids with a strong integration of renewable energy sources where both functions will be required for optimal utilisation..

5.3. HYBRID AC/DC GRIDS

High voltage direct current (HVDC) transmission avoids some of the disadvantages and limitations of AC transmission system and this is why traditional HVDC systems based on Line Commutated Converters (LCC) have a long history of success in controlling active power flow in transmission systems [41]. More recently, however, VSC technology is becoming a very promising solution with even more advantages and overcoming some of the major disadvantages of traditional LCC technology ([42] and [43]). The main advantages of VSCs are: (a) Independent control of active and reactive power without extra compensating equipment; (b) mitigation of power quality disturbances with respect to LCCs; (c) no contribution to short circuit currents; (d) reduced risk of commutation failures; (e) feeding islands and passive AC networks is possible; and (f) a multi-terminal DC grid is quite natural (therefore, DC grids must be considered).

While VSCs for high voltages (HVDC) and high levels of power are still a technological challenge, low-to-medium voltage counterparts are already a reality where versatile control algorithms are easily implemented to provide very comprehensive solutions for power flow control and quality problems at the distribution level (see previous sections). The use of DC (either in transmission or in distribution systems) can also facilitate the use of various forms of energy storage which can contribute to a more flexible control of future electric systems.

The possibility of hybrid AC-DC networks not only provides alternative solutions for old problems in electrical system but it also gives an excellent opportunity for smarter grids: (a) the coordination of the power electronics controllers is a challenging issue [44] where the availability of modern communication systems play an important role, and (b) the utilization of several forms of energy storage (often connected to the DC side) can now be considered.

5.4. EXISTING LIMITATIONS AND OPORTUNITIES FOR THE FUTURE

Semiconductors

The development of advanced power electronics devices (switches) based on silicon (*Si*) has been going on for quite a long time now and, although an enormous progress has been achieved, it is clear that *Si* has difficulty meeting the demand for some high-power utility applications as a results of limitations in its intrinsic material properties. For example, the *Si's* relatively narrow bandgap (1.1 eV) limits the voltage-blocking capacity of most *Si* devices to less than 7kV, forcing stacking packaged devices in series for high-voltage applications or the use of very complex modular converter topologies such as in HVDC applications [45]. Therefore, there is a strong incentive to develop devices having greater voltage-blocking capacity maintaining or reducing the size of the package.

In addition, *Si* devices show a relatively low thermal conductivity and their operational temperature limit is less than 150ºC. This problem requires an important thermal management effort to maintain the junction temperature below its limit. Manufacturing power electronics devices that could withstand higher temperatures would decrease the cooling requirements and therefore the size and cost of converters.

Along these lines, it is known that wide-bandgap semiconductor materials have superior electrical characteristics compared with *Si*. Power switches based on these materials should show substantial improvements in voltage-blocking capacity, efficiency, reliability, size, weight and reduced thermal requirements. Currently, the most promising solution is the one using Silicon-Carbide (*SiC*) material. The use of *SiC* would also allow increasing the operating temperature of semiconductors well above 300ºC making it possible a substantial reduction in size and cost of the thermal management system [46].

Unfortunately, over 80% of *SiC* wafer production is dominated by Cree [6] and the technology used for manufacturing is far from been mature. In addition, *SiC* cannot provide a chip-to-chip replacement of *Si* semiconductors. New device structures, processing technology and electric circuits are required in order to take full advantage of *SiC* semiconductors. First of all, the price of *SiC* devices is substantially higher than *Si* ones and Cree has projected that the best *SiC* devices will be twice as expensive as their *Si* counterparts [6]. Secondly, reliable manufacturing of *SiC* devices require a quality of material wafers which is not industrially available. Thirdly, although the basic steps of *SiC* have been demonstrated many problems remain unsolved.

Although most of the device structures tried so far were copied from *Si* technologies, they are not necessarily applicable to *SiC*. New device structures should be developed to fit *SiC* materials.

More recently, researches have also considered *GaN* wide-bandgap semiconductor materials for power electronics [47] although they still present many disadvantages compared with *SiC*-based ones: substrates are difficult to produce, many failure mechanisms in *GaN* can shorten the time between failures and building bipolar devices in GaN (such as those need for utility applications, i.e. thyristors or IGBTs) is very challenging and only MOSFETS and Schottky diodes are realistic. Therefore, GaN material does not seem to be a promising material for high-voltage power device applications [48].

Finally “diamond” based switches are viewed as the “ultimate semiconductor” [6] been intrinsically suited for high-speed, high-power and high-temperature (up to 1000ºC) applications. Diamond advantages include 2 to 10 times higher current density than present devices, high reverse blocking voltage, low conduction losses, fast switching speed, higher-temperature operation and superior heat dissipation. However, for the time being, these devices do not have significant current carrying capability been the limit of less than 1 A. Diamond material generally possesses defects, it is difficult to find a substrate to grow diamond devices and n-type doping is difficult [49], [50]. Diamond power devices are not expected to be available for another 20-50 years [6].

