Integration of Renewable Sources into Hybrid Renewable Energy Systems

Contribution on Spreading Renewables in Low Voltage Grids

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Abstract

This thesis presents the approach and research of the concept of a controlled power unit based on renewable sources interconnected to an electric grid, able to transform its input stochastic energy into an output deterministic one.

Former attempts to supply the electric networks with renewable sources have caused several issues, namely power quality issues due to the direct transfer of the renewable sources stochastic nature to the power injected into the grids. This work proposes a system with two renewable sources (sun and wind) that is able to present to its user an energy that is free of that stochastic nature. To achieve this goal a storage element and energy control strategies are used which allows regulating the power from the renewable sources, presenting therefore a controlled and controllable power at its output. Moreover it allows the raise of its economic value not only because it maintains continuously the renewable sources in their maximum power but also because of the capability of using the energy in more profitable periods as well as through the attribution of control services to grids operators.

This type of controlled system is well suited to new grid concepts and architectures, droved by the growing electricity consumption along with the decrease of the global economic resources and also by the actual concerns about energy dependence and environmental impacts. These new architectures require new capabilities from their energy suppliers, namely the knowledge of their operational conditions and the capability to control their power/energy in view of a better grid management for a better quality of energy.

An experimental platform is built to validate the approach proposed. Using real meteorological conditions the platform is used along with the proposed management strategies to validate the concept of a controlled power source.

The obtained results are satisfactory and allow supporting the spreading of renewable based energy sources interconnected to the grid. Although with a reduced scale the obtained results can be extrapolated for larger systems.

Resumo

Esta tese apresenta a abordagem e pesquisa do conceito de uma unidade com potência controlada, baseada em energies renováveis e interligada à rede eléctrica pública, capaz de transformar a estocasticidade da energia primária numa energia deterministica.

As anteriores ligações de unidades de produção, baseadas em energias renováveis, à rede eléctrica resultaram numa série de problemas, designadamente ligadas à qualidade da energia devido à transferência directa da característica estocástica daquelas para a potência injectada na rede. Esta tese propõe um sistema com duas fontes de energia renovável (photovoltaico e vento) que é capaz de apresentar aos seus utilizadores uma energia livre daquela característica estocástica. Recorrendo à utilização de um elemento de armazenamento e a estratégias de controlo adequadas, apresenta, ao utilizador, uma energia controlada e controlável. Adicionalmente, permite aumentar a sua valia económica dado manter contínuamente as fontes na sua potência máxima, ter possibilidade de transferir energia captada para períodos tarifários mais rentáveis e oferecer a possibilidade de atribuír o controlo de serviços a um operador de rede.

O conceito de gerador controlado adequa-se bem aos novos conceitos e arquitecturas de rede que estão a emergir, impulsionadas pela crescente procura de electricidade a par com a diminuíção dos recursos económicos mundiais bem como pelo incremento das preocupações políticas de independência energética e das preocupações com o meio ambiente. Estas novas arquitecturas requerem novas capacidades por parte dos seus fornecedores de energia, designadamente da informação acerca do seu estado operacional e da capacidade de os controlarem em termos de potência/energia, com vista a melhorar a gestão da rede para uma melhor qualidade de energia.

Foi desenvolvida uma plataforma experimental para validação da abordagem proposta. Utilizando condições reais de exploração, a plataforma experimental foi utilizada para testes com as estratégias de gestão energética desenvolvidas de forma a validar o conceito de uma unidade controlada de energia baseada em fontes renováveis.

Os resultados obtidos permitem apoiar a disseminação de fontes de energia baseadas em energias renováveis ligadas à rede eléctrica. Embora a uma escala reduzida, os resultados obtidos podem ser extrapolados para sistemas de maior potência.

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Chap. I – Context of renewable generation and new paradigms

There is a continuous trend in the growth of electric energy demand (***Fig. 1***), not only in the industrial/commercial environment but also, and predominantly, in the home user environment and transports (***Fig. 2***). It is expected a 2.2% growth per year between 2008 and 2035, with 80% occurring in non OECD countries with transportation demand reaching 10% of total demand by 2050 [1].

The increase in demand energy poses a problem of generation capacity. The historic solution has been supported on the installation of large power plants, involving large investments **[2**] and a higher risk **[3**] when they operate in deregulation in electricity markets.

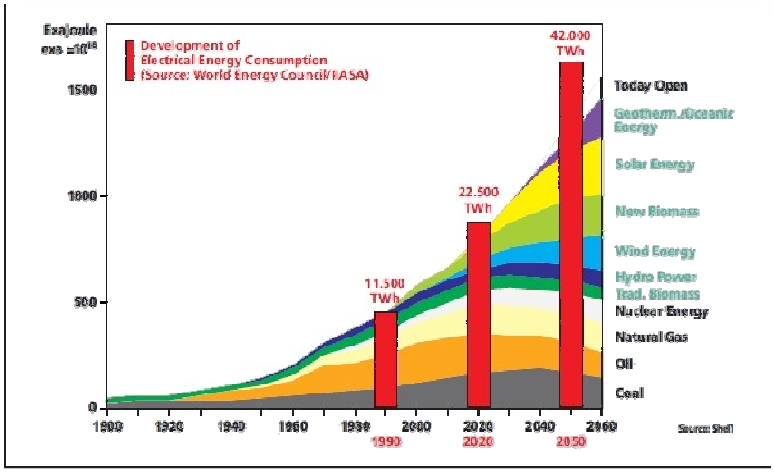

Fig. 1 - Electricity consumption and primary energy sources [4]

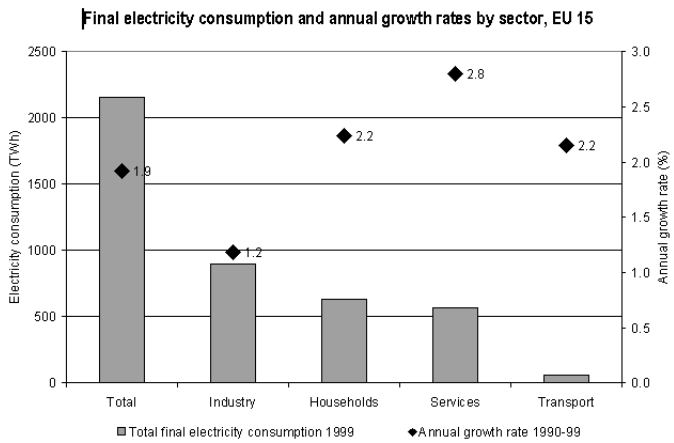

Fig. 2 – Electricity demand trend – European Environment Agency, 2002

Power generation and transmission facilities have found troubles meeting new energy demands. Transmission load is projected to grow in the next ten years by 22–25% but the grid however is expected to grow less than 4%, as a result of economic, environmental, technical, and governmental regulation constraints **[5]**[**6**].

Additionally, there are a certain number of issues that participants in the domain have to consider, as:

- Growing environmental concerns, namely with greenhouse gases (CO2 emissions associated with hydrocarbons).
- Attempt to achieve energetic independence from third party countries in order to reduce the primary fuel price and supply variations.
- Development of new economic and financial rules that arise from the deregulation of energetic markets.

These issues make the electrical environment more difficult to manage than in the past.

They also contribute to a paradigms change. The five major factors that contribute to changing views for electric systems as identified by International Energy Agency (IEA) and are:

- Developments in distributed generation technologies
- Constraints on the construction of new transmission lines
- Increase in the customer demand for highly reliable electricity
- Liberalisation of the electricity market
- Concerns about climate change

The solutions for these issues have been orientated towards the spread of decentralized generation also referred as distributed generation (DG) and to the development of new electrical system structures.

DG based on renewable sources of energy are particularly well positioned to address actual concerns such as: environmental - they do not produce wastes in the conversion process, economic - the primary energy is costless and political - the sources are available anywhere.

An historical perspective **[7]** provides an understanding framework for those points:

To understand the structure and use of current electricity supply systems and to lean about possibilities and the barriers to changing these systems Verbong and Van der

Vleuten (2002) analysed in Work Package 1 the historic dynamics of long-term electricity supply systems. They observe that, in a long-term historical perspective, the current concern or critical problem for creating a level playing field for distributed and centralised generation is remarkable. This concern seems completely opposite to the dominant critical problem in the 1950s and 1960s, which was to reduce the contribution of distributed generation to public electricity supply as much as possible, in order to achieve advantages of scale. It is no surprise therefore, that current systems have an intrinsic bias towards centralised generation. Arguments for large scale power generation during the era of scale increase and expansion were economies of scale, construction of (coal) power plants located near mining sites and integrated with hydro, investment savings on back-up units and avoiding over-capacity. Later on in many countries the introduction of nuclear power plants lead also to centralised generation. Due to the increasing availability of natural gas in many countries, environmental concerns and technological development (such as; availability of competitive smaller generators) scale increase and siting of power generation locations became of lesser importance. As a result, in the 1970s and 1980s electricity systems in some countries started to develop from central systems in the direction of hybrid systems hosting centralised as well as decentralised generation units in one and the same system. The possibilities (barriers, opportunities) for DG in the current socio-technical electricity supply systems are conditioned by characteristics of the system developed in the era of centralisation and how actors since the 1970s have been dealing with these.

1 - Decentralized generation

Decentralized generation (Europe and Asia), also known as embedded generation (South America), dispersed generation (North America), on-site generation, and distributed generation, has not yet a formal accepted definition. It can, however, be defined as the use of small-scale power generation technologies located close to the load being served **[8]**. Also in **[8]** it is argued that there is no consensus about the definition and presents some organizing view points such as: purpose, location, rating, delivery area, technology type, environment impact, mode of operation, ownership and penetration level. It also proposes a general definition as "*electric power generation within distribution networks or on the customer side of the network*".

In general the definition of DG (CIGRE, CIRED, IEEE, IEA) encompasses three main ideas **[9]**:

i) Small source of energy (sub-kW to a few MW)
ii) Interconnected anywhere in the distribution network (on the customer side of the meter)
iii) Beyond the control of transmission operator.

A DG synopsis is presented in ***Fig. 3***.

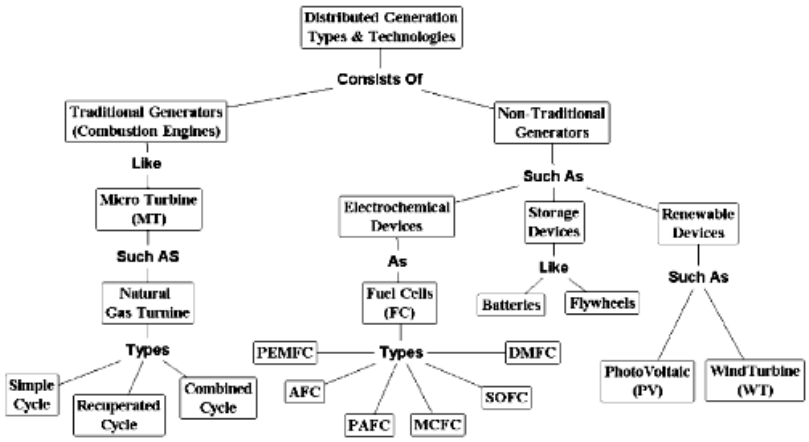

Fig. 3 - Types and technologies for distributed generation [10]

DG has been developed and supported mainly by public incentives – CERTS (USA) and Microgrids (EU) are exemplificative supported development projects – but is still not economically competitive when compared with traditional bulk power plants.

The development of the power electronics as well as the development of the information and communication technologies (ICT) have been (and are expected to continue) a leverage towards the solutions for some of the problems that decentralized generation poses to the electrical grids when (inter)connected.

While the adoption of DG appears to face difficulties related to specificities of each country, namely the characteristics of the existing centralised power system **[7**], it is nevertheless expected to continue to grow. A DG share that could reach 30% in next years, where a large amount of locally generated energy will also be consumed locally, will give the distribution network a local character **[11**].

Taking in consideration expected penetration figures, an analysis of the benefits and drawbacks that come from the spread of DG when connected to the electric network is required. From **[2**] the benefits of DG use are:

- to allow a reasonable span of reduced power (less than a kW to few MW)
- to be located close to the loads – dispersion capability through the network and losses reducing capability
- to be grid-connected or islanded operated
- to perform services
- to allow grid investments deferment
- to have reduced investment, lower installation time and little maintenance
- to allow the use of renewable generation

And according to **[2]**,**[12]**,**[13]**,the issues raised by DG are:

- Networks are designed to unidirectional power flows
- Generation units are not centrally dispatchable
- Little practice with a large number of DG interconnections
- Technical concerns of the utilities about DG connection – namely short circuit contributions and pre-defined protection schemes
- Difficulties in the distribution of grids adaptation costs
- Metering issues related with changed power flows
- Lack of interconnection standards and application processing regulations
- Utilities loss of revenue for each kWh generated by DG
- Eventual decrease of overall grid reliability

1.1 - Network impact of DG connection

In view of the issues that the spreading of DG raises it is important to have an insight on their impact when connected to existent electrical grids. The general problem with the integration of DG in existing networks is that these ones were planned "from top to bottom" as a whole, including not only the generation(s) plant(s) but also the auxiliary infrastructures needed to connect generation to grid (substations, transmission lines, protections, etc.) **[2]**,**[12]**,**[14]**. Furthermore, network connected DG usually is not able to provide system services[1] – frequency and voltage control, fault current delivery, fault "ride through" capability – necessary to ensure a stable operation of the electric system **[11]**.

More specifically DG is usually integrated in electric networks that have a control structure based on a distribution network which is a passive element for the transmission network. In this transport/distribution structure typology the generation is mainly connected to the transmission network and the power flows are unidirectional from the generation to the loads. Thus it does not needs much operational coordination (both in normal as in emergency conditions) between transmission and distribution networks **[7]**. With DG, the distribution network (usually radial with single infeed of load and fault current) becomes an active system with both consumption and generation, leading to a situation with multiple infeed of load and fault currents. Therefore, the consequence is that the electric

[1] Also referred as ancillary services.

system needs to become more flexible and to require a more integrated operation perspective **[15**],**[16**] to be able to manage the new power generated. Therefore, DG must offer dispatch capabilities and participate in frequency control. If this is attainable, DG can be viewed as a set of controllable conventional generation units that can actively reduce or increase power production in function of the network necessities. It should be noticed that most DG are connected to the network through power electronic interfaces that offer several possibilities to control the power delivered. For instance, their lack of inertia that can allow fast responses as when power system disturbances occur and synchronous generators are not always able to respond rapidly enough to keep the system stable **[5**].

One of the potential benefits of DG connected to low voltage network is an increase in service quality, reliability and security, proving that it will be integrated in an intelligent way in power system planning practices **[17**]. But the full potential of DG at distribution levels – taking over some of the responsibilities of the large conventional plants as support to the electric system in critical conditions – is still not requested **[17**]. Increased DG penetration is even desirable if they are allowed at participating in the power balance (frequency control) **[15**].

In networks with connected DG, while the magnitude of the DG power is smaller than the utility feeding substation, the system operation is not critically dependent on the local generation. If this is not the case, DG is viewed by network operators as a problem mainly due to significant impact of fault current and pre-existing protection systems – possibly the major technical barrier for wide-scale integration **[18**]**[19**]. In that case and assuming a non dispatchable capability of DG units (which is the majority case when they are renewable based) there exist a double effect of a reduction of the number of dispatchable units that were substituted by the non dispatchable DG along with the increasing demand in the remaining units. But it can also be viewed as having a beneficial effect on the customer security of supply if islanding is allowed **[15**]. Presently, however, the operational strategy in use requires the immediate disconnection of DG units in abnormal conditions.

Another potential benefit effect of DG would be to support and assist the network in abnormal conditions like black-start situations **[15**] since the energy availability stays in the DG and is not dependent on the connection to the transport network. The tripping of DG units can no longer be the standard procedure for all

sorts of disturbances and they must instead be able to withstand larger variations in voltage and frequency **[15]**. According to **[20]**, future power systems generation units must be able to:

- stay connected during grid failures
- supply short-circuit current
- be able to supply reactive power
- reduce real power with over-frequency

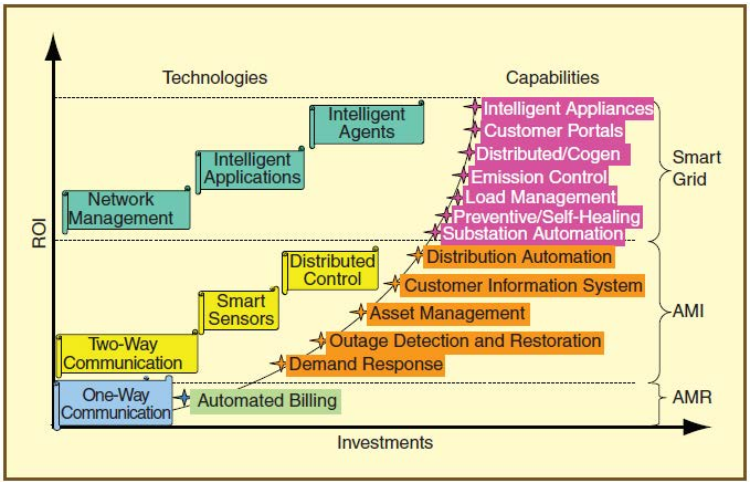

Fig. 4 – Communication and investment ROI (AMR: automated meter reading; AMI: advanced metering infrastructure) [21]

The lack of information about the operating conditions of DG units results in a certain level of uncertainty that complicates the electric system operational management. In order to achieve a more flexible and active network operation, high penetration of DG must be provided with communication capabilities. That will allow system operators to have information on which units are on-line, what are their outputs and what are their future capacities **[15]**. The existence of communication between user and provider even has an impact on the profitability of the investments as ***Fig. 4*** suggest. Actual ICT development creates a capability of universal connectivity between large varieties of network devices **[17]**. This allows real-time interaction between suppliers, operators and customers thus supporting the needed for grid flexibility, integration and controllability. The widespread of Internet can easily and costless support the penetration of small scale DG based on two-way communication that enables new services like automation, dynamic pricing and real-time power selling.

The existing Ethernet wiring is commonly used for local area networks (LANs) which are commonly available due to its popular adoption for Internet use in residential applications. So, it is an existing platform that could leverage the use of communication for the purposes mentioned here. However, this technology must be connected to a wide-area-network technology such as ADSL or a cable television system to increase communication speed if it is to be used in contexts more demanding like the electrical control and management one. Furthermore, the reliability of these networks is maintained only at a convenience level and, as such, it would be inappropriate for the transmission of the electrical protective functions this way **[22**].

Another trend is to inject intelligence into the network in view of the need for decentralized coordination and control. Software agents and electronic markets **[17**] are an attempt to achieve that goal.

The increase of DG interconnection can also lead to unforeseen issues. The excess of production, specifically when based on uncontrolled renewable sources is an example, as the cascaded problems faced by Danish electric system in 2007 that culminated in the forced stand-still of 200 MW wind production for 10 h **[16**]. The difficulties in planning and in load forecasting when DG masks load growth, the unintentional islanding that can cause safety issues and uncertainty in power system stability when major disturbances occur caused by the reduction of generation power by central units, are another examples of the complexity of DG integration.

An overview of DG applications **[23**] which helps to frame the subject is presented in ***Table 1***.

1.1.1 - An economic and marketing view

Electrical generation faces not only technological issues but also other problems not yet very familiar to them. One of them is the change from a monopoly view to an open market view. The inclusion of the marketing perspective is another change of paradigm that imposes a new behavioural.

As DG is located close to the loads less energy transport is needed which is the inverse situation faced by the central generation. This can negatively affect Distribution System Operators (DSO) business as it represents decreasing revenues to them. As DSO usually acts in a monopoly environment protected by regulations and DG suppliers in a market environment not restricted by

regulations, the development of new business frameworks would be favourable to the exploitation of opportunities perceived for DG **[17]**.

Services Provided	Combined Heat and Power	Standby Power	Peak-Shaving	Grid Support	Stand Alone
Energy	Simultaneous production of electricity and useful heat provides low cost energy to customers	Energy production is minimal and a small part of overall value	Provides alternative to high cost peak period energy	Reduces line losses, can be important in remote or congested parts of the T&D system	Must provide customer full requirements
Capacity	Provides capacity when running	Customer reserve capacity	Avoids high peak period system capacity costs	Can help to avoid T&D capacity constraints	Must provide customer full requirements
System Reserve	If the system is running at full load, by definition there is no reserve	Possible extension of current applications, but not part of most current standby systems	Could provide spinning and standby reserve during off-peak periods	Could provide spinning and standby reserve during off-peak periods	Must provide customer full requirements
Reliability	Systems are generally as reliable or more than individual utility generators. Synchronous generators increase customer reliability by 90+% but don't contribute materially to system reliability	The primary purpose of these systems is to approach 100% reliability for health and safety reasons and to avoid economic losses from grid power outages	Increases customer reliability and can be part of a utility program to reduce shortage based outages	Increases reliability due to supply shortages, T&D constraints, and storm related outages	Must provide customer full requirements
Power Quality	Provides customer some protection from grid problems; can be part of a premium quality customer system	Not a primary issue but can be part of a premium quality customer system	May help customer to avoid voltage sags and brownouts that occur during system emergencies	Can be used for power factor correction and voltage support	Must provide customer full requirements
Back-up Service	For every 1% drop in generator availability, the system requires 87 hours of back-up service. Back-up for maintenance during off-peak periods, but forced outages can occur anytime	The system is the back-up service so separate back-up service is not required	Peak-shaving can be an extension of back-up service	Grid support enhances T&D system in general, not specific to back-up service	Must provide customer full requirements

Table 1 – Possible applications and services provided by DG

From an economic point of view the use of DG poses some problems, considering a deregulated market environment. In the first place, while the overall investment in DG represents a smaller value, their unit cost (€/kWh) is bigger as they do not profit of the scale factor **[24]**. Secondly, DG poses problems of reliability which is an essential concern in liberalised markets as a high reliability implies investment and maintenance costs **[9]**.

But DG also represents a good marketing opportunity as it has the potential to fill niches – customers that are looking for their best suited service – in saturated markets where differentiation is a need. Moreover, markets are inherently dynamic and DG is well suited to respond to this characteristic: it is able to be assembled anywhere, with diversified sources, in a very short time, operated immediately and separately, with a size that can be increased or decreased and with the ability to track and follow the unavoidable market fluctuations **[13]**.

Until now, DG developers and operators are essentially concerned with energy production from their units but, based on current generic incentives, not motivated to provide services associated with system security **[17**]. Although the opportunities created by the deregulation and market framing, DG is often insufficiently rewarded, or even not rewarded at all, for their benefits to the electricity system and to the society **[17**]. They are strongly dependent on non-market support schemes **[7**] which affect their profitability.

The necessity of regulation could ensure the compensation for those benefits which, along the expected decrease costs of DG technologies, would increase the profitability and therefore the spread of this type of generation. This leverage to DG penetration allows, beside society and electric system benefits, to increment operational experience with the connection of a large quantity of DG and more particularly those based on renewable sources. A comparison of today and future costs versus revenues structure is presented in ***Fig. 5***. It shows clearly and expected and wanted evolution to a regulation of DG units as active players

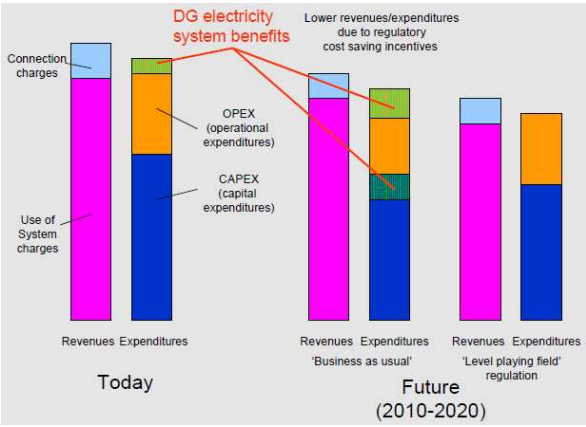

Fig. 5 – Economics of DSO [7]

In **[7**] it is suggested that the use of regulatory enactments could shape the DSO profits and therefore to provide incentives for DSO to become more efficient which will result in lower future network tariffs. ***Table 2*** presents a overview of the benefits and drawbacks for the electric system that arises from the DG connection to the networks.