Semiconductor Packaging

As mentioned above, higher-temperature operation is a clear advantage of newly proposed semiconductor materials. However, advances in this line would require a careful reconsideration of semiconductor packaging: (a) identification and/or development of new materials to use in existing packaging concepts, (2) new concepts for high-temperature package designs, (3) design and development of alternative processes and assembly and (4) methodologies for testing high-temperature electrical properties.

Advances in power electronics switches would benefit, globally, applications in smarter electric power systems. Voltage-blocking capacity is, clearly, an important issue in transmission systems while it is not such a big concern in distribution systems or in renewable energy generation. Faster switching, a more efficient operation and higher operating temperature would certainly benefit all applications.

Reliability

Reliability of power electronics converters is an important concern. Therefore, developing test facilities to investigate the full spectrum of events that a device or a system may see over the course of its life is of paramount importance. For this purpose, close collaboration between research groups and industry is essential because, while the former can generate and test new ideas in experimental prototypes, the latter must (a) write the specifications for the final product (b) provide realistic and practical scenarios and (c) gain confidence in the use of this new technology.

Regulation

Distributed energy resources are costly to install because of the price of the technology elements, because there is no standard installation process and because of the applicable strict grid codes (often stricter than those applicable to conventional generators). Equipment manufacturers have to work hard to reduce the capital and installation costs while the regulation framework must incentivise the use of distributed generation for additional ancillary services. A market of ancillary services could promote the installation of smart distributed-generation units where cost would not be justified based purely on real power generation. In fact, utilities are already promoting a number of new initiatives that are changing the way they view and operate their networks. For example, an advanced metering infrastructure can automate billing, can provide means of affecting time-of-use rates and load-demand management as well as data to help with energy conservation, loss reduction and outage management [2].

Promising developments

Power transformers are key elements in traditional power systems but, recently, the interest on electronic (or solid state) transformers (SST) is gradually growing [3]. Nowadays, the realisation of such a device with a DC intermediate stage and a high-frequency transformer is preferred because it is the most flexible and can fulfil additional functions such as the improvement of the input and/or output power quality or the integration of energy storage or renewable energy generation into the DC link. It is estimated that a high-power and medium-voltage SST ensuring the same functional capabilities of a typical back-to-back DC link, will be about one third of the size of conventional transformers [3] but, at the same time, it is still seen as a much more expensive and less reliable solution than its classical competitor [2].

Electric vehicles (EV) are now seen as an interesting proposal due to the need to reduce CO_2 emissions all over the globe. This type of vehicle greatly relies on power electronics, not only for the traction system but also for the interface with the grid to charge the batteries. A large deployment of EVs would load distribution networks heavily and the solution must be investigated at once. Due to the demonstrated flexibility of power electronics converters of the power range needed for EVs, these could be called to help with ancillary services in distribution networks and to fulfil a back-up power function [3], above all if intelligent communication systems together with an advanced (and fair) metering system are implemented. However, there are many issues to be resolved before this scenario can be made realistic. For example, to start with, a large infrastructure development is needed (power electronics, communications and data analysis). Secondly, hierarchical control algorithms should be developed. Thirdly, efficiency of the whole system should be thoroughly investigated and, last but not least, an appropriate regulatory frame work should be stablished.

6. CONCLUSIONS

Power electronics is (and will go on being) one for the leading technologies in the development of smarter grids because it makes things possible. Needless to say that power electronics already has a strong presence in electric power systems but its potential is still very promising. Power electronics is called to build the actuators with which information technologies will drive electrical systems to a more efficient and more sustainable horizon. However, the road to the final change is still full of obstacles.

First of all, the revolution needed on electronic switches is not here, yet. When ready, more efficient, more compact and more flexible power converters will be possible to modernise industry from household appliances to large transmission systems. This revolution not only needs further advances in semiconductor technologies but also a large step ahead in packaging and cooling systems.

Secondly, utilities have to gradually build confidence on this new technology and this is why a large number of pilot installations must be planned and built. Power systems require highly reliable devices to be able to maintain (or even improve) the overall system security to which we are all used to. However, care should be taken not to judge reliability using much tougher requirements for power electronics than for more conventional technologies although some of the existing grid codes (newly promoted) are good examples of this unfair comparison.

Finally, the prize barrier has to be knock down, either because power electronics is made substantially cheaper or because the advantages of a more flexible operation of the system makes the extra cost worth paying for. Most probably both circumstances will gradually take place in the medium-to-long term but the latter seems to be closer for the time being, above all if a favourable regulatory framework is provided.

This document has reviewed the most important applications of power electronics to smarter power systems and has highlighted the main difficulties (and opportunities) power electronics is facing.

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