The use of the concept of net-metering can also encourage consumer's investment in alternative methods of energy generation like DG while still using

conventional utilities **[25]**. It provides them with an immediate refund and can leverage the growth of small energy systems **[26]** that are fundamental to encompass storage.

Some growing trends in DG domain can be described **[27]**,**[28]**:

- Real-time pricing (differentiation in electricity prices in function of different time periods (e.g. hourly) according to its marginal cost)
- Paid-for-Performance Incentives
- Alternative Pricing and Rate Incentives
- Regional Emergency Operating Procedures
- Emerging Incentives that Differentiate Reliability Needs

	DG can create benefits to the electricity system:	DG can create costs to the electricity system:
Network related	• *Distribution capacity cost deferral:* the development of small-scale DG facilities near a load can postpone necessary investments in additional distribution and transmission capacity absolutely or temporarily. DSOs can benefit from these new DG facilities as it can reduce their investment costs in upgrading or extending the distribution network. The costs of distributing electricity differ from location to location, and placing DG facilities in 'high-cost areas' may reduce costs for DSOs. • *Operational cost savings:* distributed generation can reduce costs for operation and maintenance of the distribution system. Values regarding engineering costs include: - reduction of losses, - voltage support, - reactive power support equipment life extension. • *Congestion relief.* • *Reliability improvement:* through grid relief and therefore a lower probability of blackouts or brownouts.	• *Connection costs:* the connection of the DG plant to the distribution network incurs expenses regarding connection lines and grid upgrade, depending on the location of the DG facility. When choosing the location of a DG facility close to an existing grid may reduce connection costs. • *Metering costs:* metering of DG production presents a cost that is allocated outside the network, and can be attributed to the DG operator. The costs for a management and control system that collects automatically metering data and provide control signals to the DG plants should, however, be attributed to the DSO. • *Costs for network upgrade and extension:* induced by DG plants. • *Costs for additional planning efforts.* • *Transaction costs* (e.g. administration costs etc.)
Energy related	• *Contributions to (peak) load reduction:* to backup capacity and to balancing power. • *Flexible option values* (e.g. short lead times for DG, contribution to balancing power, etc.) • *Improvement of security of supply* (e.g. through ICT systems and/or better forecasts) • *Avoidance of overcapacity:* avoidance of overcapacities or at least reduction of reserve margins compared to more centralised systems. In traditional power systems an increasing demand of electricity was solved by installing a new 'central' power plant. In todays market environment, over-dimensioning of power plants may be a risky investment. Small-scale DG plants are better equipped to respond to short-term demand changes. • *Less lumpy generation investment.*	• *Reserve costs:* when installing a large capacity of intermittent DG sources (e.g. wind and PV generators) a certain backup of power needs to be available. This can be another DG source (illustrating that DG can act as reserve capacity also) or centralised source. DG that is 'controllable', such as CHP plants that can be operated independently from heat demand, can contribute to reserve capacity. • *Balancing costs:* there might be a need for additional balancing power because of the intermittent character of some DG sources (such as wind or PV systems). Generally, the ability to balance the distribution system depends on the way that a DG generation facility is controllable and can present a burden or a benefit to the distribution system. • *Costs for additional system services.* • *Control costs:* in the case of controllable DG plants.

Table 2 – Costs and benefits for the electricity system induced by DG [7]

1.2 - New grid architectures

The theme of new architectures for the electrical grids is object of a large number of published materials.

In opposition to the transport grids, the conventional network design at the distribution grid led to less sophisticated control and management structures and low

automation level. The increase of DG connections and ageing assets calls for more active networks strategies and technologies at the distribution level **[29]**.

Besides physical access to the network, DG faces a problem of access to the energy trading market such as day ahead, intraday, balance and ancillary markets **[7]**. With small DG units the problem is even worst as, besides access regulations, they have a problem of scale not only of power but also economic. The restriction of access to the markets by small power generation units is understandable since it would be virtually impossible to manage (possibly) thousands of such small units. Additionally, the costs of gathering knowledge necessary for a successful participation in the market are largely fixed costs and it gives advantage to the powerful participants **[7]**. The solution probably involves the aggregation of small (or medium) units, where a single entity controls multiple units, allowing them to act as a large generator and to be competitive with respect to large conventional generation plants. Moreover this association allow at achieving not only scale but also sources diversity and other applications can therefore be considered **[26]**.

The separation of operational control and ownership is an important principle that could enhance the flexibility of the electric systems through the coordination of multiple units. The use of aggregation could allow the non-discrimination against any specific generation technology by network operators which is especially important for balancing and reserve markets **[7]**. In fact and under current rules, the operators contract such services usually with minimum 1 MW quantities **[30]**.

There is already some work developed about aggregation schemes such as Microgrids and Virtual Power Plants (VPP) showed in ***Fig. 6*** and ***Fig. 7***. The former encompasses generation and loads and as a geographical scope. It can be operated in a grid-connected or islanded mode. The latter encompasses generation only and has a commercial scope in the sense that generation can be physically located anywhere **[17]**,**[31]**.

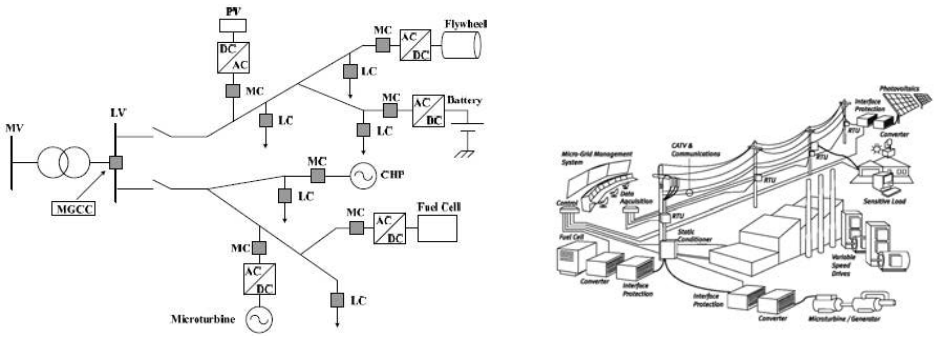

Fig. 6 – Microgrid example [32]

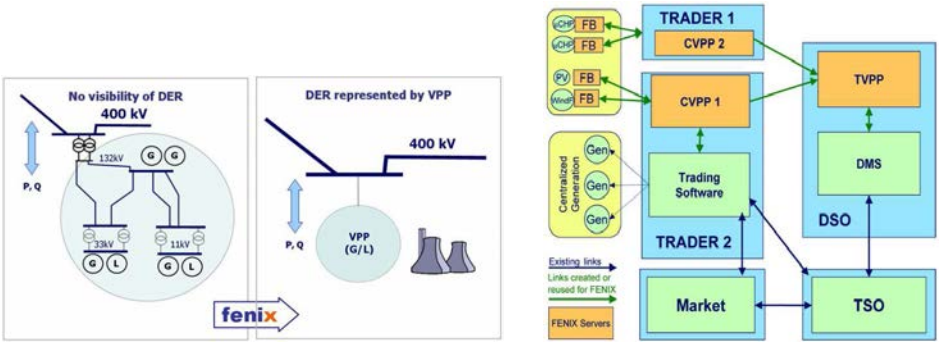

Fig. 7 – VPP example [http://fenix.iwes.fraunhofer.de/html/what.htm]

The advantage of the Microgrid concept is the ability to operate even when it is not connected to the grid, as in the case of failure of the network, providing a local continuity of supply **[17]** to the loads that it serves. The advantage of the VPP concept is the ability to be a flexible representation of a portfolio of DG that can be used to make contracts in the market and to offer services to the system operator **[31]**.

There are a large number of potential players that might be interested to serve as aggregators: automobile constructors, battery manufacturer/distributors, cell phone network providers, distributed generation manager, etc. **[33]**,**[17]**.

Besides the aggregation issue, a more generic concept is the concept of smart grid which aims to foresee future networks. Smart grid is a relatively new concept that points out to the application of information technology to power systems **[35]**. Although not significantly different from actual conventional electric grids it means to lead to improved cost-efficiency and effectiveness **[35]**. In this architecture the objectives includes activation of demand (based on two-way interactive ICT), grid

monitoring and management, advanced maintenance advanced metering infrastructure, renewable integration, electric vehicle (EV) and vehicle to grid (V2G) **[36]**. The concept aims to attain a grid that possesses the following characteristics:

- self-heal
- motivate and include consumers in energy decisions
- resists attack
- provide power quality
- accommodate all generation and storage options
- enable markets
- optimise assets and operate efficiently

This concept is illustrated in ***Fig. 8***, ***Fig. 9*** and ***Fig. 10***, presenting the characteristics described above.

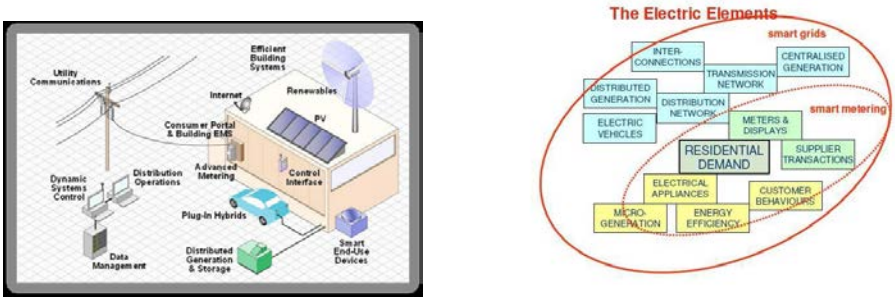

Fig. 8 – Smart grid concept (Inovgrid) and technologies and solutions perspective [35]

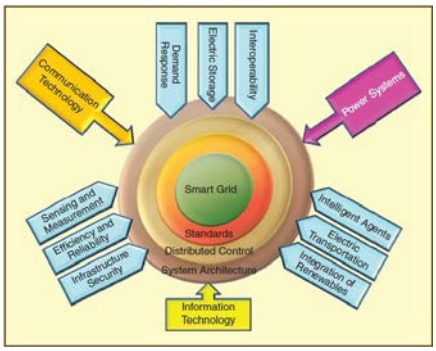

Fig. 9 - Basic smart grid ingredients [21]

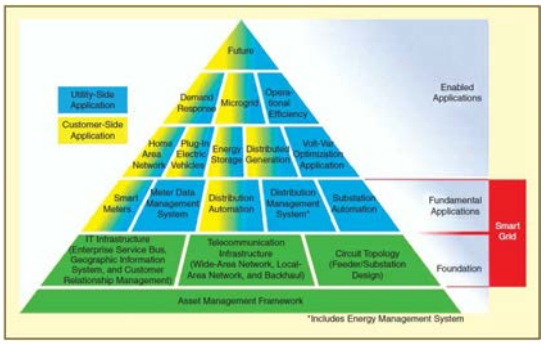

Fig. 10 – Smart grid pyramid [21]

In the same sense **[14]**,**[37]**, refers that power delivery system of the future will be:

– Interactive with consumers and markets
– Self-Healing and Adaptive (to correct problems before they become emergencies)
– Optimized (to make best use of resources and equipment)
– Predictive rather than reactive (to prevent emergencies ahead rather than solve after)
– Accommodates a variety of generation options
– Integrated to merge all critical information
– More Secure

The intelligent grid is the power system that is capable of assessing its health in real-time, to predict its behaviour, to adapt to new environments, to handle distributed resources and stochastic demand, and to optimize response to the smart appliances. It is a tool that allows electric utilities to focus on evolving true business drivers by enabling cost containment, end-to-end power delivery control, and a more secure infrastructure **[14**].

2 - Renewable energies issues

According to the International Energy Agency (IEA), *renewable energy resources are resources that are generally not subjected to depletion. Such resources can be heat and light from the sun, force of the wind, organic matter (biomass), falling water (hydric), ocean energy and geothermal heat* **[8**].

Renewable energy sources are valuable assets when considering their 'anywhere' availability (energetic independence, decentralized gathering) and free cost (economy). It is expected a growth of renewable energy generation for the coming years, with a baseline scenario developed for the EU-25 showing an increase of Combined Heat and Power (CHP) and Renewable Energy Systems (RES) up to 36% in 2030 **[7**]. A prognostic of 100% renewable energy supply based on domestic resources even being physically possible **[39**]. ***Fig. 11*** presents the past and forecasted cost for renewable energy technologies that supports the idea of a renewable generation growth.

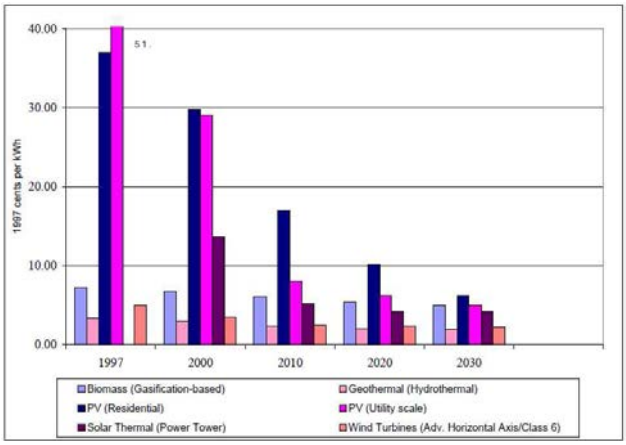

Fig. 11 - Levelized cost of electricity forecast for renewable energy technologies [40]

Nevertheless, renewable sources may contribute to aggravate grid congestion and protection coordination problems. Indeed, the variability of primary resources as wind and sun (***Fig. 13*** and ***Fig. 14***) lead to significant power variations and flicker if they remain uncontrolled as in the grid "connect and forget" strategy.

In EU some penetration levels of RES, namely those based on wind, are beginning to undermine integrity and security of the electric system **[17]** due to that strategy that was used so far. To evidence that issue ***Fig. 12*** shows the effects of wind power in the electric systems.

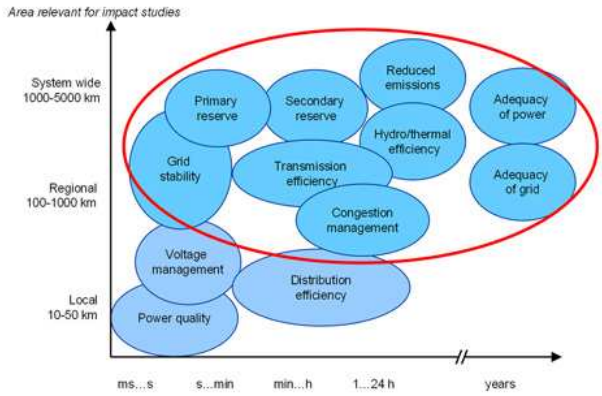

Fig. 12 - System Impacts of Wind Power [41]

The sun is also a variable source where the power gathered can quickly drop by 60% causing sudden variations in node voltages which are not problematic if the connection density is low but can become severe in the inverse case **[42]**, especially in the case of connection to long distribution feeders **[43]**. The match between the PV peak power generation and the grids peak consumption is normally not met. However, there is

sometimes a coincidence of electrical consumption of some type of loads (commercial for instance) that peak in the early afternoon. In these cases the total PV generation in a utility system can help to reduce the peak network load, even though it may have no impact on the peak load at the residence where the PV is installed **[22]**.

Renewable type sources are stochastic and, in their genesis, uncontrollable and not dispatchable therefore supposedly unable to ensure an adequate reliability of supply. ***Fig. 13*** and ***Fig. 14*** evidences the stochastic nature of the primary input characteristics, typical wind speed and sun radiation.

So, renewable generation adds significant uncertainty to power systems management as they are extremely dependent on accurate forecasting for power balance between generation and consumption **[3]**,**[11]**. Moreover, renewable generation systems are usually feeding their instantaneous maximum power, to achieve an economic leverage **[11]**. An example of such connection problems is the economic question of considering the expansion of the new transmission capacity for accommodating 60 strong wind days in a year **[11]**.

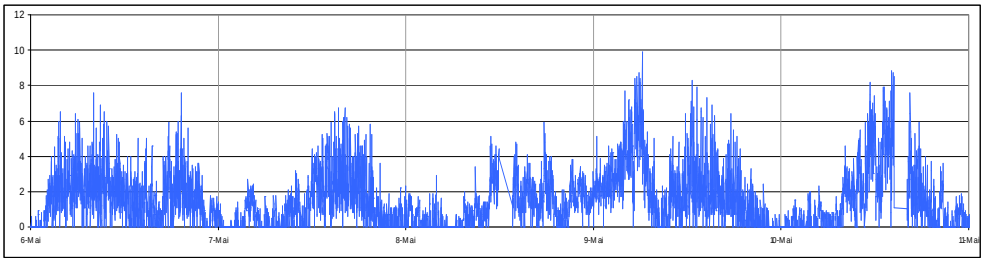

Fig. 13 - Wind profile example for one week (local data). Values in m/s.

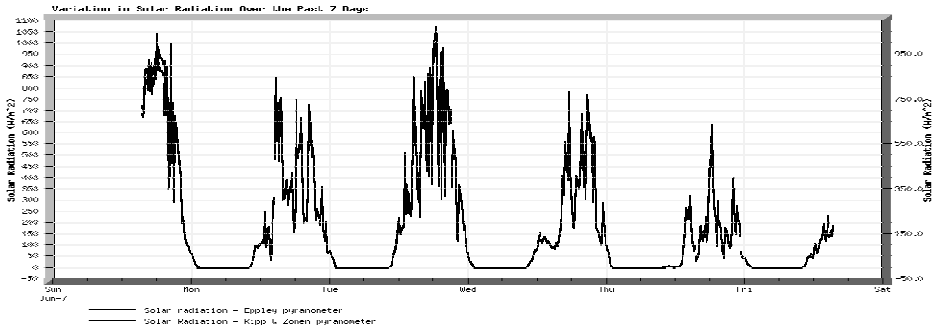

Fig. 14 - Radiation profile example for six days [http://geog-www.sbs.ohio-state.edu/weather/]

Therefore the uncontrolled connection of renewable generation to the power grid translates directly in quality problems **[44**],**[15**],**[18**] – frequency and voltage variations – or management – bidirectional power flows – if the used strategy is "connect and forget" (feed power not controlled). This strategy only works well, if the amount of renewable power is much lower than the grid power in the point of connection **[11**],**[15**],**[18**]. Recently, transmission grid codes have started imposing voltage-ride-through capabilities, voltage support and active power reserves for new wind farms **[45**], showing a possible change in the usual connection strategy.

Although two survey respondents mentioned cumulative harmonics as a source of concern for the future, and the topic arises in the literature occasionally, the literature, experimental results, and utility feedback indicate that harmonic pollution and excitation of power system resonances are not problems, as long as high-quality sinewave inverters are used **[22**].

Even considering that the connection of generators with different renewable source inputs can attenuate the issues of the power injected in the grid that does not solve all the problems. ***Fig. 15*** depicts the power delivered to the grid for a combined wind and sun generators where one can see the variations not only in high frequencies (minutes or seconds wind variations – power problem) but also in low frequencies (hour sun variation – energy problem).

Such power profile can pose problems of congestion (midday period) or loss of load (reduced or no generation periods) such as the eventual combination of high generation and reduced consumption that could probably be shut down by a high frequency limit set point **[44**] or be curtailed by a local dump load resulting in a net loss of available energy and, consequently, a larger payback period.

As the penetration of renewable energy continues to increase, the variation of such energy sources may become the single largest source of variability on the power system. The variability must also be understood in terms of short-term behaviour affecting the unit commitment and load following reserves **[34**].

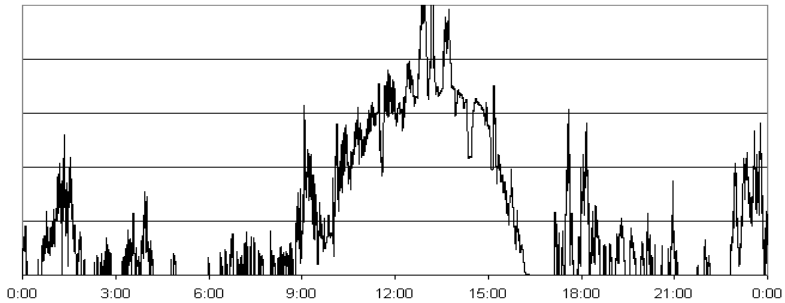

Fig. 15 – Combined wind-photovoltaic uncontrolled generation power example

Grid connection issues related to stochastic renewable sources can be dealt through a combination of load management and storage **[30]**,**[42]**,**[34]** providing that the dimension of the generator unit in not very large, as it is difficult to store large quantities of electric energy (excepting the case of hydro storage). Storage may be purchased to allow for better operation of localized portions of the power system (taking strain off transmission during constrained periods) or even using it to support the power system as a whole. Alternatively, the storage may be sourced from an electric-vehicle-to-grid arrangement, with an agreement on how often the system can cycle the batteries and how much it is allowed to draw them down.

Another type of solution lies in the use of hybridisation **[46]** – compensation of the weakness of one with the strength of another – whether in the sources (***Fig. 16***), whether in the storage or even in the energy carrier **[16]**.

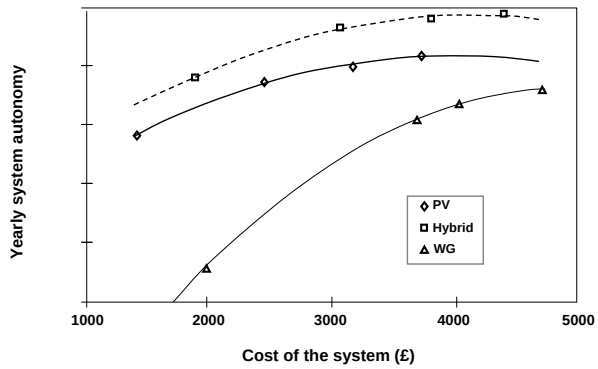

Fig. 16 - Yearly system autonomy versus system cost for single photovoltaic, single wind and hybrid photovoltaic-wind system

An economic point of view is also relevant to the analysis of the use of renewable sources. ***Fig. 17*** shows the correlation between wind production and spot market prices where one can notice that decreasing wind production drives up prices and increasing

wind production drives down prices **[16]**. This behaviour calls for RES that can be controllable, not only to circumvent that problem but also to be able to take an economic advantage of price variation.

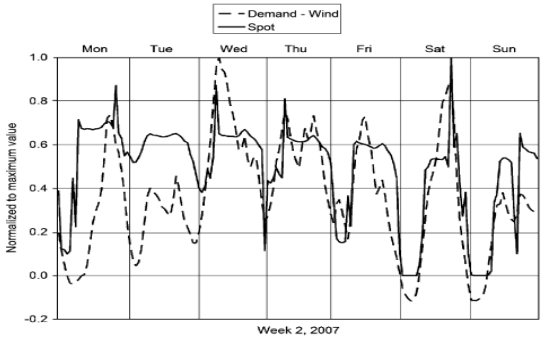

Fig. 17 - Normalized spot market prices and electricity demand minus wind production

System design decisions, whether in terms of contractual agreements or the instalment of physical equipment, must be based on accurate information about the degree of flexibility that is required. If high levels of non-scheduled renewable energy are employed in the system, these will tend to dominate the flexibility requirements. A careful assessment of the renewable energy resources (their variability and its effects on the power system) is vital when re-negotiating contracts or considering installation of physical equipment **[34]**.

It is worth to be noticed that despite the free cost of the primary energy involved in renewable sources their use involves technology that is neither costless nor emissions free.

The related renewable emissions issue is also referred in **[23]** where it is mentioned that DG can have sources based on combustion that corresponds to the more mature DG technologies and so, well placed to capture much of the early market but with a local emissions impact. In order to have a more wide perception, ***Table 3*** shows renewable energy payback times and associated emissions for various technologies **[8]**.

Comparison of energy amortisation time and emissions of various energy technologies

Technology	Energy pay back time in months[a]	SO_2 in kg/GWh[a]	NO_x in kg/GWh[a]	CO_2 in t/GWh[a]	CO_2 and CO_2 equivalent for methane in t/GWh[b]
Coal fired (pit)	1.0–1.1	630–1370	630–1560	830–920	1240
Nuclear	N.A	N.A.	N.A.	N.A	28–54
Gas (CCGT)	0.4	45–140	650–810	370–420	450
Large hydro	5–6	18–21	34–40	7–8	5
Renewable distributed generation technologies					
Micohydro	9–11	38–46	71–86	16–20	N.A.
Smallhydro	8–9	24–29	46–56	10–12	2
Windturbine					
4.5 m/s	6–20	18–32	26–43	19–34	N.A.
5.5 m/s	4–13	13–20	18–27	13–22	N.A.
6.5 m/s	2–8	10–16	14–22	10–17	11
Photovoltaic					
Mono-cystalline	72–93	230–295	270–340	200–260	N.A.
Multi–cystalline	58–74	260–330	250–310	190–250	228
Amorphous	51–66	135–175	160–200	170–220	N.A.
Geothermal	N.A.	N.A.	N.A.	N.A	50–70
Tidal	N.A.	N.A.	N.A.	N.A	2

[a] *Source:* Kaltschmitt et al. [22].
[b] *Source:* Lewin [23], Fritsch et al. [24], also Ackermann [25]; All figures include direct and indirect emissions based on average German energy mix, technology efficiency, solar radiation and typical lifetime.

Table 3 - Payback time and emissions for various energy technologies [8]

2.1 - Hybridization

Hybrid systems are proved to more reliable and economic more advantageous as they combine two less reliable sources **[46]**. The union of both sources can solve, to some extent, some of the problems of sources variability but demands a more complex control when compared to a single source **[46]**. The optimal operation of combined different components requires a further and higher layer – supervisor – that looks for individuals and coordinates them to accomplish some defined objectives.

2.2 - Storage

There are multiple storage technologies available, such as:

- biomass
- hydrogen fuel cell
- hydro based
- compressed air energy storage (CAES)
- heat pump
- redox flow cell
- electrochemical batteries (Pb, Li, …)
- flywheel
- superconducting magnetic energy storage (SMES)
- capacitor

There are many ways of categorizing the storage technologies, one of them, which is interesting for the present context, is based on the time properties as presented in ***Table 4*** **[47**]:

Full Power Duration of Storage	Applications of Storage and Possible Replacement of Conventional Electricity System Controls.	Biomass.	Hydrogen. Electrolysis +Fuel Cell	Large Hydro	Compressed Air Energy Storage (CAES)	Heat Or Cold Store + Heat Pump.	Pumped Hydro	Redox Flow Cells.	New And Old Battery Technologies	Flywheel	Superconducting Magnetic Energy Storage (SMES)	Supercapacitor	Conventional Capacitor or Inductor
4 Months	Annual smoothing of loads, PV, wind and small hydro.	✓	✓	✓									
3 Weeks	Smoothing weather effects: load, PV, wind, small hydro.	✓	✓	✓									
3 Days	Weekly smoothing of loads and most weather variations.	✓	✓	✓	✓	✓	✓	✓					
8 Hours	Daily load cycle, PV, wind, Transmission line repair.	✓	✓	✓	✓	✓	✓	✓	✓				
2 Hours	Peak load lopping, standing reserve, wind power smoothing. Minimisation of NETA or similar trading penalties.	✓	✓	✓	✓	✓	✓	✓	✓				
20 Minutes	Spinning reserve, wind power smoothing, clouds on PV		✓	✓	✓	✓	✓	✓	✓	✓			
3 Minutes	Spinning reserve, wind power smoothing of gusts.		✓				✓	✓	✓	✓			
20 Seconds	Line or local faults. Voltage and frequency control. Governor controlled generation.							✓	✓	✓	✓	✓	✓

Table 4 – Applications and duration of storage technologies

The main task of a storage unit is to insert flexibility in the manipulation of electric energy as the ability to rapidly vary real power where storage can play a significant role **[5**]. Investments in power storage have the potential to improve the integration of DG into power networks and to optimize power output, producing only when the demand is high **[17**], what improves systems availability **[26**] and favours dispatch ability.

Storage technologies are therefore excellent candidates to overcome the variability of renewable sources, compensating the excess or deficit of the relation load consumption-generated power and allowing profits maximization by relating time of delivery with cost of electricity and possibly providing services (which are necessary to have energy available for) such as active and reactive power, voltage and frequency control, emergency power during outages, etc. **[47**].

The connection to the network can also benefit from storage as into flexible AC transmission systems (FACTS) devices providing services like independent real and reactive power absorption/injection into/from the grid, leading to a more economical and/or flexible transmission controller **[5**].

Custom power devices address problems found at distribution level such as voltage sags, voltage swells, voltage transients, and momentary interruptions. The

most common approaches to mitigate these problems focus on customer side solutions such as UPS systems based on battery energy storage **[5]**.

Other benefits of storage, related by **[5]**, are involved with deregulation, together with transmission limitations and generation shortage that have recently changed the power grid condition. These are related with system reliability and power quality. The ability to rapidly damp oscillations, respond to sudden changes in load, supply load during transmission or distribution interruptions, correct load voltage profiles with rapid reactive power control, and still allow the generators to balance with the system load at their normal speed.

However, while storage is perceived as a good option to control renewable power there is still problems related with their use, fundamentally the relation cost-energy-power. ***Fig. 18*** and ***Table 5*** **[48]** give an overview of the advantages and disadvantages for some storage related technologies. ***Fig. 19*** and ***Fig. 20*** **[49]** show the cost and life cycle of several storage technologies and means to essentially highlight the economic weight that specific storage technologies have in the investment (cost) and re-investment (life-cycle) of RES (and especially small RES), ultimately determining their financial viability.

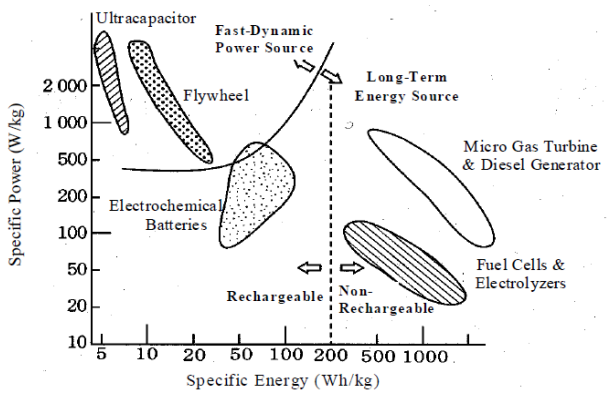

Fig. 18 – Main energy backup systems

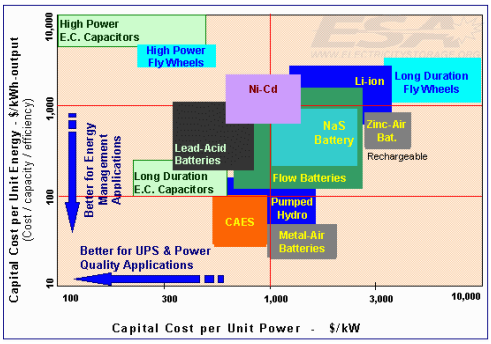

Fig. 19 – Storage capital cost

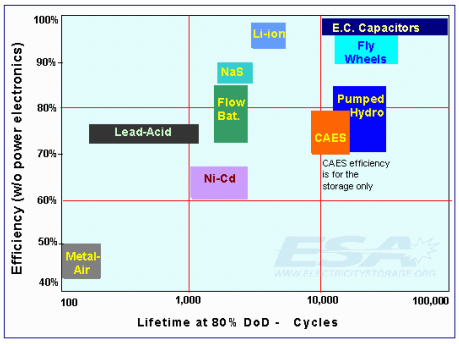

Fig. 20 – Efficiency and cycle life of storage technologies

Technologies		Advantages	Disadvantages	Potential Improvements
Superconducting Magnet Energy Storage (SMES)		High power density	Low energy density. High auxiliary needs. Expensive technology.	Lower costs. Higher energy density. Higher charging speed.
Supercapacitors		High power density. Long cycle life. Very fast recharge.	Low energy density. Requires advanced power electronics. Expensive technology.	Lower costs. Higher energy density.
Battery technologies	*Lead-Acid*	Mature technology. Familiar. Inexpensive.	High maintenance requirements. Low energy density. Low power density. Short cycle life. Environmental hazards. High voltage of deep discharging. Capacity depend on temperature increasing.	Depth of discharge. Performence at low ambient temperatures.
	Sodium-Sulphur (NaS)	High power density. High energy density. High efficiency. Mature technology.	Expensive technology. High temperature of work.	Lower cost
	Vanadium Redox (VRB)	High power density. High energy density. To use in huge aplications.	Early-stage technology. Expensive technology. Rugged standardization.	Lower cost. Improvement standardization process.
	Zinc-Bromine (Zn-Br)	High power density. High energy density. To use in huge aplications.	Early-stage technology. High cost of maintenance. Toxic components. Fast corrodible components.	Lower cost. Improvement of control and supervisor systems.
	Lithium-Ion (Li-ion)	High power density. High energy density. High efficiency.	Early-stage technology. Expensive technology. Difficult eksploatation.	Lower cost. Improvement of control and supervisor systems. Improvement of temperature gradients independent.
	Nickel-Cadium (Ni-Cd)	Mature technology. High mechanical resistance. High energy density. Long cycle life.	Expensive technology. Toxic components.	Lower cost. Improvement of recycling process.
	Nickel– Metal -Hydride (NiMH)	Mature technology. High mechanical resistance. High energy density. Long cycle life. Lower number of toxic components in comparison with Ni-Cd betteries.	Expensive technology	Lower cost. Improvement of recycling process.
Fuel Cells		Relatively high efficiency CHP systems (high temperature fuel cells)	Expensive technology. Difficult fuel production. Sensitive on sulphur compounds. Unoverload capacity.	Lower cost
Pumped hydro		High power density. High energy density. Mature technology.	Geographical limited. Expensive to site and build. Long construction time To use in huge aplications.	Turbine efficiency
Compressed Air (CAES)		High power density. High energy density. Mature technology.	Geographically limited. Expensive to site and build. Long construction time. To use in huge aplications. Requires fuel input.	Adiabatic capability (requires thermal storage)
Flywheels		High power density. Long cycle life. Very fast recharge.	Low energy density. Large standby losses.	Lower costs. Higher energy density.

Table 5 – Advantages and disadvantages of storage technologies

Each storage technology has advantages and disadvantages when considered for power system applications but battery and flywheel systems have the advantage of being modular and cost effective. The adoption of batteries (lead acid and lithium

ion basically) as the usual storage type is related to the mature manufacturing technology and relatively low cost of acquisition. Namely when compared with their actual close competitor, the fuel cells, difference which is stressed when operational (maintenance and substitution) costs are added.

However, the operation of batteries is still a complicated task. State of charge (SOC) and state of health (SOH) determination, actual chemical conditions **[50]** and operating temperature and finally the utilization conditions, are issues that have not yet been satisfactory solved. For example, to maintain power balance between stochastic sources and loads leads to high current charge/discharge variations in the batteries which contrasts with the manufacturers recommendations and will shorten their lifespan **[51]**.

The "on-line" management operation is also problematic because it involves dimensioning (usually oversizing) and control in order to avoid under/overcharge or excessive stress (deep charging/discharging) in the batteries. One possible solution is to hybridize storage, where the most common association are batteries with fuel cells – the former with good power density and good dynamics, the latter one with good energy density but slow dynamics **[52]**.

Nevertheless, V2G is a domain of adoption of batteries to operationalize electrical storage. Furthermore it is a solution that does not involve a large investment in storage by using existing (and underused) capacity of vehicles **[33]** what can also be used in non-vehicle based systems as the stationary home storage.

While batteries are the most used storage technology it must be stressed that they do not solve all the problems related with power systems. Other storage technologies are receiving attention for utility applications such as flywheels, advanced capacitors and superconducting energy storage systems (still in the prototype stage) **[5]**. In terms of power quality ultracapacitors are increasing its relevance, presenting lower energy density than batteries but possessing a higher power capacity. Recently, such capacitors have been explored for energy storage, since they are more efficient than batteries and offer higher lifetime in terms of charge-discharge cycles. However, they involve leakage (intrinsic and due to parasitic paths in the external circuitry), which precludes their use for long term energy storage **[53]**.

Fig. 21 presents a synopsis roadmap of the points focused on the present chapter.

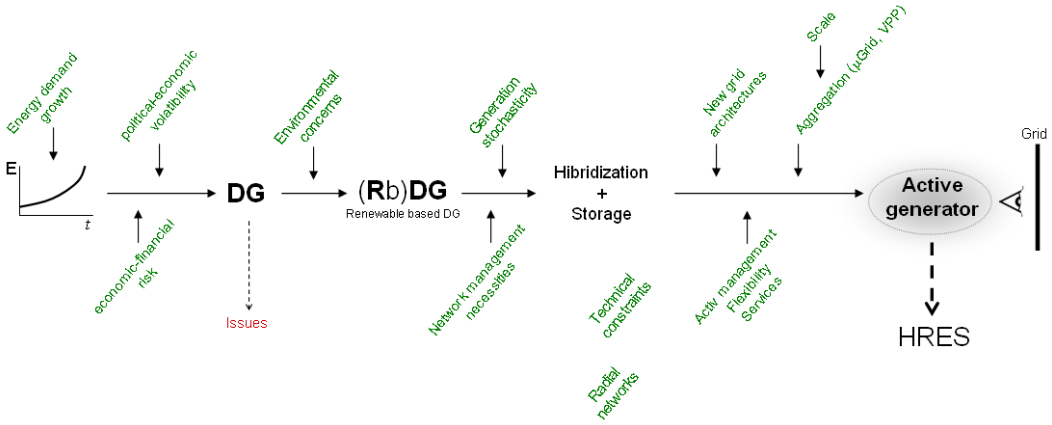

Fig. 21 – Synopsis of the key points outlined in Chapter I

3 - Objectives of the thesis

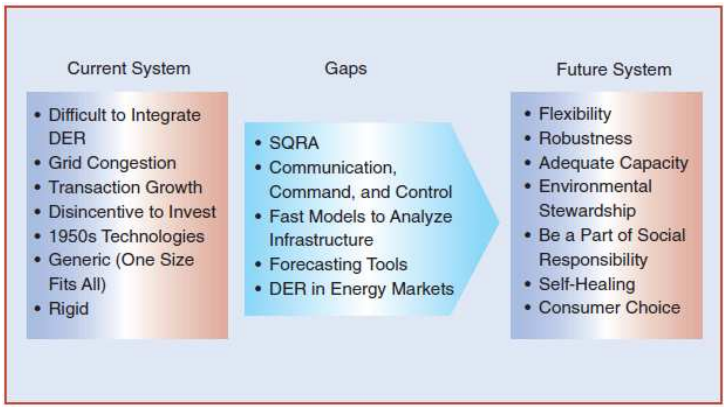

Fig. 22 – Current and future electric systems [49]

According with future electric systems (***Fig. 22***), the main objective of the thesis is to propose a small hybrid renewable energy based system architecture, with control and management methods, which respond to the issues and concerns of modern and future power systems turning it in an active and flexible electrical generator.

While the general approach is towards distributed generation, a perspective of application in very small systems is adopted. The underlying idea is similar to the strategy driving from V2G or CHP and is supported by the smart grid concept. That is, to take advantage of existing infrastructures and willingness receptivity from electricity

customers to implement small systems that statistically contribute to solve network and socio-political issues.

The dispersion of those infrastructures allows a statistical effect and the actual political support to the spread of internet provides the necessary ICT infrastructure. Aggregation modes have potential to solve scale related grid operators concerns and the separation of ownership and operation can solve the eventual lack of necessary operational knowledge.

Being a small system the economic performance is fundamental. Therefore the control of the operation of the renewable energy sources at their optimal (maximum) power output, managing the power balance by using (electrochemical) storage in the DC bus is fundamental. This will allow the system to maximize the investment return.

Another concurrent intermediary strategy is to manage the available energy such as to take advantage of variable market energy prices and/or providing services such as peak shaving, reserve response, etc. in order to attain a reward that overcomes the mere energy selling.

The global strategy is to turn stochastic energy sources into controlled deterministic power through the use of common and cheap storage and suitable control schemes. ***Fig. 23*** illustrates this underlying strategy. Power flows are controlled through power electronics and global management is performed by a microcontroller enabling not only a diversity of control and communication capabilities but also taking advantage of the software flexibility. The use of software makes possible to rapidly and effortless to change through diverse strategies thus making possible to adapt the generation system to dynamic conditions.

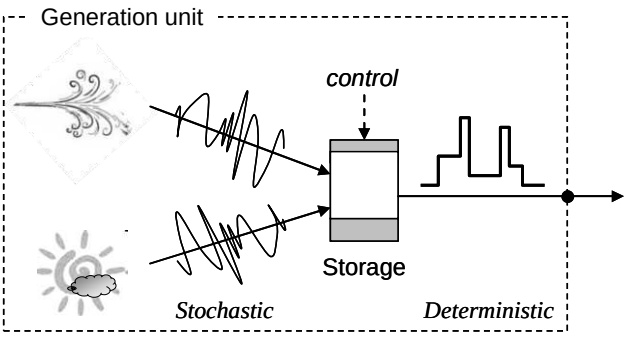

Fig. 23 – Generation unit (GU) global strategy

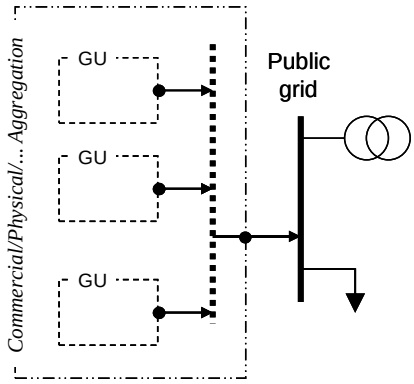

Fig. 24 – Small systems (GU) aggregation

4 - Contributions

The main scientific contributions of this thesis are the following ones:

- To approach and research the integration of different renewable energy sources into a unique electric generation system – an hybrid renewable energy system (HRES) – in order to improve this type of systems in terms of energy quality as well as its economic value;
- The proposition and validation of a power balancing strategy for a HRES in order to control the power injected by renewable based units in the grid while maximizing generated power through keeping running on MPPT algorithms for all the sources;
- The proposition of a better economic value for hybrid generation units through the attribution of control services to grid operators;
- The proposition of different energy management strategies with the definition of the operating modes for the controlled HRES in order to ensure energy and power availability;
- The design and experimental implementation of a HRES in order to demonstrate the validity of renewable sources hybridization and its controllability;

These contributions can be extended for different hybrid power systems, which embody renewable energy sources, and a medium-term energy storage system. Also to point out to advantages in monitoring, controlling and managing generation sites with

different renewable energy sources integrating, in the same space, energy storage capacity, either electrical or non-electrical, as a unique generation system.

5 - Thesis layout

The thesis is structured in 7 chapters.

Chapter I provide a multi-environment framework of the needs and requirements of active generation units in actual and future electric power systems. It establishes a clear approach for the development of the work to be carried out. Within this approach the main objectives and contributions to the field of hybrid renewable energy systems (HRES) are presented.

Chapter II reviews distributed generation architectures and grid interconnection issues in conjunction with modern grids structures that are arising. It concludes for the need for new approaches to renewable based generation systems, namely for controlled ones that suits well the requirements of functionalities for electrical grids.

Chapter III analyses and defines models for the different elements integrating the HRES and establishes a suitable computational simulation tool appropriate to work out the issues proposed for the thesis.

Chapter IV frames the domain of grid services, namely HRES availability and grid operation safety, establishing appropriate strategies for developing HRES.

Chapter V presents the design and implementation of an experimental platform suitable to validate the results carried out in the thesis. Relevant characteristics are discussed and tested in order to validate the platform itself and dynamic as well as management system features.

Chapter VI presents the application of control and management strategies to the experimental HRES in order to prove the main contributions established within this work.

Chap. VII draws the conclusions and suggests related future work.

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Chap. II - DG energy system architectures and grid interconnection

Distributed generation, decentralized and local control, self organization and autonomy are trends of today's electric power systems. While several benefits like addressing environmental concerns, energy independency and market participation in the distributed nature of electric generation are recognized, there are still pending issues and potential benefits in this form of electricity participation that must be solved and developed. Increase of highly reliable electricity demand (power quality interconnection) issues, new value-added services and effective integration in old and new network architectures are main examples.

The use of the “connect and forget” DG has been the strategy commonly used to a recent time but the increasing relative weight of this kind of generation in the network has began to pose several interconnection problems. Those problems, along with the actual operational effects on the grids, tend to divert the interest of the electric network operators in their use. This reluctance of grid operators toward DG penetration lies in the integration of such type of systems in networks not planned to support them as well as the financial impacts that they also imply. The trend must therefore be to view DG units as an integrated help to electric networks operation and not only as a generation source. Furthermore, from a user point of view the perspective of simply selling energy (or avoiding buying it) has proved to not being able to cover the investment made in DG, specially that based on renewable sources, taking in consideration the comparative energy prices of bulk generation. This means that from both perspectives DG is expensive and a source of problems.

The existence of incentives towards the reduction of the financial barriers to the spreading of DG has caused a rise in the renewable based units connected to the grid. The issues raised by the injection on the grid of stochastic power have grown in a direct proportion. The financial support to the DG as a passive generator is also not sufficient to ensure an effective and harmonious integration with the existent electrical infrastructures neither to reimburse the investment. Therefore the trend for a different type of reward, other then the mere price of energy, to promote the existence of adapted DG is necessary. This earning aims to reward not only the good DG grid behaviour but also the potential offer of services to the grid as a contributor for the improvement of the grid management.

The electric network must be seen as an actively manageable integrated unit (over-passing problems as saturation lines by re-routing power for example) view that is technically and economically advantageous and favours the integration of DG in deregulated electricity markets **[1]**. This view is supported by the difficulty (both in time duration and calculation capacity) of a system operator to schedule a large number of DG units while maintaining a high efficiency and guarantee of safety during failures. The trend to distributed nature, autonomy, coordination, cooperation and adaptability in view of efficient integration of all network components, calls for innovative control, architectures and communication capabilities, specifically in the case of DG.

Whereas the scale factor of large unit power plants allows a low cost for energy delivered, they concurrently have an intrinsic stiff behaviour that is expressed in the use of long term contracts. Inversely, DG has the potential to no longer be an isolated – in the sense that it must sense the network and take actions to adapt the best way to participate in a stable grid operation – but an integrated part of the electrical network. That is, with possibility of reporting its operational (power) and future (energy) conditions and being able to accept online requirements – operational coordination.

Fig. 1 depicts an historical overview of DG interconnection, presenting a typical architecture for power flow between renewable sources and grid as well as the evolution of the concept for renewable generators.

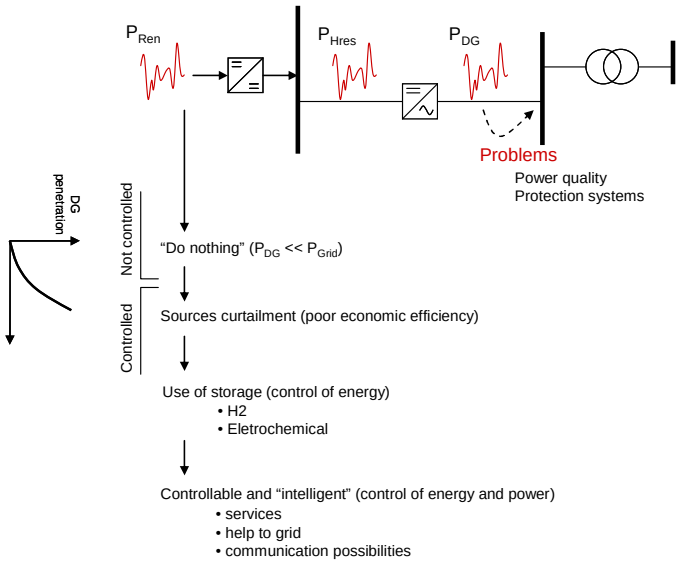

Fig. 1 - DG interconnection historical overview

1 - DG grid interconnection

Power systems impose a set of restrictions for the connection of DG to the electric network to prevent unexpected effects on their operation. The magnitudes of the issues that arise from DG interconnection to electric networks are primarily related with the penetration level of DG. A low penetration level is fairly innocuous, diluted by bulk generation capabilities and grid control schemes, but the spreading of such type of generation raises a large range of problems if the electric network does not evolve from passive to a more active role. Operational issues such as power quality, protection and reliability are among the first encountered, especially when DG becomes the major 'local' source of power. DG units tripping at abnormal conditions, grid connected fault detection, impact on network losses and islanding behaviour are other issues to be considered **[1]**,**[2]**.

Effects of the DG connection to electric networks are related to the following points **[1]**,**[3]**,**[4]**:

- Voltage control (regulation)
- Power quality
- Fault levels
- Protection schemes
- Power losses
- Network abnormal operation (islanding)

Therefore, taking in account the need of carbon alternatives to the power production as well as the environmental concerns, the present need for power generation based on renewable sources seems unavoidable. The valuation of the electrical networks concerns, which are based on past issues caused by these generation technologies connection to the grid, seems to favour the development of studies and new solutions for grid connection.

2 - DG systems architectures

DG was initially looked as a way to supply remote or isolated areas with a small amount of power and away from the more heavily loaded feeders. Their architecture was simple and they were connected in weak feeders without concerns about the quality of the energy they provided. In the past decades however they have evolved towards more complex architectures more adaptable to the issues they found.

DG architectures and topologies embrace a large variety of items, such as:

- nature of the power gathered (AC or DC)
- system elements (single or hybrid sources and/or storage)
- power levels (from few kW to hundreds of MW)
- points of connection (low and high voltage distribution grids or transmission grids)
- primary energy source technologies (internal combustion, wind, photovoltaic, hydrogen, etc.)
- operation modes (stand alone or grid connected)
- interfaces types (directly coupled and inverter coupled)

DG has begun with diesel generators in isolated sites and in weak grids but has had a big development with wind energy followed by photovoltaic technologies. In terms of energy sources the first wind based DG technology was non-hybrid and based on asynchronous generators later replaced by synchronous generators. Initially with fixed operation speed and pitch control directly connected to the grid – which transfers the variability of the stochastic nature of the source to the electrical network – they evolved to variable speed with the support of power electronics and the development of sophisticated control algorithms **[5**].

The next evolutionary step consisted in the use of power electronics and then in the integration of control strategies. This further allowed the control of active and reactive power and consequently the control of frequency and voltage that is the control of power quality. They face the stochastic nature of the wind contrarily to the deterministic nature of diesel based generators which led to several issues such as load following, disconnection after faults, turbulent power profiles (quality problems) and voltage regulation **[6**].

These problems, mainly related to the interconnection to the public grids, were diluted as long as their power weight was small when compared to the public grid power. The architectures used in such type of DG were based on AC control but the development of power electronics led the architectures to the generalized back-to-back topology (AC/DC/AC) as shown in *Fig. 2* **[5**],**[7**],**[8**].

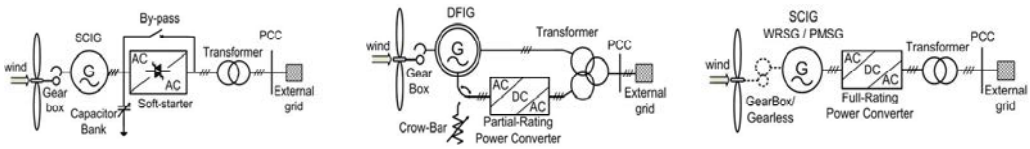

Fig. 2 - Single source wind architectures for grid connection

The same configurations are applicable to non-wind based generation such as diesel or, in a more generalized way, internal combustion engines and microturbines. The formerly combination of diesel with wind generation **[9**] allowed to bypass the stochastic behaviour of the last through the use of diesel fuel. The key strategy was nevertheless to complement diesel generation in view to reduce fuel consumption.

Photovoltaic based DG is actually one of the highest growing technologies. Its advantage lies in the insurance of everyday sun existence, even with variations due essentially to clouds, but with a distribution that does not match the load **[10**]. Similarly to wind based DG, initial PV generation (and later fuel cell and batteries based systems) was also non-hybrid and with the growing power also faced the same problems than wind as, for instance, the power variation caused by cloud transients **[11**]. The main difference to wind is the DC nature of the generated power which implied different topologies.

The architecture differences here are related to the modules association of PV panels – initially centralized in a DC-AC converter, latter decoupled by strings each one with its DC-AC converter and lately with a DC-AC converter by panel – see *Fig. 3* **[7**],**[12**]. The objectives of the different architectures were to make more flexible the connection and not to be dependent on a central point of control.

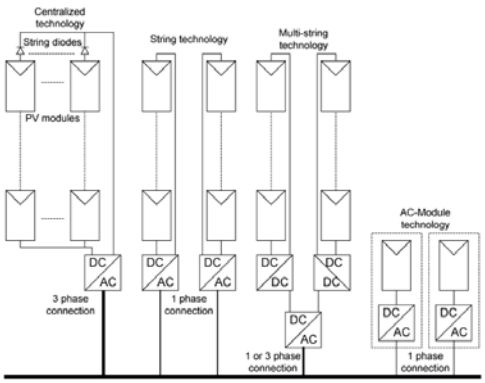

Fig. 3 - Single source PV architectures for grid connection [12]

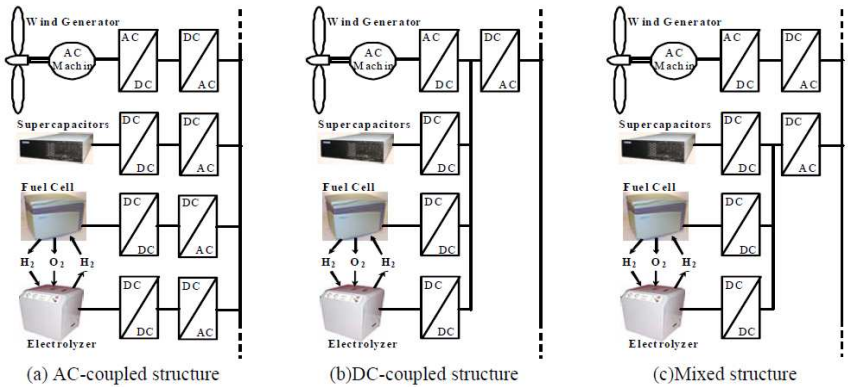

Fig. 4 – Coupling structures [13]

2.1 - Hybrid DG

The use of a single type of renewable source results in an over-sizing of the DG power sources what implies a high investment. Due to the growing power contribution of renewable based generation, DG tends to hybridize source architectures. The objective is to mitigate the "weakness" of one stochastic source by another stochastic source or by a deterministic one obtaining a combined efficiency higher than that of a single source type. The most common combination is the wind-PV but other associations are also used as wind-diesel, wind-storage, PV-diesel, Fuel cell (FC)-diesel, etc.

The integration of different elements characteristics can be done based on AC, DC or mixed coupling **[14]**,**[15]** as depicted in *Fig. 5*. DC coupling is, in general, simpler and DC/DC converters are easier and cheaper than DC/AC. By far the most used configuration has a DC intermediary bus followed by a stand alone or grid connected AC bus. There are nevertheless some cases where the architecture is only DC **[16]** or only AC **[17]**,**[18]** but they are a minority when the system is involved with energy sources/storage hybridization. The connection between the two buses is done with an inverter which deals also with grid issues such as reactive power and power quality. A review of the literature (**[30]**-**[57]**) shows that the DC bus voltage is generally either maintained by direct connection to batteries, by cascading control loops (first loop to control power and secondary loop to control output voltage) or by the grid connected inverter.

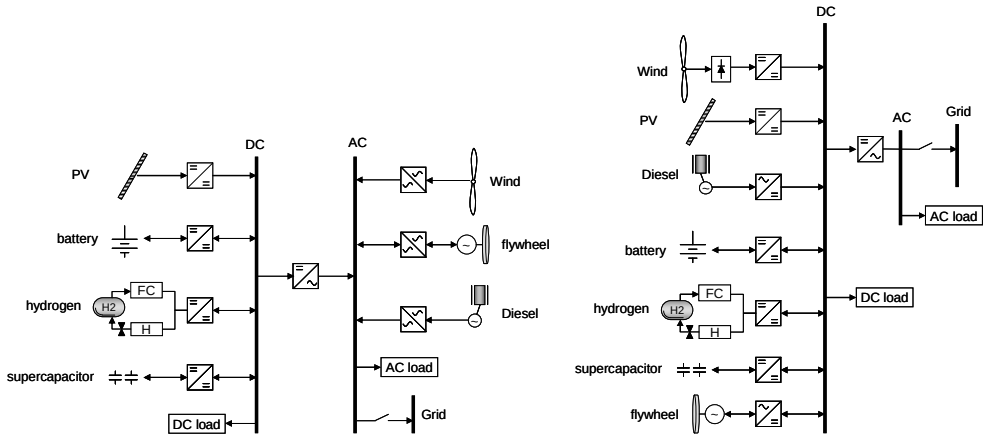

Fig. 5 – Hybrid system elements interconnection

DC bus voltage level is a key point in the DG systems. A high voltage level favours the simplicity of connection of the DC bus to the inverter but is an obstacle in the case of use of small power generation sources. The use of transformers either of high frequency (before the inverter) or low frequency (after the inverter) allows at matching voltage levels and avoids the solution of paralleling large sources paralleling or the use of a DC-DC converter, besides the isolation it can provide.

2.2 - Energy storage

Along with the growth of DG power the rise of the market perspective in the energy business lead DG systems to embody the capability of storage. Storage not only circumvents connection issues (supplying reactive power and voltage, frequency control and other valences) **[19]** but also introduces an additional freedom degree in the system control. As such DG is able to displace energy from one time period to another **[20]** as suggested in ***Fig. 6***. The first case refers to short-term and the second to long-term storage. While initially storage was used mainly to control stochastic renewable power (curtailment), the potential management flexibility allows energy to be traded when it is more demanded or when it is more profitable. This flexibility embraces the dependence on the renewable sources variability therefore taking advantage of actual or potential spot prices variation **[20]**,**[21]**. Additionally it allows not only to provide gathered renewable energy when needed or wanted but also to get energy from the grid when there is excess in it and to participate actively in islanding situations **[22]**.

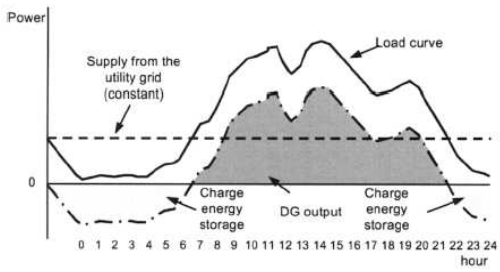

Fig. 6 – Supply-demand control [23]

2.2.1 - Storage technologies

There are several technologies available for storage from large to small capacities and with very different capabilities (Chap.I, 2.2). A summary listing of the existing technologies is presented:

- Hydro
- Thermal
- Compressed air
- Flow batteries
- Hydrogen
- Electrochemical
- Flywheel
- Superconducting magnetic
- Capacitors

The analysis of the comparative merits of each technology can be grouped by **[24]**:

- Capacity
- Power capability
- Depth of discharge
- Discharge time
- Efficiency
- Durability
- Autonomy
- Costs
- Adaptability
- Self discharge
- Mass and volume density

- Reliability
- Monitoring and control requirements

2.2.2 - Batteries

By far the most used storage technology in small applications is the electrochemical one (mostly batteries).

This technology further divides itself in several types that are listed below:

- Lead Acid Battery (Pb)
- Sodium-Sulfur battery (NaS)
- Vanadium Redox Battery (VRB)
- Zinc Bromine Battery (ZnBr)
- Nickel Cadmium (NiCd) Battery
- Nickel Metal Hydride (NiMh) Battery
- Lithium Ion (Li-ion) Battery

The most used one has been the Lead-acid due to its maturity, simplicity of utilization and relatively low cost due to scale economy of their spread use. They nevertheless suffer, in certain circumstances, from a lack of energy capacity and/or a lack of power density.

Moreover they have a complex behaviour related with complex chemical reactions and temperature that affects namely the estimation of their state of charge **[25]**. Because SOC only can be misleading the concept of State of Health (SOH) is a valuable indicator of how much energy a battery can effectively supply. This is fundamental for predictable systems, as the controllable generators with renewable sources are intended to be, since they rely on the capacity of energy stored to complement the variability of their sources **[26]**. The estimation of the SOC is mainly done by one of the following forms:

- Density measurement
- Voltage measurement
- Charge counting

Li-ion batteries have had a large growth lately as they are able to circumvent some of the deficiencies of the Pb technology namely lifetime and efficiency (see ***Table 1***) but still suffers from a high comparative cost. Their energy and power density are also higher than Pb batteries. Conversely they have intrinsic potential for explosion and are less tolerant to voltage deviations.

Storage Type	Power	Duration of Discharge	Efficiency (%)	Lifetime	Total Capital Cost (USD/kW)
Li Ion	5 MW	15 min to several hrs	90 (DC)	15 years	4000-5000
Lead Acid	3-20 MW	10 sec to several hrs	75-80 (DC) 70-75 (AC)	4- 8 years	1740-2580

Table 1 - Characteristics comparison of Li-ion and Pb batteries [27]

Hidrogen storage (fuel cells) can be a good complement to the batteries with their higher density of energy. Unlike batteries fuel cells does not need to be charged for the consumed energy since the fuel is continuously supplied. But they suffer from low efficiency (50-60%) when compared with batteries (70-90%) **[28]** and are more expensive. Nevertheless as long as small scale is concerned it is an effective alternative to be considered.

2.3 - DC bus based architectures

As referred in **[29]**, the use of architectures based in a common DC bus allows for simpler and cheaper system components and easier control. This is a main advantage for small systems where the production cost of energy is higher, as it does not have the leverage of economy of scale (neither in cost equipments nor in energy production). Moreover the simplicity of the DC bus based architectures supports modularity therefore turning it in a more widely acceptable system and avoiding system specificity costs as replacement parts and expertise from maintenance personnel. Modularity also potentially allows a more widely manufacturing volume production of related system elements with the corresponding reduction of components cost **[15]**.

As long as the relative strength of DG delivered power compared with the power necessary for the loads is small and therefore not causing any significant problems to the grid, the main objective is to deliver as much as possible in

order to maximize the profits of the investment made on the renewable based system. This strategy leaded to simpler control perspectives that mainly sought to dump the maximum possible energy and use the grid as a back-up to balance local loads when there are not enough renewable generation **[30]**.

The spread of DG, and the corresponding issues that it causes in the grid, calls for more elaborated control and management that encompasses dynamic control, power dispatching, efficiency of storage and fuel based elements, management set-points definition, sources power control and delivered power quality. From another point of view the management of the system energy has to deal not only with purely technical issues but also with economic analysis such as sizing and market related relations with time and prices.

Literature on the subject is mainly focused in control **[31]-[57]**, sizing/economical analysis **[58]-[59]** and energy management strategies **[60]-[64]**. Key points are stability, grid issues interconnection concerns (voltage and frequency control). More particularly, the research on DG hybrid focus at the:

- compensation of elements with slow dynamics
  [31],[37],[38],[40],[55],[63]
- DC bus power management
  [14],[31],[32],[34],[42],[54]
- DC bus voltage control
  [14],[31],[60]
- efficiency of hydrogen related units
  [32],[37],[41],[47],[61],[62],[64]
- efficiency of charge/discharge of batteries
  [30],[32],[34],[45],[52],[57],[62],[63]
- definition of operation set-points
  [44],[59]
- sources power control
  [14],[30],[39],[45],[49],[50],[51],[53],[55],[56],[60],[63]
- grid interconnection issues
  [14],[30],[35],[36],[39],[41],[48],[54],[55]

The integration of renewable based DG from a perspective of energy markets (namely short term markets – day ahead and intraday market) that

means a combined analysis of control and management seems to have not received in the investigation of DG systems as much attention as it deserved.

With the spreading of DG, which means that in certain places the main power generation tends to come from DG, issues arising from the interconnection with utility grids imply a change in the strategy of operation of renewable based DG. That change would be appreciated either from the perspective of the grid as having less delivered power fluctuation (and, if possible, with time control over the power) and from the perspective of the DG owner as having larger flexibility of operation options (that could adapt production to a better economical exploitation).

Therefore future DG systems must be controllable in a dynamical operation as well as in interdependency with grid operators. As electricity is a form of energy which is difficult to store in large quantities small systems using small affordable storage capacities (batteries, hydrogen, capacitors, CHP), if sufficiently disseminated, can work as a large storage capacity and, with suitable control schemes, to be controllable.

A generic DC bus based generation system is presented in *Fig. 7*. In this architecture the most used renewable sources are wind and sun along with batteries for storage and an inverter to interconnection to the grid. The loading is mostly composed by AC loads either in the public grid or in a private grid (mostly stand-alone), but also by DC loads.

There are also cases where generation source is fossil based, mostly based on diesel generators but also natural gas **[14]**,**[44]**,**[51]**,**[55]**,**[59]**. The use of diesel based generation is nowadays only relevant in particular cases where an absolute availability of power is mandatory. The most used storage technologies are batteries – mostly lead acid because of cost, but lately with predominance for Li-Ion – followed by hydrogen. Storage is either directly connected to the DC bus or connected through DC-DC converters. Hydrogen has the advantage over batteries that it can be used to completion and does not need recharging strategies to enlarge life cycle **[58]**,**[61]** but suffers from slow dynamics that must be complemented with batteries or ultra-capacitors therefore adding complexity and cost to the system.

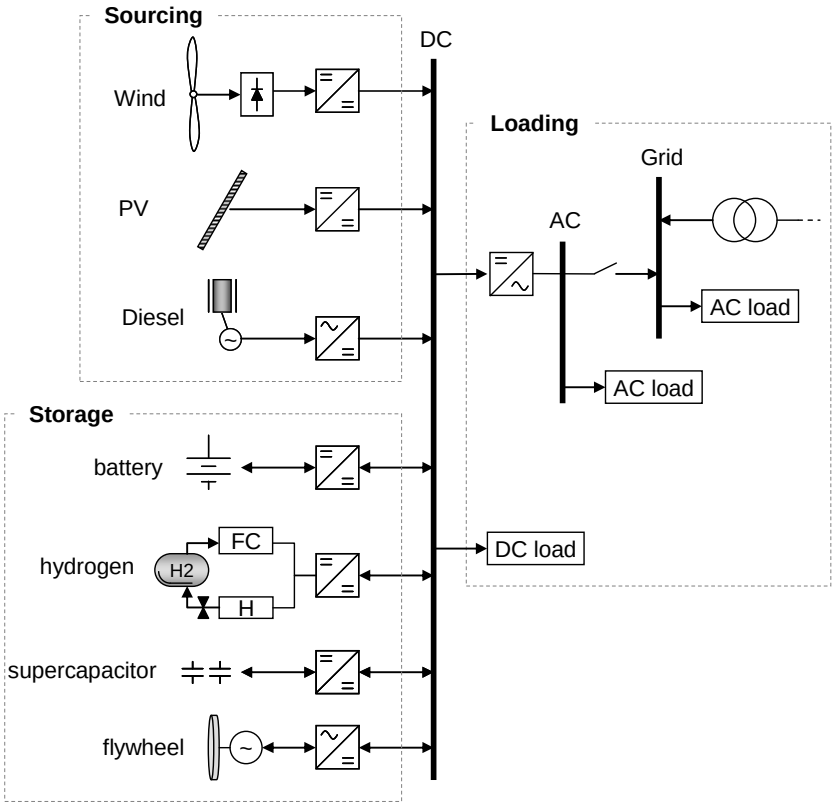

Fig. 7 - DG generic hybrid main subsystems

2.4 - New grid architectures

The insertion in the grid of a multitude of individual DG units can cause as many problems as it may solve **[65]**. As the number of DG increases Distribution Systems Operators (DSO) face serious difficulties in controlling and managing this large number of elements along with the increasing complexity of the grid protection functions **[66]**. The resultant complexity can be solved by some form of aggregation and consequent autonomous control and management that allows at presenting to the utility grid operator a single entity. From the point of view of the grid operator something that is therefore more manageable. There is an aggregation concept presently that is relevant to the controllable DG's: the microgrid. Due to the relevance of the approach of microgrids in recent developments in the domain, an explanation of them is done.

2.4.1 - Microgrid

The microgrid concept allows at alleviating the high number of DG by physically aggregate physical components – generators and loads – and

treating them as a single and manageable entity with a single point of connection to the utility grid. As such, this arrangement masks to the grid operators a certain number of technical items that are managed and controlled internally.

Microgrids are clusters of loads and generators grouped in physical small grids where DG and loads are controlled in an integrated fashion with the possibility of working connected to grid or in an islanded way. They therefore enhance reliability of loads supply and are especially useful in areas where the grid is weak. *Fig. 8* presents an example of a microgrid.

In grid connected mode the power delivered is constant and in islanded mode – typically during abnormal conditions of operation – DG are controlled in such a way that maintains suitable active and reactive power, voltage and frequency levels for the internal loads **[66]**.

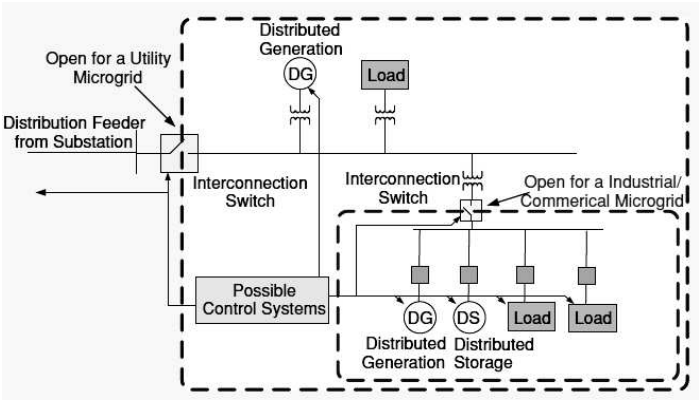

Fig. 8 – Microgrid example

In order to be capable of satisfying the mentioned requirements and in the assumption of a high weight of renewable generation in the DG part, storage capacity **[67]** is mandatory since the time response capabilities of certain generators or the stochastic characteristics of others do not ensure a proper energy balance **[65]**. The use of inverters to connect DG to the microgrid implies a low inertia turning microgrids sensitive to disturbances but they also allow a flexible operation of the sources **[68]**.

There are presently two concepts for microgrids architectures: the European MicroGrid and the American CERTS (*Fig. 9*, *Fig. 10*).

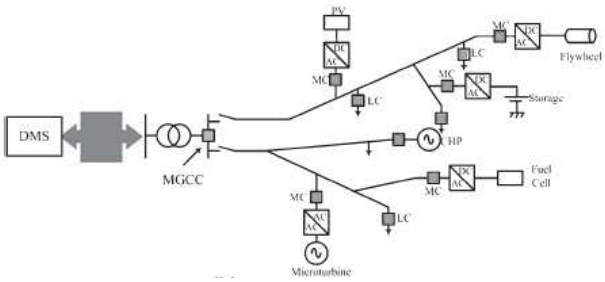

Fig. 9 – Microgrid EU concept

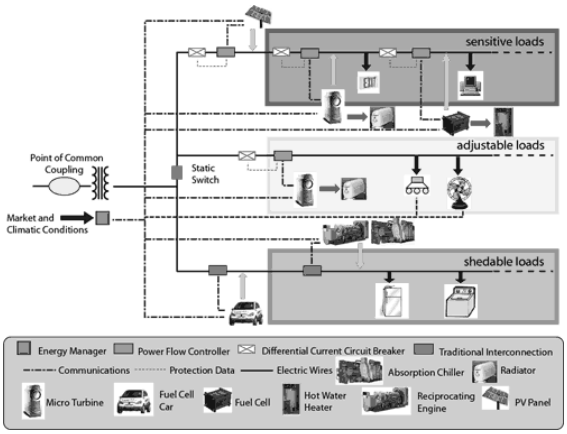

Fig. 10 – CERTS microgrid concept

The EU MicroGrid optimizes generation and schedule loads based on forecast and energy prices, ensures satisfaction of the regulations of the distribution system operator (DSO), coordinates the different actors inside the microgrid and supervises islanded operation, load shedding and reconnection issues as black start and resynchronisation **[69]**. In the MicroGrid concept storage is implemented in a central unit whereas in the CERTS concept each generator possesses its own storage unit **[69]**.

The basic operation of the CERTS MicroGrid depends on the Microsource Controller to regulate power flow, voltage at each microsource interface and insure that each microsource rapidly picks up its share of the load when the system islands. In addition the ability of the system to island smoothly and to automatically reconnect to the bulk power system is another important operational function. The Energy Manager provides for system operation of the MicroGrid through dispatch of power and voltage set points to each Microsource Controller. The protection coordinator must respond to both system and MicroGrid faults **[70]**.

2.4.2 - Technical challenges

The control of a microgrid must ensure a plug and play capability, fast grid connection and disconnection, active and reactive power independent control and dynamic capacity to serve the loads **[71]**.

Microgrids in islanded mode must ensure control of voltage and frequency of several internal generators, switching capabilities including black-start and protection of loads, lines and generators **[66]**.

3 - Conclusions

The spread of DG generation especially with stochastic renewable sources raises a series of issues when interconnected to the grids. These issues calls for new approaches to renewable generation based systems. Namely microgrid architectures that have been developed, that demands for controlled renewable generation units. These ones suits well the requirements of new functionalities for grids with a high level of renewable power.

Architectures along with the hybridization of the renewable generation sources overcome some issues, namely the reduction of the stochastic nature of the power injected at the interconnection to the grid.

If the increase of renewable power is to be performed, the use of storage is mandatory to face their stochastic nature and to be able to add value to the energy either in tariff earnings either in services offered. The adoption of lead acid technology while not being the best technical solution allows to implement the storage with a lower initial investment cost.

These conclusions are the support to the work developed in the next chapter where the dynamic behaviour analysis of a hybrid renewable generation system (HRES) is performed. Its sources are wind and photovoltaic integrated into the same power system which includes a storage capacity. The system to be analysed will allow at concluding on the behaviour of the HRES not only in technical issues but also in economic ones, the both present in the microgrid approach.

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Chap. III – Renewable sources integration

The proposed hybrid renewable sources based system is composed by two renewable generation sources – wind generator and photovoltaic panels – a storage system – batteries – and loading through a grid connection (***Fig.1***). The integration of the various modules is made through a DC bus.

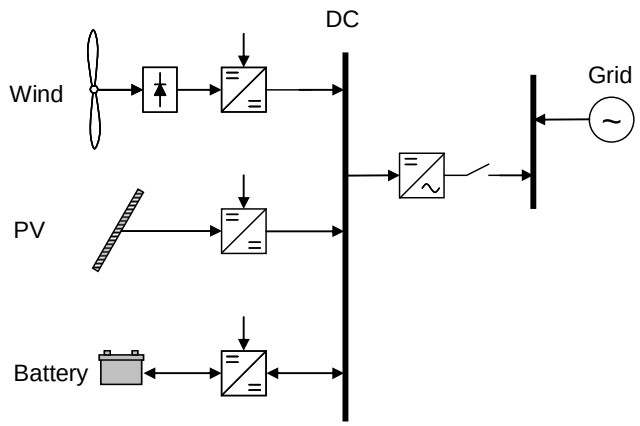

Fig.1 - Hybrid system architecture

The objective is to attain a controllable and deterministic power delivery in view of overcoming the variability of the renewable sources. ***Fig. 2*** depicts the profile of the sum of the power of the two renewable energy sources, wind and sun. If these sources are directly connected to a load (grid) the power injected at the common connection point would consist in power spikes, due to the wind, in the top of a bell shaped power, due to the sun. The sudden power changes of the spikes interfere with power regulation and the power distribution density of the sun does not coincide with the general load profile of a grid. It is supposed that the injected power value is relatively high in relation with the power at the point of connection such as it can cause interference. ***Fig. 3*** shows the power delivered to the load (grid) after being processed by the HRES. In the case it presents to the point of connection not only constant power for a well-defined time periods but also a known and pre-determined power profile.

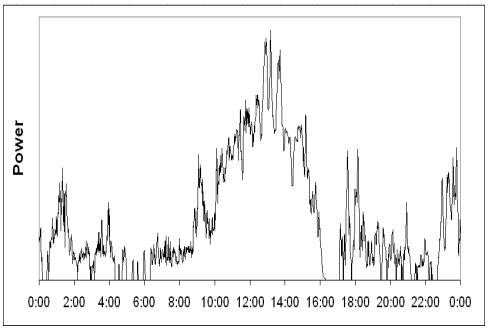

Fig. 2 – Uncontrolled wind and sun power injection

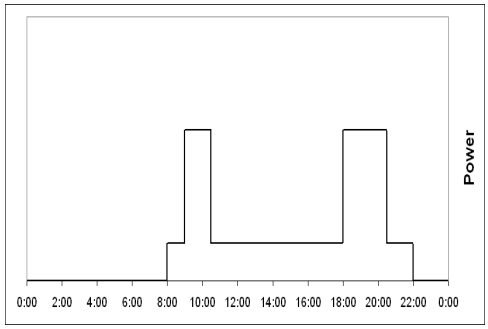

Fig. 3 – HRES controlled wind and sun power injection

The remainder of the chapter deals with the definition of the hybrid system simulation model that allows assessing the validity of the HRES objectives. The system is separated in relevant units and adequate models to assess its behaviour are built. Control and operation strategies for the system as a whole are defined and tested and conclusions are taken. The simulations are based on real wind and sun radiation input values. The development of such a system will bring an added economic value to the generated power which is also analysed.

1. Hybrid system elements modeling

1.1. Wind source

The wind generator subsystem is composed of a turbine, a permanent magnet synchronous generator (PMSG), a rectifier and a DC-DC converter (***Fig. 4***). It should be noticed that usually small wind generators have the rectifier in the nacelle in order to save wire (three wires in three phases AC to two in DC) and reduce the number of slip-rings (three to two).

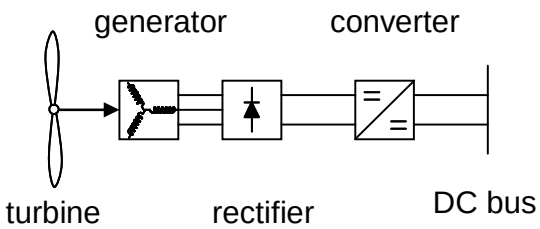

Fig. 4 - Wind generator components

1.1.1. Wind turbine

The power captured from the wind by the turbine is a mechanical power represented by:

$$P_m = \frac{1}{2}\rho A v_w^3 C_p(\lambda, \theta) \quad \textbf{(1)}$$

where ρ [kg/m^3] is the air density, A [m^2] is the blades surface, v_w [m/s] is the wind speed and C_p is the turbine power coefficient that is related with the fraction of wind power that is possible to capture by the particular mechanical configuration of the wind turbine. The specific mechanical characteristics are represented by the blade pitch angle θ and the tip speed ratio λ, defined as:

$$\lambda = \frac{\omega R}{v_w} \quad \textbf{(2)}$$

where ω [rad/s] is the mechanical angular speed and R [m] is the length of the blades. The control of a wind turbine is usually accomplished through the control of the tip speed ratio what implies the control of the rotational speed according to the linear velocity of the wind. The rotational speed is in turn a function of the equilibrium between the "motor" torque (turbine) and the "load" torque (electrical generator). The power coefficient of a turbine is a parameter that is difficult to get and is usually obtained by tabular methods (that supposes knowledge of all mechanical characteristics parameters) or by polynomials (obtained through non-linear interpolation methods). Typical curves that express the relation between output power and rotational speed for different linear wind speeds is shown in ***Fig. 5***.

The relation between torque and angular speed is obtained through the known relation:

$$P_m = T_m \omega \quad \textbf{(3)}$$

with P [W] the power and T [Nm] the torque.

The torque in conjunction with the masses of the turbine and generator results in an angular speed given in a simplified form by:

$$\omega = \int \frac{1}{J}\left(T_m - T_e - F\omega_m\right)\cdot dt \qquad \textbf{(4)}$$

where J [kg/m^2] is the moment of inertia[1] of the rotational parts, T_m [Nm] is the turbine torque, T_e [Nm] is a resistant torque and F the friction associated to rotating components. In the studied case the electromagnetic torque (T_e) is easily established as a function of the current that results from the application of the output voltage to a load.

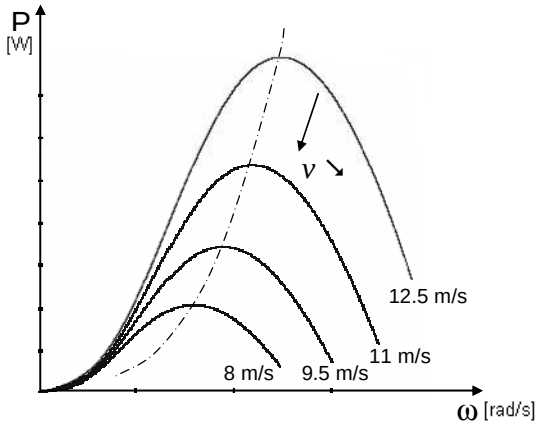

Fig. 5 - Turbine power variation with wind speed (dash-point line is the locus of maximum power for various wind speeds)

1.1.2. Electrical generator

The resulting torque is applied to the axle of an generator that produces an electrical output which, in the case of a permanent magnet synchronous generator, is characterized by output voltage and frequency variable with the wind speed. Modelling of the PMSG can be done by the d-q theory **[1]**:

$$-v_s = i_s R_s + \frac{d\Psi_s}{dt} + j\omega_e \Psi_s \qquad \textbf{(5)}$$

$$T_e = 1.5p\left(\Phi_{PM} i_q + \left(L_d - L_q\right)\cdot i_q i_d\right) \qquad \textbf{(6)}$$

[1] The used value of moment of inertia was obtained through local experimentation of a Bergey XL.1 wind generator

with,

$$\frac{d\omega_m}{dt} = \frac{1}{J}\left(T_e - T_m - F\omega_m\right) \quad \textbf{(7)}$$

relating the angular speed with the system masses, the angular forces and the friction,

$$\frac{d\theta_m}{dt} = \omega_m \quad \textbf{(8)}$$

relating the angular position and the angular speed,

$$\omega_e = p\omega_m \quad \textbf{(9)}$$

relating the electrical and mechanical angular speed through the number of poles

Using space vector variables, equation 5 becomes:

$$v_s = v_d + jv_q \quad \textbf{(10)}$$

$$\Psi_s = \Psi_d + j\Psi_q \quad \textbf{(11)}$$

$$\Psi_d = \Phi_{PM} + L_d i_d \quad \textbf{(12)}$$

$$\Psi_q = L_q i_q \quad \textbf{(13)}$$

$$i_s = i_d + ji_q \quad \textbf{(14)}$$

the PMSG dynamic equations are given by:

$$\frac{di_d}{dt} = \frac{1}{L_d}\left(V_d - R_s i_d + L_q \omega_e i_q\right) \quad \textbf{(15)}$$

$$\frac{di_q}{dt} = \frac{1}{L_q}\left(V_q - R_s i_q - L_d \omega_e i_d - \Phi_{PM}\omega_e\right) \quad \textbf{(16)}$$

where v_s [V], i_s [A] and Ψ_s [Wb] are the phase voltage, current and flux linkage respectively, ω_m and ω_e [rad/s] are the mechanical and electrical angular speeds, T_m and T_e [Nm] are the mechanical and electrical torques, θ_m [rad] is the

mechanical position angle, i_d [A], v_d [V], Ψ_d [Wb] and L_d [H] are the d-axis current, voltage, flux linkage and inductance and i_q [A], v_q [V], Ψ_q [Wb] and L_q [H] are the q-axis current, voltage flux linkage and inductance, Φ_{PM} [Wb] is the permanent magnet flux linkage, R_s [Ω] is the phase resistance, J [kg.m^2] is the moment of inertia, F [Nm/rad.s] the viscosity friction and p is the number of pairs of poles.

1.1.3. Rectifier

Wind turbines with synchronous generators have their three phase voltage and frequency dependant on the wind speed. Such small wind turbines usually have their generator output applied to an uncontrolled rectifier in order to reduce the number of mechanical switches and connection cables. In a generated power perspective the difference is not a major concern as the diode losses are minor than semiconductors losses in controlled rectifiers.

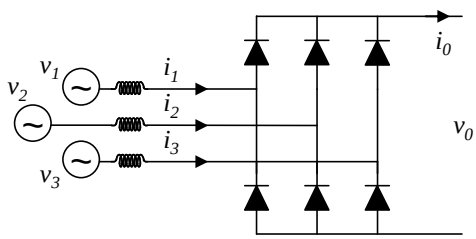

Fig. 6 - Three-phase uncontrolled rectifier

In this case, resulting output voltage can be represented by a DC and ripple components **[2]**:

$$V_0 = \frac{3\sqrt{3}}{\pi} V_m \tag{17}$$

$$\tilde{v}_0 = -\frac{3\sqrt{3}}{\pi} V_m \sum_{k=1}^{\infty} \frac{2}{36k^2 - 1} \cos(6k\omega t) \tag{18}$$

where V_m is the amplitude of v_i:

$$v_1 = V_m \cos(\omega t),\ v_2 = V_m \cos\left(\omega t - \frac{2\pi}{3}\right),\ v_3 = V_m \cos\left(\omega t - \frac{4\pi}{3}\right) \tag{19}$$

1.1.4. DC-DC converter

In order to control the operating electrical characteristics of the wind generator to achieve power control, namely maximum power extraction, a DC-DC converter is used. The DC-DC converter allows at presenting to the wind generator a controlled equivalent resistance. As the resistance seen by the generator influences electrical output power, and in consequence turbine rotational speed, it is therefore able to change its operating point thus allowing at optimizing turbine power coefficient by choosing optimal operational tip ratio and therefore to extract the maximum available wind power.

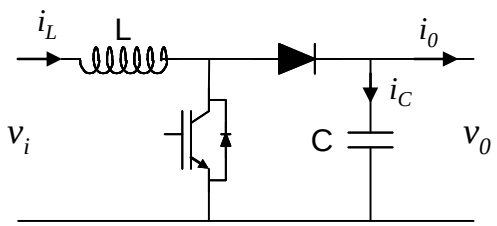

Fig. 7 - booster DC-DC converter

In the case of a booster converter,

$$V_0 = \frac{1}{1-D} V_i \qquad \textbf{(20)}$$

where V_i *[V]* and V_0 *[V]* are the average voltages of input and output respectively and D is the duty factor of the PWM wave applied to the converter semiconductor switch.

Supposing a constant output load (R_o) the DC-DC converter is able to present to the wind generator output an equivalent resistance (R_i):

$$R_i = \frac{V_i}{I_i} = \frac{(1-D)V_o}{\frac{I_o}{(1-D)}} = \frac{(1-D)^2 V_o}{I_o} = (1-D)^2 R_o \qquad \textbf{(21)}$$

1.2. Photovoltaic source

1.2.1. Photovoltaic generator

The sun subsystem is composed of a photovoltaic panel connected to a DC bus trough a DC-DC booster converter. As in the wind generator the role of the converter is to dynamically change the operating point of the photovoltaic panel in order to extract the maximum available power from the sun and injecting it into a regulated voltage DC bus.

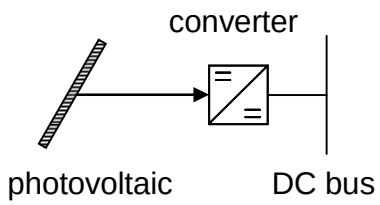

Fig. 8 - Photovoltaic generator subsystem components

There are several models to represent photovoltaic panels, being the most usual the one based on either single or double diode **[3]**.

For the scope of this thesis a single diode model (***Fig. 9***) is adopted which characteristics model the panel behaviour as an individual power source. The relation between current and voltage is **[4]**:

$$I_0 = I_{ph} - I_{rs}\left[e^{\frac{e(V_0+R_S I_0)}{AKT}} - 1\right] - \frac{V_0 + R_S I_0}{R_{SH}} \qquad \textbf{(22)}$$

where I_0 [A] is the output (load) current, I_{ph} [A] is the photovoltaic generated current, I_{rs} [A] is the diode reverse saturation current, V_0 [V] is the panel terminal voltage, R_S [Ω] is the series resistance, R_{SH} [Ω] is the shunt resistance, e [C] is the electron charge (1.6×10^{-19}), T [K] is the cell temperature, K [J/K] the Boltzmann constant (1.38×10^{-23}) and A is a factor representing the diode quality (1-2).

As the shunt resistance is much higher than the series resistance the second term of the equation can be eliminated.

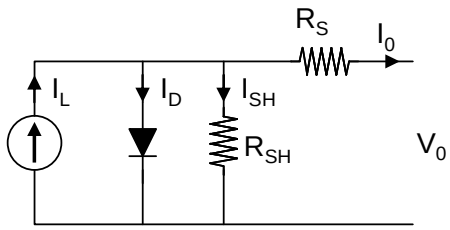

Fig. 9 - Photovoltaic model

The typical characteristic current and power versus voltage are depicted in ***Fig. 10***. Their variation with temperature and radiation variation is displayed in ***Fig. 11***.

The figures show the existence of an operating point where the power is maximized (P_{MPP}) corresponding to a determined operating voltage which depends on the load resistance (V/I) but also on the dynamic characteristic of that point as function of the environmental changes (temperature and radiation). This means that to maintain the photovoltaic panel dynamically in his maximum power the load resistance must also dynamically change, which is accomplished through a DC-DC booster converter that presents to the panel an equivalent resistance optimizing the power flow.

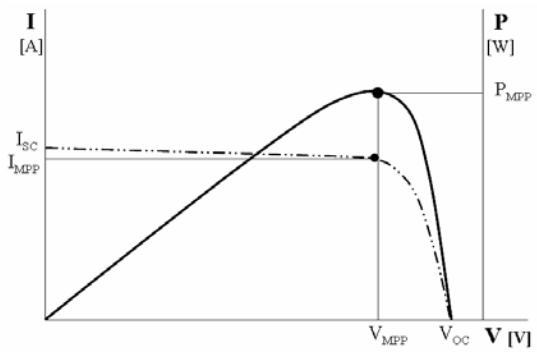

Fig. 10 - P/V and I/V photovoltaic characteristic curves

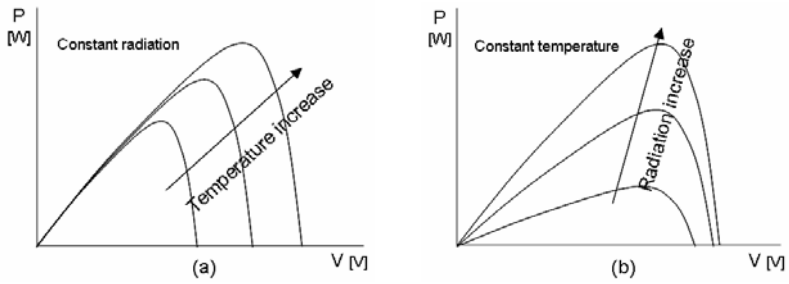

Fig. 11 - P/V curves in function of temperature and radiation variations

Equation 21 can also be presented as **[5]**:

$$I = I_{sc}\left(1 - K_1 e^{K_2 V^m - 1}\right) \quad \textbf{(23)}$$

with:

$$K_1 = 0.01175 \quad \textbf{(24)}$$

$$K_2 = \frac{K_4}{V_{oc}^m} \quad \textbf{(25)}$$

$$K_3 = \ln\left(\frac{I_{sc}\left(1 + K_1\right) - I_{mpp}}{K_1 I_{sc}}\right) \quad \textbf{(26)}$$

$$K_4 = \ln\left(\frac{1 + K_1}{K_1}\right) \quad \textbf{(27)}$$

$$m = \frac{\ln \frac{K_3}{K_4}}{\ln \frac{V_{mpp}}{V_{oc}}} \quad \textbf{(28)}$$

Where I_{mpp} [A] and V_{mpp} [V] are the current and voltage at the maximum power, I_{sc} [A] is the short circuit current and V_{oc} [V] is the open-circuit voltage.

Manufacturers provide characteristic parameters under standard test conditions (STC) with a radiation of 1000 W/m^2, temperature of 25ºC and an air mass[2] of 1.5. Therefore adaptation of the Equation 22 must be made to adapt photovoltaic panels to changing radiation and temperature which is made through

[2] Angle the sun makes with the perpendicular to the earth surface (AM = 1.5 corresponds to an angle of 48.2º)

short-circuit current temperature coefficient (α [A/ºC]) and open-circuit voltage temperature coefficient (β [V/ºC]).

$$\Delta I = \alpha\left(\frac{X}{X_{ref}}\right)\Delta T + \left(\frac{X}{X_{ref}} - 1\right)I_{cc} \quad \textbf{(29)}$$

$$\Delta V = -\beta\Delta T - R_S\Delta I \quad \textbf{(30)}$$

Cell operating temperature (T_C) [ºC] can be extracted from actual ambient temperature (T_a) [ºC] and from values of normal operating cell temperature (NOCT) provided by the manufacturer:

$$T_C = T_a + \frac{G}{800}\left(T_{NOCT} - T_{a,\mathrm{Ref}}\right) \quad \textbf{(31)}$$

where $T_{a,Ref}$ [ºC] is the temperature used to specify NOCT and G [W/m^2] is the actual radiation. The NOCT is defined as the temperature reached by open circuit cell with 800 W/m^2, air temperature of 20ºC, 1 m/s wind speed and open back side of the cell. This parameter aims to adapt a model to operating conditions that are different from the STC conditions (25ºC for 1000 W/m^2).

The effect of actual operating conditions is then computed as a new value of voltage and current for equation 22 as:

$$V' = V_{STC} + \Delta V \quad \textbf{(32)}$$

$$I' = I_{STC} + \Delta I \quad \textbf{(33)}$$

where

$$\Delta I = \alpha\frac{G}{G_{STC}}\Delta T_C + \frac{G - G_{STC}}{G_{STC}}I_{SC,STC} \quad \textbf{(34)}$$

$$\Delta V = -\beta\Delta T_C - R_S\Delta I \quad \textbf{(35)}$$

$$\Delta T_C = T_C - T_{STC} \quad \textbf{(36)}$$

1.2.2. DC-DC converter

In order to control the operating electrical characteristics of the photovoltaic generator to achieve power control, namely maximum power extraction, a DC-DC converter is used. The DC-DC converter allows at changing the load resistance as seen by the photovoltaic panel as referred in section 1.1.4 and is depicted in ***Fig. 12***.

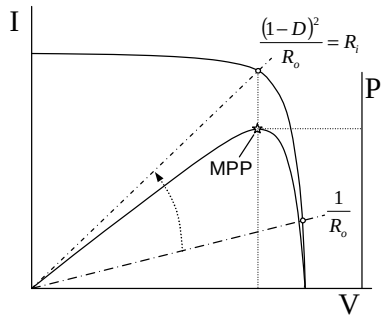

Fig. 12 - Effect on photovoltaic equivalent load in function of converter duty change

This way and considering a constant load, the operating point of the photovoltaic panel can be changed in response to changing environmental conditions in order to operate as to generate the maximum power.

1.3. Grid connection

The grid connection can be implemented by a voltage source inverter, also responsible to regulate the DC bus voltage, as depicted in ***Fig. 13***. The role of the several elements is described in the following sections.

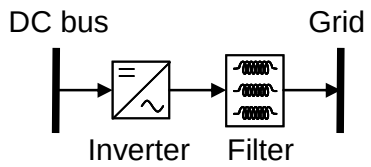

Fig. 13 - Grid connection through inverter and filter

As the inverter is supplying a grid which is a regulated voltage source its operation is identical to a controlled rectifier, operating in the second quadrant, which

regulates the input DC bus voltage. This operating characteristic is important in the development of this thesis. For these conditions, to control the generated power to be injected into the grid means to control the power injected into the DC bus, controlling the several power flows of system components connected to it.

As the key proposal of the thesis is to control the different power flows, controlling the power that the HRES puts available in the DC bus, no further research is made on the inverter operation.

1.3.1. Inverter

The inverter is modelled by equivalent average equations where the voltages are obtained through the DC bus voltage and the average current from the line currents **[6]**,**[7]**,**[8]**.

$$\begin{aligned} v_{inv} &= m_v \cdot v_{DC} \\ i_{inv} &= m_i \cdot i_L \end{aligned} \qquad \textbf{(37)}$$

where m_x is the inverter command (modulation index). As the grid is a voltage source, the power flow is regulated controlling i_L.

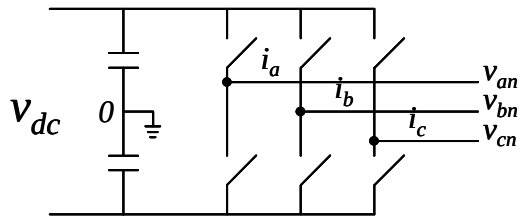

Fig. 14 - Three phase inverter

The inverter output voltages are given by:

$$[v_{ab}, v_{bc}, v_{ca}] = f(v_{dc}) \qquad \textbf{(38)}$$

and the resulting currents are:

$$i_{dc} = f\left([i_a, i_b, i_c]^T\right) \qquad \textbf{(39)}$$

Where *f* is a transfer function related to the switching functions of six switches (S) of the inverter, resulting from the comparison of a triangular wave with a sinusoid representing the desired sinusoidal output voltage (control voltage):

$$f_V = [f_{S1a}, f_{S1b}, f_{S1c}] \text{ and } f_I = [f_{S2a}, f_{S2b}, f_{S2c}] \quad \textbf{(40)}$$

The resulting voltages are then:

$$v_{a0} = \frac{v_{dc}}{2} f_{S1a},\ v_{a0} = \frac{v_{dc}}{2} f_{S1b},\ v_{a0} = \frac{v_{dc}}{2} f_{S1c} \quad \textbf{(41)}$$

where "*0*" is the reference point and f_{S1x} is the result of the comparison of the magnitude of the control signal with the triangular signal.

From the voltage to reference voltages the line-line voltages are computed as:

$$v_{ab} = v_{a0} - v_{b0},\ v_{bc} = v_{b0} - v_{c0},\ v_{ca} = v_{c0} - v_{a0} \quad \textbf{(42)}$$

The phase voltages are then:

$$v_{an} = v_{a0} - v_{n0},\ v_{bn} = v_{b0} - v_{n0},\ v_{cn} = v_{c0} - v_{n0} \quad \textbf{(43)}$$

and the currents are:

$$i_a = \frac{v_{an}}{z},\ i_b = \frac{v_{bn}}{z},\ i_c = \frac{v_{cn}}{z} \quad \textbf{(44)}$$

where *z* is the impedance seen by the inverter.

The DC current is then computed as:

$$i_{dc} = i_a f_{S2a} + i_b f_{S2b} + i_c f_{S2c} \quad \textbf{(45)}$$

Expression (45) shows that the three-phase currents injected in the grid are a function of the DC current supplying a DC load.

The assumptions made in 1.3 along with the expression (45) supports the analysis of power flows at the DC bus only.

1.3.2. Filter

In order to model the connection of the voltage source inverter to the grid it is used the following expression:

$$L\frac{di_L}{dt} = \left(v_{inv} - v_{grid}\right) - r_L i_L \qquad \textbf{(46)}$$

where i_L is the line current, L [H] and r_L [Ω] are the line inductance and resistance used to connect the inverter voltage (v_{inv}) to the grid voltage (v_{grid}).

In state space form:

$$L\frac{di_L}{dt} = \frac{1}{3}\begin{bmatrix} 2 & -1 \\ -1 & 2 \end{bmatrix}\left[v_{inv} - v_{grid}\right] - r_L i_L \qquad \textbf{(47)}$$

1.4. DC bus

The expression of the DC bus voltage for the hybrid system given by:

$$v_{bus} = \frac{1}{C_{bus}}\int I_C dt \qquad \textbf{(48)}$$

where I_C [A] is the current through the capacitor resulting from the current contributions of the various elements,

$$I_C = I_{PV} + I_{Eol} - I_{Inv} \pm I_{BB} \qquad \textbf{(49)}$$

with I_{PV} the current of the photovoltaic generator, I_{Eol} the current of the wind generator, I_{Inv} the current to the inverter and I_{BB} the current to or from the battery bank.

1.5. Storage system

The storage system is responsible to deliver power when the combined wind and photovoltaic are insufficient to satisfy the programmed load or to store it in the inverse case (excess of renewable power).

The used energy storage is based on electrochemical technology, specifically lead-acid batteries.

There are several models for batteries **[9]**,**[10]**,**[11]**,**[12]**. The model used is based on a simple model and considers initial and maximum SOC (State Of Charge) that indicates the available energy, efficiency of the energy charge and discharge and the self discharge rate **[13]**, as it is accurate enough for the goals of this thesis. The model of the battery represents a voltage source in series with a resistance (***Fig. 15***) which values depend on the specific operation at every time (charge and discharge over time) and presents to the exterior a voltage V_{bat}.

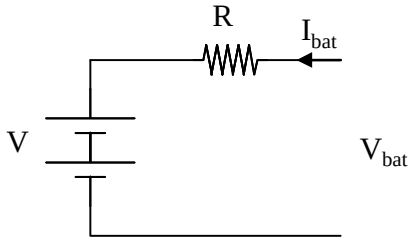

Fig. 15 - Battery model

The state of charge of the battery is defined as the percentage of the actual capacity to its nominal capacity. This expression does not take in account the degradation of the battery due to its age and conditions of use usually expressed in terms of State of Health (SOH).

$$SOC = \frac{Q}{Qn} \quad \textbf{(50)}$$

where Q [Wh] is the battery capacity and Q_n is the nominal capacity.

During the operation of the battery the values of its internal resistance (R) and internal voltage (V) change. Therefore the equations used to reflect these dynamic characteristics in the battery model are:

$$V_{charge} = (2 + 0.148k) \times n_S \quad \textbf{(51)}$$

$$V_{discharge} = (1.926 + 0.124k) n_S \quad \textbf{(52)}$$

$$R_{charge} = \left(\frac{0.758 + \frac{0.1309}{1.06 - k}}{SOC_{\max}} \right) \times n_S \quad \textbf{(53)}$$

$$R_{discharge} = \left(\frac{0.19 + \frac{0.1037}{k - 0.14}}{SOC_{\max}} \right) \times n_S \quad \textbf{(54)}$$

$$k = \frac{SOC}{SOC_{\max}} \quad \textbf{(55)}$$

where n_S is the number of 2 V cells and $SOC_{\max}$ [%] is the maximum capacity of the used battery.

The battery voltage at a given instant is therefore:

$$V_{bat} = V_{cd} + I_{bat} R_{cd} \quad \textbf{(56)}$$

where the index *cd* represents charge or discharge depending on the particular situation and I_{bat} is negative if the battery is discharging.

The instantaneous value of the SOC is given by:

$$SOC(t + \Delta t) = \frac{SOC(t)}{3600}(3600 - sd\Delta t) + \varepsilon\left(V_{bat} I_{bat} - R_{cd} I_{bat}^2\right) \quad \textbf{(57)}$$

where ε is the charge/discharge efficiency and sd [h^{-1}] is the self discharge rate.

1.6. DC-DC converters

There are two types of DC-DC converter used in the hybrid system: a booster for control of sources and discharge of stored energy and a buck for storing energy. The modeling is made considering the two possible states of the switch (On and OFF) and averaging them by duty factor times.

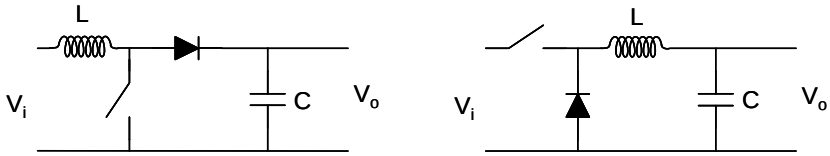

Fig. 16 - Booster and buck DC-DC converters

The operation of the booster converter is analyzed, considering:

On state:

$$\begin{cases} \dfrac{di_L}{dt} = \dfrac{1}{L} v_i \\ \dfrac{dv_C}{dt} = \dfrac{1}{C} i_C \end{cases} \quad \textbf{(58)}$$

Off state:

$$\begin{cases} \dfrac{di_L}{dt} = \dfrac{1}{L}(v_i - v_C) \\ \dfrac{dv_C}{dt} = \dfrac{1}{C}(i_L - i_C) \end{cases} \quad \textbf{(59)}$$

Taking in consideration the switching times $t_{ON} = DT$, $t_{OFF} = (1-D)T$ and the average inductance current and capacitor voltage, where D is the duty factor:

$$\begin{cases} \dfrac{di_L}{dt} = \dfrac{1}{L} v_i(D) + \dfrac{1}{L}(v_i - v_C)(1-D) \\ \dfrac{dv_C}{dt} = \dfrac{1}{C} i_C(D) + \dfrac{1}{C}(i_L - i_C)(1-D) \end{cases} \quad \textbf{(60)}$$

…

$$\begin{cases} i_L = \dfrac{1}{L}\int (Dv_C + v_i - v_C)dt \\ v_C = \dfrac{1}{C}\int (i_i - Di_i - i_C)dt \end{cases} \quad \textbf{(61)}$$

Where L is the booster inductance, C the output capacitance, R the load resistance, v_i and v_o the input and output voltages, i_L the inductor current (input current), i_C the capacitor current and i_o the output current that depends on the output voltage and load resistance ($i_o = v_o / R$).

In the state space format:

$$\begin{bmatrix} \dot{i}_L \\ \dot{v}_C \end{bmatrix} = \begin{bmatrix} 0 & (D-1)/L \\ (1-D)/C & -1/RC \end{bmatrix} \times \begin{bmatrix} i_L \\ v_C \end{bmatrix} + \begin{bmatrix} 1/L \\ 0 \end{bmatrix} \times v_i \quad \textbf{(62)}$$

Considering the duty factor as the control input of the booster converter the transfer function may be expressed as **[14]**:

$$\frac{\hat{v}_o(s)}{\hat{d}(s)} = \frac{V_O}{D_O L_e C} \frac{(1-\frac{sL_e}{R})(sR_C C + R_C/R + 1)}{s^2 + s\left[\frac{(R_L/D_O{}^2)+(R_C/D_O)}{L_e} + \frac{1}{CR}\right] + \frac{(R_L/D_O{}^2)+(R_C/D_O)}{L_e CR} + \frac{1}{L_e C}} \quad \textbf{(63)}$$

The operation of the buck converter is analyzed, considering:

On state:

$$\begin{cases} \frac{di_L}{dt} = \frac{1}{L}(v_i - v_C) \\ \frac{dv_C}{dt} = \frac{1}{C} i_C \end{cases} \quad \textbf{(64)}$$

Off state

$$\begin{cases} \frac{di_L}{dt} = \frac{1}{L}(-v_C) \\ \frac{dv_C}{dt} = \frac{1}{C} i_C \end{cases} \quad \textbf{(65)}$$

Taking in consideration the switching times $t_{ON} = DT$, $t_{OFF} = (1-D)T$:

$$\begin{cases} i_L = \frac{1}{L}\int (Dv_i - v_C)dt \\ v_C = \frac{1}{C}\int (i_L - i_o)dt \end{cases} \quad \textbf{(66)}$$

In the state space format:

$$\begin{bmatrix} \dot{i}_L \\ \dot{v}_C \end{bmatrix} = \begin{bmatrix} 0 & 1/L \\ 1/C & -1/RC \end{bmatrix} \times \begin{bmatrix} i_L \\ v_C \end{bmatrix} + \begin{bmatrix} 1/L \\ 0 \end{bmatrix} \times v_i D \quad \textbf{(67)}$$

2. Control characteristics

2.1. Individual control of operating point for each source

2.1.1. Maximum power extraction

Most generators exhibit a non-linear characteristic with their power curve presenting normally a somehow bell shape. Furthermore renewable energy based generators are subjected to climatic changes (wind speed in wind generator and radiation and temperature in photovoltaic) that result in changes in their operating

points. Therefore a dynamic seeking of maximum power through time is needed in order to achieve the best economic efficiency.

2.1.1.1.Wind generation

Wind generators have a non-linear power characteristic (***Fig. 5***) and their maximum power changes with the wind speed. The global objective is to develop a control method that does not require measurement of wind speed (sensorless system) either directly with an anemometer or indirectly through rotor speed or frequency measurement and that it is independent from the system characteristics. Several methods to achieve maximum power extraction are reported in the literature such as Tip Speed Ratio (TSR), Hill Climbing (HC), Artificial Neural Networks (ANN), Fuzzy logic and others **[5]**,**[15]**,**[16]**,**[17]**,**[18]**. From these alternatives, fuzzy control method is adopted as it presents the advantages of not needing an accurate model of the controlled system, of using control rules based on linguistic description (easier tuning) and of having a non-linear and adaptive operation mode which gives it a robust performance under input and output variations **[19]**.

As the hybrid renewable based system is a small system with concerns about the investment cost, it is decided to take the DC output of the wind generator as input to the DC-DC converter. This strategy avoids the addition of mechanical slip-rings to transfer the three phase PMSG voltage lines from the moving part of the wind generator to the fixed one or the use of additional sensors to get control conditions as wind speed sensors.

The control of the wind generator to achieve maximum power extraction is therefore made through the controlled operation of a booster DC-DC converter. As the mechanical time constant is much higher than the converter time constant there is a lag between the electrical and mechanical power and since the converter output is essentially capacitive, having a response as the shape showed in ***Fig. 17***.

This behaviour restrains the control, as the smooth relation between the mechanical power and angular speed is lost (dashed line). Instead, what the

controller sees is a sharp increase, followed by a smooth decrease of power over the time (solid line). The Maximum electric Power Point Tracking (MePPT) control mechanism has, therefore, to wait for a new equilibrium point for the electric power, after a change in system conditions caused by changes of duty factor in the DC-DC converter, before deciding to increase or decrease the duty factor. After reaching this point, the fuzzy controller computes the next duty factor for the converter PWM controller.

The equilibrium point is determined by the slope of the electric power through time ($\Delta P/\Delta t$). When the slope reaches a minimum value it generates a clock impulse that activates the fuzzy control computation of the new duty factor. ***Fig. 18*** presents the blocks of the controller. The value of this minimum slope determines the stability and the speed of convergence – such high the minimum slope, higher is the speed of convergence to the MPP but it also results in some oscillation in the convergence process. The fuzzy controller takes the change in power and voltage to compute the duty factor of the PWM for the DC-DC booster converter (***Fig. 19***). Fuzzy rules are shown in ***Fig. 20***.

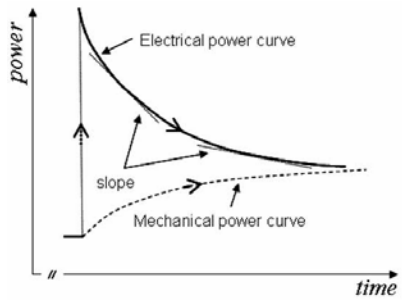

Fig. 17 – Different time responses for mechanical and electrical (booster output) parts

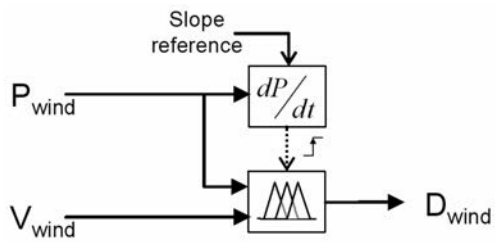

Fig. 18 – MePPT for the wind generator

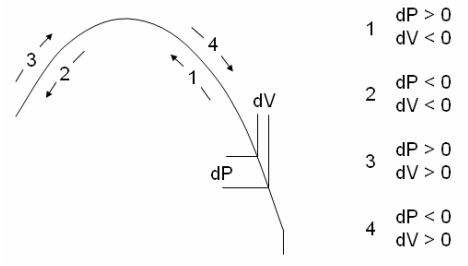

Fig. 19 – MPPT and the change in power and voltage

		dP				
		NB	NS	Z	PS	PB
dV	NB	NB	NS	Z	PS	PB
	NS	NS	NS	Z	PS	PS
	Z	Z	Z	z	Z	Z
	PS	PS	PS	Z	NS	NS
	PB	PB	PS	Z	NS	NB

Fig. 20 - Fuzzy rules for MePPT

The operation of the MePPT is inherently slow, as it must wait for the settling of power, which is dependent on inertia. Therefore, the MePPT will only work efficiently in sites with low turbulence in the wind. It produces nevertheless an improvement in the operation of the generator with a fixed operating point and an improvement in the start-up, where the operating point can be very far from the MPP.

2.1.1.2.Sun generation

Photovoltaic generators present a non-linear output characteristic (***Fig. 10***). Their maximum power point location changes with radiation and temperature changes. Therefore, if the operating characteristics remain fixed the power extracted from them will be lower than the maximum attainable.

This behaviour implies a dynamic seeking of maximum power facing to changing environmental conditions. Several methods to achieve maximum power extraction from photovoltaic sources are reported: Hill climbing, Perturb and Observe (P&O), Incremental Conductance (IncCond), Fractional

Open-circuit Voltage and Fractional Short-circuit Current, Fuzzy logic, Neural network, Ripple Correlation Control (RCC), Current Sweep, DC-Link Capacitor Droop Control, dP/dV or dP/dI Feedback Control and Load Current or Load Voltage Maximization **[21]**,**[22]**.

From these alternatives and for the same reasons related to choosing of a MPPT algorithm for the wind generator (see 2.1.1.1) fuzzy logic algorithm is adopted.

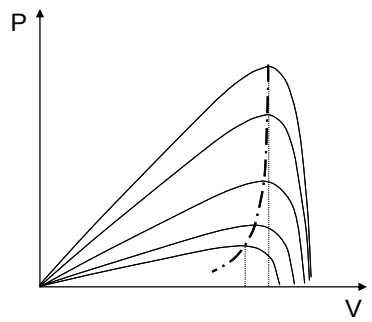

Fig. 21 - Locus of maximum power points (dash-point line) for changing radiation

For the characteristic power curve of a photovoltaic generator the maximum operating point can be defined as the point where the slope is zero. To the right of this point the slope becomes negative and to the left positive. Thus the ratio of power versus voltage (or current, in which case the curve will be mirrored) between two operating points is able to define if the operating point is in the half left or half right of the power curve. The change of the slope (see ***Fig. 19***), along the time, defines if the operating point is moving towards or away the maximum power point and if it is near or far from it.

The fuzzy controller to achieve MPPT has two inputs: error (ε) signifying the slope and change of error ($\Delta\varepsilon$) signifying the change of slope, defined as:

$$\varepsilon_k = \frac{\Delta P}{\Delta I} \quad \textbf{(68)}$$

$$\Delta\varepsilon_k = \varepsilon_k - \varepsilon_{k-1} \quad \textbf{(69)}$$

and one output (D), the PWM duty factor controlling the DC-DC converter.

The change of the duty factor will change the operating point and the resultant set of voltage and current is obtained. The controller compares the new point against the former one and through the analysis of ε and $\Delta\varepsilon$ values decrements/increments the duty factor such as the operating point approaches the maximum. The controller implements this algorithm with the fuzzy rules presented in ***Table 1***.

The rules used in the controller design are:

		ε				
		NB	*NS*	*Z*	*PS*	*PB*
Δε	*NB*	Z	Z	NS	PS	PB
	NS	Z	Z	Z	PS	PB
	Z	NB	NS	Z	PS	PB
	PS	NB	NS	Z	Z	Z
	PB	NB	NS	PS	Z	Z

Table 1 – PV fuzzy rules

2.1.2. DC bus power regulation

The power equilibrium between renewable sources generation and load consumption is a condition for system stability. So the excess of power generated must be withdrawn and deficit power must be provided such as a constant power to the load is ensured even if the renewable power is floating.

The power difference is managed through the storage battery using two DC-DC converters connecting the battery to the DC bus to allow the bidirectional power transfer. A booster converter is used to provide power to the bus and a buck converter to store power from the bus, each of them working independently but exclusively. Although other topologies could be used (as Sepick or buck-booster) it is found that modularity is best served this way because in the eventual failure of one the remainder could continue to operate. Since the system is dependent of the power equilibrium through the battery regulation, this architecture allows it to remain working subjected obviously to restrictions (for instance, if the charging module is out of service only in situations where load is higher than generation the system could remain in operation).

The power flow regulation is ensured by two proportional-integral (PI) controllers, one for each battery connected converter.

A digital PI controller is governed by the expression:

$$u[k] = K_P e[k] + K_I T \sum_{i=0}^{k} e[i] \tag{70}$$

where *u[k]* is the control variable – the duty factor of one of the two battery connection converters – and *e[k]* is the error between actual bus voltage and its reference. *k* is the discrete time, *T* the sampling period and K_P and K_I the proportional and integral gains respectively.

As the imbalance between generated and consumed power increases, the error between reference and actual bus voltage also increases too. The use of this error into the PI controller makes the duty factor of the concerned converter to rise as faster as the error is larger, subjected to the proportional and integral gains, and therefore to compensate the power imbalance.

2.2. Global supervisor

While there are several units independently controlled they have to be globally managed in order to operate the system towards a certain objective and in an integrated form. The HRES needs therefore to include a global supervisor to guarantee renewable sources maximum power and storage-bus power flow interactions to keep dynamic stability of the bus and to provide a controlled power to the load.

The supervisor role is to proceed to the sampling of the different values at a defined time period, compute controller's values and to command each one. It is also its responsibility to avoid inadmissible stresses over the units as battery currents and electronic switches. Finally it takes operation decisions subordinated to some defined operation strategy as for instance to supply or not the load or the amount of power to be delivered.

In particular the global controller acquires the values of wind and sun generated power and based on the power to deliver to the load determines the excess, lack or null power necessary to the power balance (see ***Fig. 22***). The balance is made through the storage system (batteries) with two DC-DC converters (buck for charging and booster for discharging) and proportional-integral controllers controlling them. The global controller also takes in account a minimal and maximal SOC, established by the user, and maximal charge and discharge battery current.

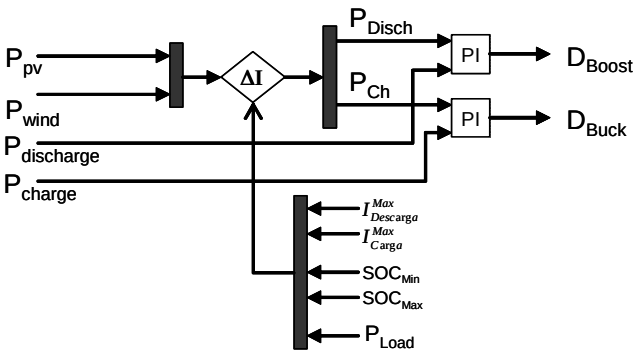

Fig. 22 - Global control

The algorithm showing the process of achieving power balance and battery restrictions in the hybrid system is shown in the flowchart of ***Fig. 23***.

P_{renew} is the renewable sources power gathered, P_{load} and P'_{load} are the programmed and the actual (reprogrammed) power to be delivered to the load, P_{BB} is the power to be exchanged with the storage batteries, $P_{BB_ch_max}$ and $P_{BB_disch_max}$ are the maximum charge and discharge power the batteries can handle, SOC_{max} and SOC_{min} are the user defined maximum and minimum charge for the storage batteries.

The definition of the maximum and minimum values is important not only because it relates to the physical characteristics of the storage unit but also because it allows some kind of energy management to be performed. In the physical limitations perspective it can be mentioned that there are conditions where a programmed load power can not be maintained namely because of the depletion or fullness of storage energy or the excessive power to be transferred to/from the batteries. In the energy perspective it can be mentioned the need of sufficient capacity allocation to allow at

gathering and storing of renewable energy when they exist but not required by the load and conversely when the load requires more power than it is available in renewable generation. This is possible through SOC management.

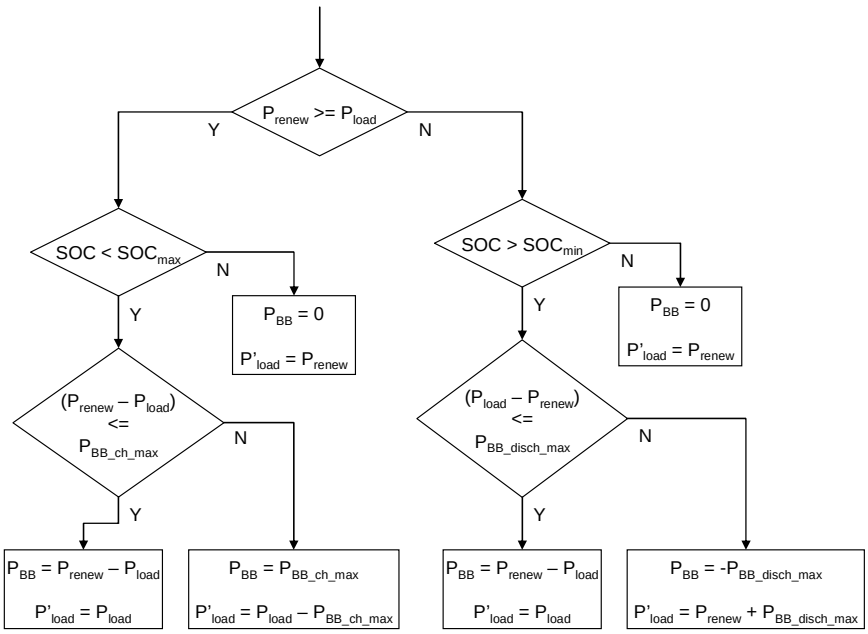

Fig. 23 - Flow chart of the global controller

3. Simulation assessment of the HRES operation

In order to assess the controlled power system operation subjected to some energy management strategy, computational analysis is a valuable tool to the perform research on the subject. Several different environments are available that allow modeling characteristics of systems. The first goal of this work being the analysis of the dynamic behavior of the HRES in terms of the power flows in the DC bus, Matlab/Simulink platform is chosen as appropriate for this task.

In following sections models for the different elements of the HRES are built and discussed with the simulation results presented for the more relevant. The derived blocks are then assembled in a global model with the addition of control and global management (supervisor) functions in order to research the global system behavior.

3.1. Simulink models

3.1.1. Wind generator

The wind source is composed by a wind turbine, a PMSG and a booster DC-DC converter to achieve power flow established according to the fuzzy maximum power point tracker. The control of the wind generator is based on the rectified DC output power as presented in 2.1.1.1. ***Fig. 24*** presents the wind turbine and generator coupled to a DC-DC converter controlled by the fuzzy maximum DC power tracking module. The output of the model is a voltage to be connected to the central DC bus and the input is the wind speed.

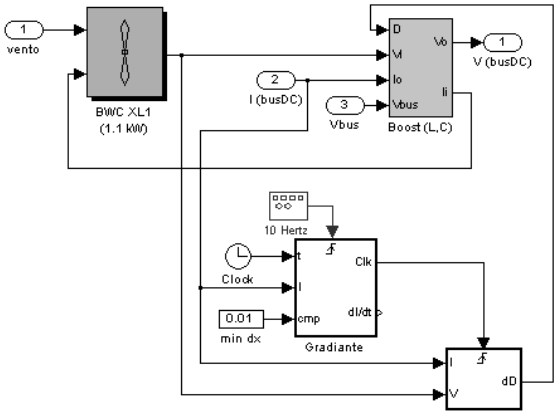

Fig. 24 - Wind generator Simulink model

The wind generator is further decoupled in mechanical and electrical subsystems (***Fig. 25***). A mechanical subsystem receives wind speed and returns a mechanical torque which is then transformed in an angular speed. The resulting value is used to input to the generator model that returns an AC voltage which is then rectified to return the DC voltage.

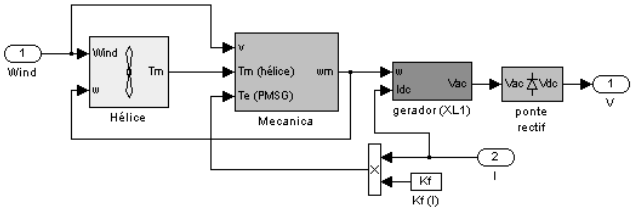

Fig. 25 - Turbine, generator and rectifier Simulink model

The angular speed (ω) is obtained from:

$$\omega = \int \frac{1}{J}\left(T_{mec} - T_{ele}\right) \cdot dt \qquad \textbf{(71)}$$

Where J [kg/m^2] is the moment of inertia of the turbine and generator and T_{mec} [Nm] is the mechanical torque and T_{ele} [Nm] is the resistant electrical torque. The moment of inertia was obtained through local experimentation of a Bergey XL.1 wind generator. Additionally, the mechanical block incorporates a condition to simulate the real start-up of the wind generator (that is, the output power is zero for winds below 3 m/s). The permanent magnet synchronous generator (PMSG) and the rectifier are modelled according to [23].

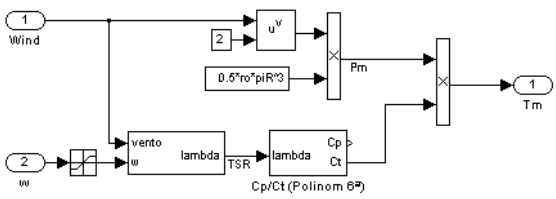

Fig. 26 - Aerodynamics Simulink model

The coefficient power (C_p) is calculated by two sixth grade polynomials, obtained from polynomial trend in an excel spreadsheet as illustrated in ***Fig. 27*** and applied to the model as depicted in ***Fig. 28***.

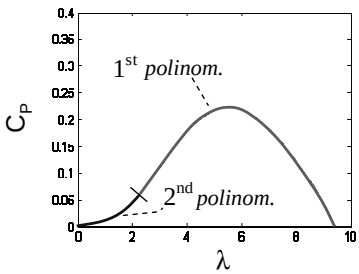

Fig. 27 - Coefficient power (Cp) versus tip speed ration (λ)

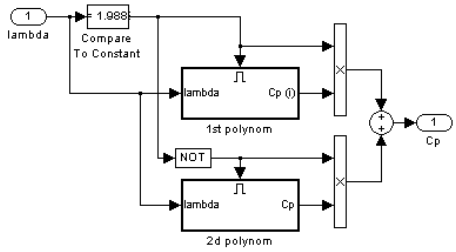

Fig. 28 - Simulink first and second power coefficient polynomials

The model uses one additional block to represent the decrease of generated power when wind speed rises above a certain limit (***Fig. 29***) which represents the physical mechanical breaking of the turbine.

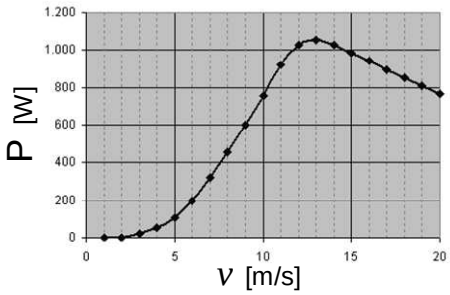

Fig. 29 - Generator power versus wind speed for Bergey XL.1

3.1.2. Photovoltaic generator

The photovoltaic source is modelled according to 1.2.1 and implemented in Simulink as depicted in ***Fig. 30***. The array has as inputs the radiation and temperature values as well as the resultant current drained. Also showed are the booster converter to control the PV array operating point which receives the voltage from the PV and the DC bus and the DC bus corresponding current. The converter is controlled through the duty factor defined by the fuzzy controller which receives the power and voltage from the array as its inputs.

The PV array is further decoupled in several blocks which implements the equations 23-36, defined in 1.1.2, and presented in ***Fig. 31***. The model incorporates the possibility to define different combinations of parallel/series arrangements based on the characteristics of one panel.

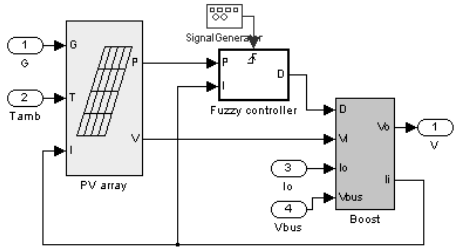

Fig. 30 - PV generator, Fuzzy controller and DC-DC converter Simulink model

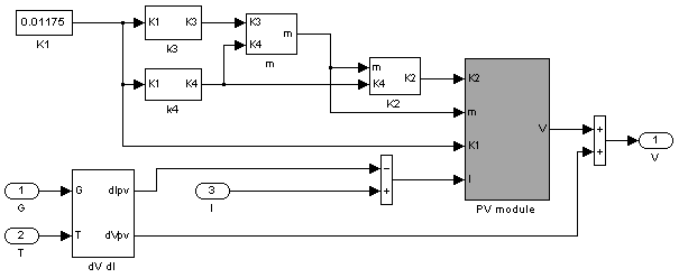

Fig. 31 - Photovoltaic array Simulink model

The fuzzy controller to achieve MPPT has two inputs: error (ε) and change of error ($\Delta\varepsilon$) and one output (D) as depicted in the blocks of ***Fig. 32***. The resulting duty factor is the input of the DC-DC converter depicted in ***Fig. 35*** and ***Fig. 36***.

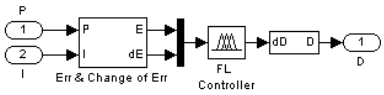

Fig. 32 - PV Fuzzy logic control Simulink model

3.1.3. Storage system

Equations 51-57 of section 1.5 are implemented in Simulink and the model is shown in ***Fig. 33***. The model is divided in three components: SOC calculation, internal charge and discharge voltage and resistance and output voltage. It takes a current (positive or negative depending on the need to charge or discharge the battery) as input and outputs the battery voltage and the correspondent SOC.

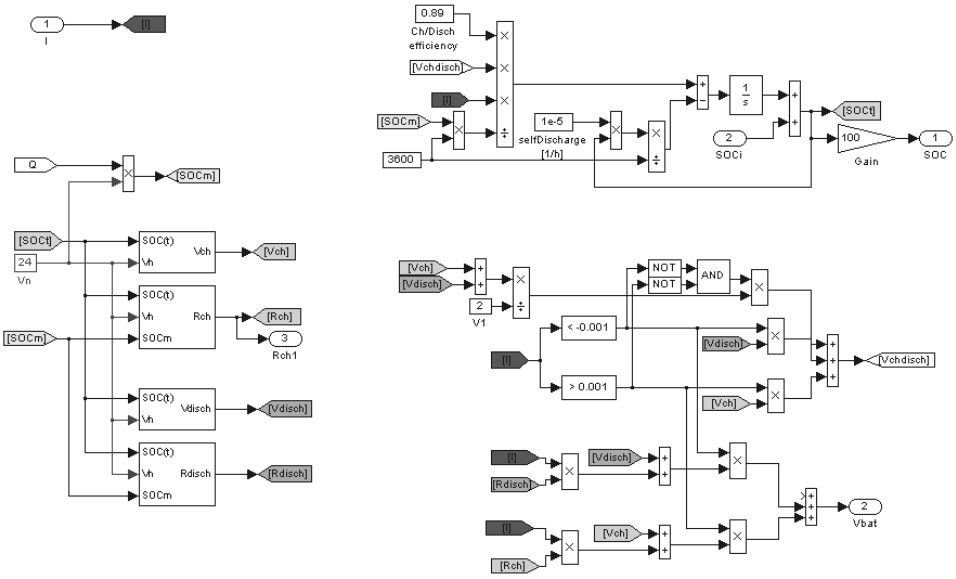

Fig. 33 - Lead-acid battery Simulink model

3.1.4. DC bus

As the DC-DC converters that interconnect the elements with the DC bus are modeled as voltage sources (section 3.1.5), the current is determined by an additional block. It takes the output voltages of the DC-DC converters and the voltage of the DC bus and determines, through an equivalent resistance (R(out)), the value of the current. Current is only delivered if the output voltage of the converter is higher than the bus voltage minus the voltage drop in the diode otherwise it is zero.

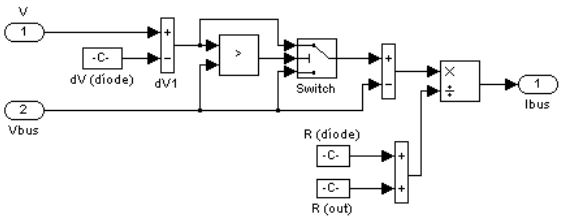

Fig. 34 - Voltage to current interconnecting model

3.1.5. DC-DC converters

The expressions obtained in section 1.6 model the operation of the DC-DC converters. The Simulink models of the booster and buck converters are shown in ***Fig. 35*** and ***Fig. 36***.

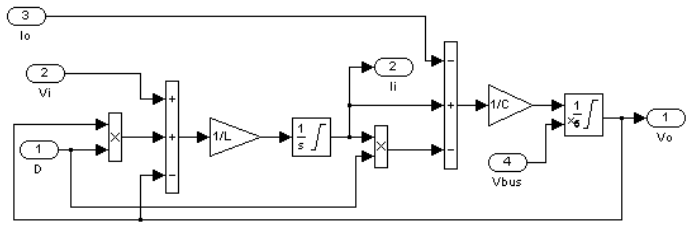

Fig. 35 - booster converter Simulink model

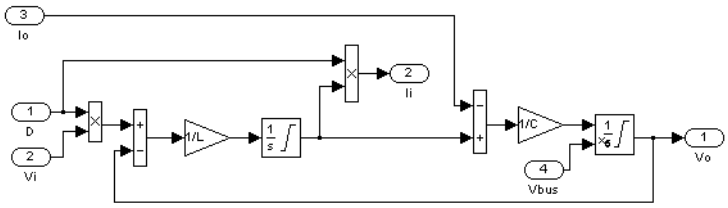

Fig. 36 - Buck converter Simulink model

3.2. Analysis of computational results

The behavior of two components – MePPT controller and DC-DC converters – is presented in the following sections.

The MePPT algorithm uses the same algorithm than the PV MPPT the difference being the additional method of triggering the fuzzy computation. The triggering is periodic in the PV MPPT since it has no inertia, the remainder being the same that in MePPT.

The DC-DC converters because they are the key elements that effectively regulate the power flows in the system and therefore important in the analysis of the dynamic behavior of the system.

3.2.1. MePPT

The MePPT algorithm and methods were described in section 2.1.1.1 and its operation simulated. The results on the operation of the wind generator are presented in ***Fig. 37*** and in ***Fig. 38***.

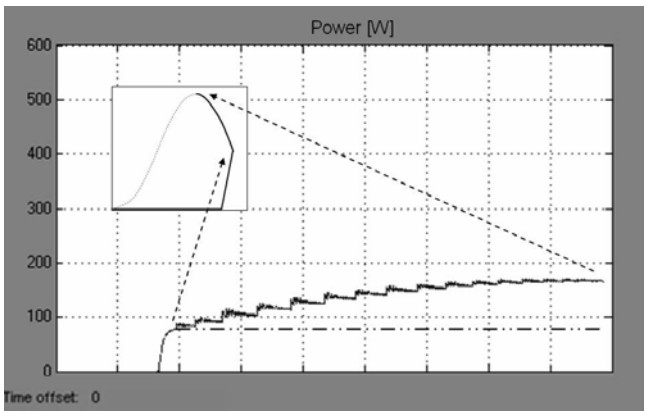

Fig. 37 - MePPT in wind generator startup

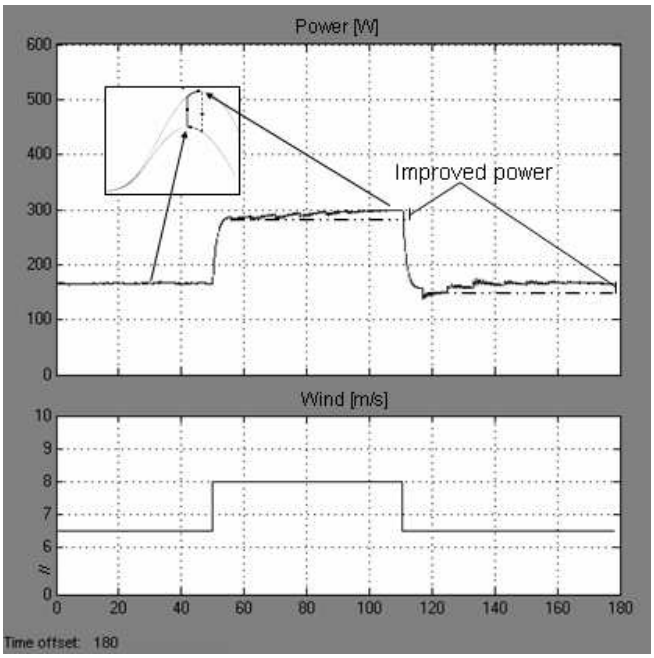

Fig. 38 – MePPT in normal operation with wind speed step changes

These displays show an increase in the output power in both the cases especially in the situation where the wind generator as started to operate (***Fig. 37***).

As mentioned the MePPT is slow as it depends on the mechanical inertia not operating adequately in conditions of high turbulence. It takes around 180 seconds

to attain the maximum power for the start up situation and around 70 seconds for a wind speed step change of 6.5 m/s to 8 m/s. With these time figures the control is ineffective as long as the wind speed changes within a time frame lower than the time taken by the generator inertia to settle down, since the power change due to wind speed change is undistinguishable from a power change due to the converter action. But it will be able to increase the power gathered as soon as the wind settles for a while being therefore an improvement when compared with its uncontrolled operation.

3.2.2. DC-DC converters

The operation of the averaged DC-DC converters was compared with their counterpart model of *SimPowerSystems* Toolbox. The results are satisfactory as it can be seen in ***Fig. 39***. They therefore can be used with the assumption that the more dynamic characteristics of the converters are not important for the purpose of this thesis.

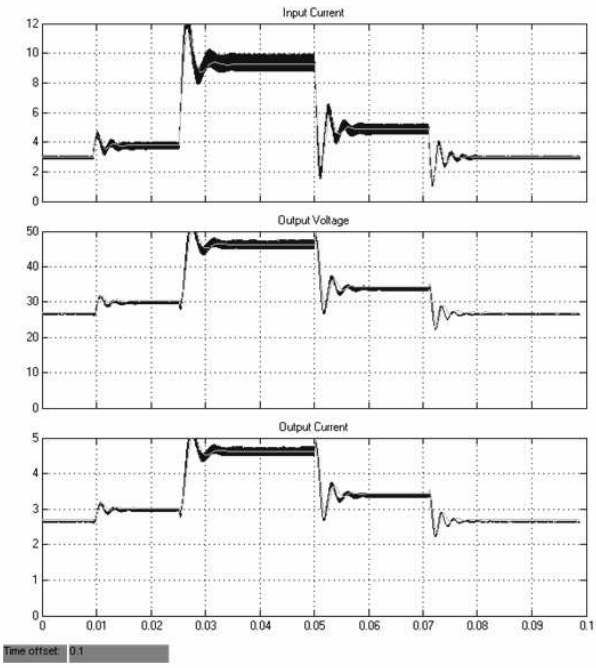

Fig. 39 - Comparison between average model (grey line) and SimPowerSystems (black line) for booster DC-DC converter

3.2.3. Hybrid system model test results

After validation of the several elements, they were assembled in a global model (***Fig. 40***) and its behavior assessed. As the HRES presents a set of state conditions imposing different operation conditions the analysis to be performed requires the creation of a scenario that embraces those possible states in order to validate the global model.

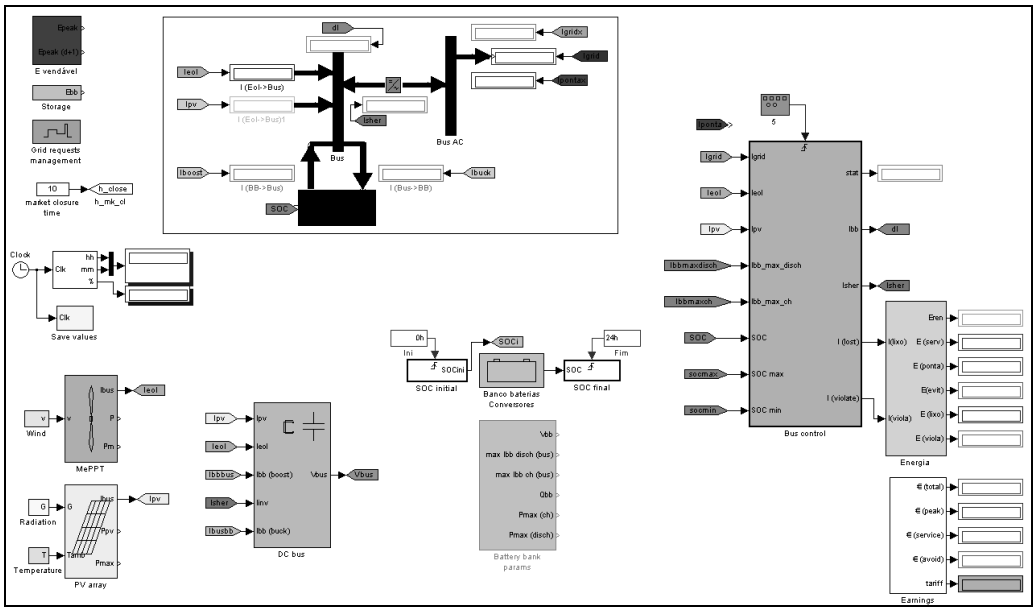

Fig. 40 – Overal simulation system

The operation of the hybrid HRES with wind, sun and programmed load power (***Fig. 41*** to ***Fig. 43***) is analyzed and results presented in ***Fig. 44***. The test is conducted by applying the presented wind and sun radiation series as inputs to the sources models along with the load conditions and activating the control and management referred in previous sections. The simulation is conducted with a variable step type solver during one complete day with averaged results saved for every simulation second. The control algorithm runs every 100 ms and the step size optimized for minimum error considering the one day simulation duration.

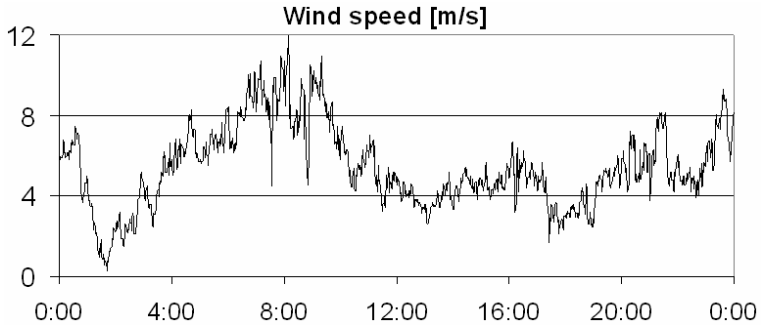

Fig. 41 - wind speed serie

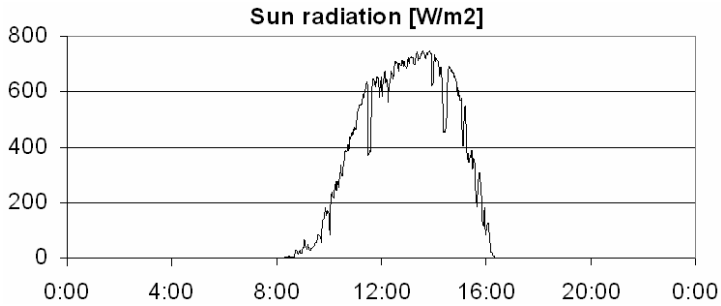

Fig. 42 - sun radiation serie

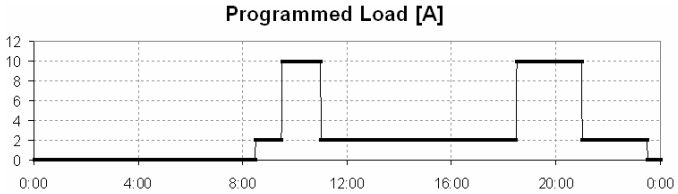

Fig. 43 – Programmed deliverable power

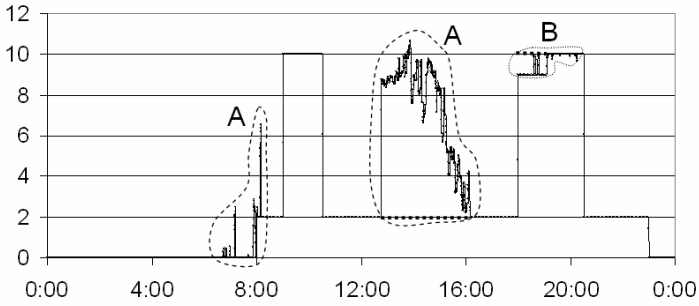

Fig. 44 - Delivered power

Analysis of the results shows that the system is able to workout real conditions operation as the results obtained by simulation are in accordance with the ones expected from calculation.

From the energy management perspective results show that storage capacity plays a key role on the management of the energy and has implications in the load commitment. Depicted in ***Fig. 44*** are two cases caused by relatively low capacity storage: A and B. In A, the power provided to the load is superior to the programmed value (the part of the excessive power, already transferred to the batteries) what will mean a lost of part of the captured energy and a possible penalty for violation of the programmed load power. This case represents an excessive power supply (EPS) of 8%, defined as the ratio between the excess of energy from the system to the required load energy. In B, the lack of power also means a violation of the programmed load power. This case represents a loss of power supply (LPS) of 1.48%, defined as a ratio between the deficits of energy of the system to the required load energy. The increase of the capacity from 220 to 440 Ah solves those deviations even in situations where one of the sources (wind or sun) would not be present during the 24 hours.

Analysis of global results although not contemplating all of the semiconductors switches and sources dynamic characteristics seems adequate for testing the behavior of the hybrid power system in a control perspective as also in a energy management perspective. This allows performing tests where control factors can be changed and different management strategies can be implemented which is to be done in chapter IV.

4. Conclusions

This chapter has established the models for the several required HRES elements. Initially with an analytically approach followed by their implementation in terms of computational analysis the models are discussed then integrated in a whole system.

The computational analysis is performed in the Matlab-Simulink environment as it reveals to be adequate for the thesis purposes with results conforming to the analyzed system expected performance.

In the following chapter the HRES model is used to analyze its behavior under several operational strategies and to asses its response to different cases related with its application as a controlled generator connected to the electric grid.

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Chap. IV – HRES availability for scheduling

1 - Context

DG generation, either renewable source based or not, presents relevant benefits due to its modularity and it can therefore be easily integrated in distribution systems. This fact can allow the relieving or postponing of investments in system expansion **[1]**. Furthermore although peak load represents about 20-30% of the supplying daily time in practice the networks operate most of the time in off-peak mode **[2]**.

The stability of the electrical grid is critically dependant on the availability of power as without a sufficient amount it can become unstable and collapse (blackout) [3]. The electrical systems reliability and availability are strongly related with the link between consumption profile and generation capability to deliver power when needed.

In view of future power systems, renewable based DG units must be able to flexibly control their operation. Interruptible load programs that earn compensation in exchange for a commitment to control power delivered are needed but they require, besides control capability, an exchange of information between the producer and the grid operators. In the perspective of small DG connected in the low voltage grid the controllability is important since the majority of the customer interruptions happens in these networks **[4]**.

As referred in Chap I, it is generally accepted that with the increasing of DG connected to the low voltage grids these can no longer be regarded as passive elements of the electrical network. Due to fluctuating power from uncontrolled renewable energy sources and loads the frequency and voltage fluctuation of power system becomes an issue as bigger as the renewable weight is increased. The benefits of the connection of DG to the grid are only ensured as long as they are integrated up to the planning level and not only connected. In the other side owners of DG units are essentially concerned with energy production and therefore not motivated to provide services associated with system safety as voltage support and active power reserves [4].

The main role of the electrical networks tends to change not only because the former reasons but also due to the spreading of the concept of micro, smart and virtual grids. In

[5] it is presented the concept of active network with the grid being essentially a connectivity provider, allowing links between generation and consumption. The implications are a need of cooperation to balance generation and consumption that may involve curtailment of renewable power generation, changing the ratio of heat/power of CHP or changing the power scheduling of V2G. This means that the DG units must not only be 'contactable' but, for the sake of the investment economic health, also be capable of supporting a dynamic management.

2 - Added value of determinism

The DG added value of achieving the attribute of determinism when involved with renewable sources can be analyzed in a technical as well as in an economic base. The first analysing the characteristics of the power delivered to the grid and the second viewing and analysing the generated power as a product to the grid operator.

2.1 - Technical value

The uncertainty of the renewable power generation, together with real-time load variation and system contingencies, leads to a higher level of unsafety of the power system. As a consequence the grid operator must increase reserve margins, adopt generation rescheduling strategies to counteract the effects of estimation errors and of the next possible contingencies, and finally update old tools for power system safety analysis. If the above actions are not performed, black-out episodes might take place **[6]**.

Periodic maintenance outages are usually used in electrical systems to ensure their adequate operation. The use of new generation technologies, when connected to a grid not planned to support them, embodies eventual operation problems that can lead to unexpected outages. These ones are generally disruptive and threatening to people and property. Not only the effects means the unavailability of dependant power equipments and processes, leading to economical as well as other losses more difficult to compute, but they also implies the consequent run-on of local backup generation that are costly (both because of the cost of primary fuel and its stocking as

well as the opportunity cost) and environmentally damaging **[7]**. This security, quality and availability context, in a grid analysis point of view, can be illustrated with ***Fig. 2***.

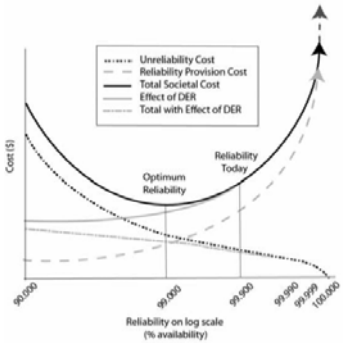

Fig. 1 - Costs and reliability involved with DG [7]

Power, frequency and voltage control, congestion management, power losses reduction and power quality control are named ancillary system services that are required to help managing the grids. These services are usually provided by conventional generation but recently also requested to DG as long as their weight increases.

Power quality can be increased by supporting voltage and reducing voltage dips, perform active filtering and phase balancing. While some of these issues are mainly dependent on the use of power electronic (grid connected) inverters operational capabilities, they have nevertheless to rely on their input power availability and stability to perform adequately. With an uncontrolled, renewable energy based, power input feeding the inverter it will be difficult to ensure those services and benefits.

2.2 - Economic value

One of the major concerns in liberalised markets is the satisfactory response to customer requirements, particularly the supply continuity. Industrial and commercial company's competitiveness, safety, public health and others factors are dependant on electricity and on its continuous availability.

As the load energy is an uncertain quantity the grids operators have to match generation with consumption power through the time. This match is made by several

forms including the use of the day and intraday market where, as in all markets, the prices are regulated through demand and supply laws as also by the law of 'need' which is related with opportunity time. As such a lowering of the costs of energy supply when compared to spot peak market prices is a strong possibility for the DG to explore.

Therefore to achieve that the DG is able to ensure its capability of delivering the energy and power contracted with the market becomes an issue. Moreover those contracts are negotiated with some antecedence which turns the energy availability less reliable especially when DG has stochastic sources as the primary source of power.

Within a large time frame a small DG unit is unable to ensure energy continuity even with associated storage capacity.

Not serving as substitutes for large power plants the concept of controlled DG has an inherent economic value. Such value although not usual and visible encompasses the help they can offer to the grid by producing local power, reduction of demand during peak power periods and minimizing line congestions. In **[8**] electrical losses values of 4.2 to 8.9 % are referred caused by aging of the transmission and distribution equipment and congestion. The substitution of generation based on fossil fuels also means less carbon emissions and therefore has an economic as well as an environmental benefit, this last one of difficult evaluation.

Although DG uses more expensive sources, particularly in the renewable sources cases, this cost is quickly offset by the increase of the benefits they can bring such as the avoidance of down-time expenses and the reduced installation and operational costs **[9**].

To compute the economic value of a power system the cost of energy (*COE*) can be used **[10**]:

$$COE = IC + COM + CF \tag{1}$$

where *IC* is the system investment which encompasses the cost of equipment and its installation, *COM* is the operation and management cost and *CF* is the fuel cost, zero in the case of renewable sources.

The financial merit of an investment can be analysed by the Internal Rate of Return (IRR) which is a planning indicative figure to whether or not proceed with the installation. The investment is as much worthy as the IRR exceeds the interest rate, the difference being the net earning. As the interest rate is changing through the time and due to inflation the IRR is actualized by the Net Present Value:

$$NPV = \sum_{t=0}^{n} \frac{CF_t}{(1+ir)^t} = 0 \qquad (2)$$

where *CF* are the cash flows, *ir* the interest rate and *t* the time period.

CF can be approximated by:

$$CF = (8760 \times CC) \times E_N \qquad (3)$$

where *CC* is the capacity credit, *8760* the annual number of hours and E_N the nominal energy that the system is able to generate.

The operational evaluation of the system can then be computed through the Return On Investment (ROI), and the Payback Time (PB):

$$ROI = \frac{CF - IC}{IC} \qquad (4)$$

where *CF* is the investment gains (cash flows) and IC the investment costs

$$PB = \frac{SC}{CF} \qquad (5)$$

where SC is the system cost along the time.

Capacity Credit, Effective Load Carrying Capability (ELCC) that uses Loss of Load Expectation (LOLE) or Loss of Load Probability (LOLP) are expressions trying to assess the relative contribution of a particular generator to the electrical network to which it is connected to **[3]**. They could be used in a planning phase to better assess the values used in the cash flows which are dependant on the expected energy production.

3 - System behaviour under different dispatch rules

The present work proposes a hybrid power system exclusively based on renewable energies that intends to answer some of the issues of grid connected DG. It relies on the storage capacity to cope with the variability of its sources in order to deliver a controllable power to a load as well as in integrating into the same site renewable sources with different generating conditions.

The controllability concept embraces constancy of delivered power during a specified time interval and the capability of freely change its value, as needed, from one time interval to another. It also aims to be able to adequately service abnormal and unscheduled requests from a grid manager. The term grid operator has a wide meaning that encompasses microgrid, VPP, smartgrid or utility grid operators.

In that sense it matters to define several modes of operation to assess the value of a controlled, renewable based, power generator system. Those modes of operation are viewed, besides the usual energy selling, in a service perspective and under market laws of operation.

3.1 - Intraday market energy selling

If the HRES plans to sell energy in the day market it has to comply with the rules of operation markets: that is to present the offer with some antecedence (14 hours in

the case of MIBEL) for one complete day (see ***Fig. 2***). In that sense it has to ensure the reliability of the system, that is, the availability of the energy and power offered for the next 24 hours of supply. To comply with those constraints and to maximize the economic value of his operation, the HRES must incorporate a forecast method and a scheduling mechanism.

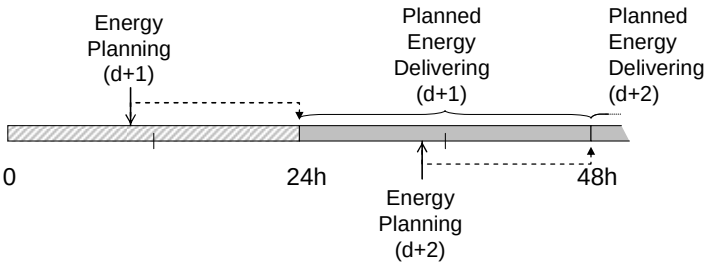

Fig. 2 – Intraday market energy scheduling

3.1.1 - Available energy forecasting

The expected stored energy at the beginning of the next day is determined by:

$$E_{24}^{*(BB)} = E_{10}^{BB} + c \times E_{10-24}^{*(ren)} - E_{10-24}^{L} \quad \textbf{(6)}$$

where E_{10}^{BB} is the energy in the storage at the time of prediction (10:00), c a coefficient accounting for the variation of actual renewable energy from normal values, $E_{10-24}^{*(ren)}$ the expected renewable energy from the remaining time of the present day and E_{10-24}^{L} the remaining load energy programmed for the present day. The coefficient c is computed as the ratio of gathered to expected renewable energy for the period from 0h to 10h:

$$c = \frac{E_{0-10}}{E_{0-10}^{*}} \quad \textbf{(7)}$$

where the expected energy is the statistical mean energy for the site.

The energy that can be expected to be sold in the next day is determined as:

$$E_{24-48}^{*(L)} = E_{24}^{*(BB)} + E_{24-48}^{*(ren)} \quad \textbf{(8)}$$

where $E_{24-48}^{*(ren)}$ is the expected normal renewable energy for the next day.

3.1.2 - Scheduling

The scheduling of the energy is accomplished taking the energy available to deliver in the period and computing the energy deliverable in peak hours:

$$I_{BB}^{\max} \times V_{DCbus} \times \Delta t_{peak} \quad \textbf{(9)}$$

where $I_{BB}^{\max}$ is determined by the batteries characteristics. This value ensures that the system is always capable of delivering the maximum scheduled power (not being dependant on wind and sun variability) and therefore capable of always maintaining the availability provided that there is enough energy in the system.

If the energy available is higher than the maximum energy deliverable in peak hours, then the remaining is delivered in full hours:

$$E_{h(full)} = E_{24-48} - E_{h(peak)} \quad \textbf{(10)}$$

This strategy avoids the eventual saturation of the storage and the consequent incapacity of gathering and use of 'future' renewable energy, while incrementing the earnings of sold energy.

If it is supposed that the HRES is connected to the LV grid one can additionally compute the avoided losses as **[11]**:

$$\mathrm{P}_{avoid} = 2f - 1.5f^2 \quad \textbf{(11)}$$

$$f = \left(\frac{I_{delivered}}{I_{LVgrid}^{ref}} \right)^2 \quad \textbf{(12)}$$

with $I_{LVgrid}^{ref} = 1000A$ for a urban grid in a branch fed by a 400 kVA transformer. The earning due to this power is determined at the same commercial price and tariff periods than the normal purchased energy.

3.1.3 - Results and analysis

The behavior of a HRES upon the discussed issues is analyzed by simulation of the system. The analysis is performed based on typical conditions of wind and sun and adopting the architecture established for the HRES.

The simulation is conducted with the wind and sun radiation profiles presented in ***Fig. 3*** and ***Fig. 4***. These profiles correspond to a sunny day with running clouds and modest wind with an average velocity of 4.8 m/s and a standard deviation of 2.4 m/s.

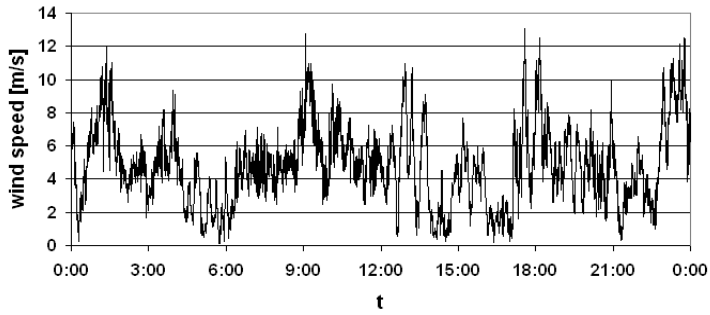

Fig. 3 – Wind speed profile

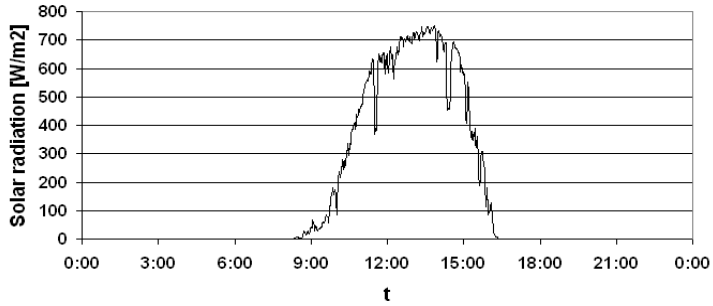

Fig. 4 – Radiation profile

The analysis test is performed with varying environmental conditions: the first three days with winter radiation but no wind, the next three days with winter radiation and wind followed by one day with only winter radiation and the last two again with winter radiation and wind. The bank of batteries has a capacity of 225 Ah to 630 Ah, 36 V, with a maximum SOC of 95% and a minimum one of 20% (~4 kWh). The maximum current is 70A and 66A for discharge and charge respectively.

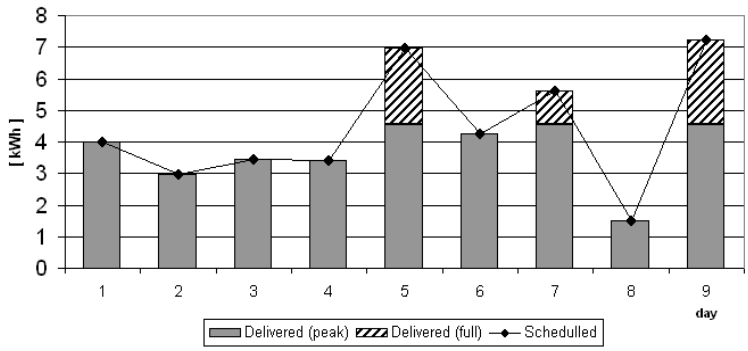

Fig. 5 - Delivered versus scheduled energy for 9 days

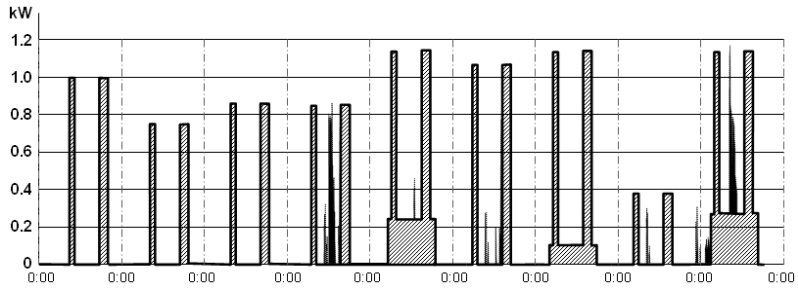

Fig. 6 - Delivered (grey areas) energy and wasted (black areas) renewable energy

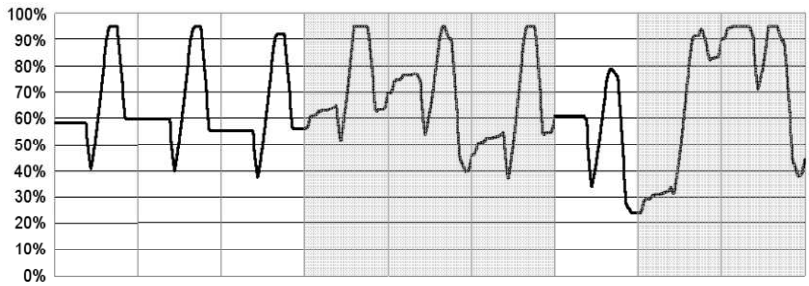

Fig. 7 - SOC variation of battery bank during the 9 days

day		1	2	3	4	5	6	7	8	9
Renewable energy	kWh/day	3,8	3,8	3,8	5,9	5,9	5,9	3,8	5,9	5,9
Schedulled energy	kWh/day	3,3	3,7	3,4	3,4	6,9	4,2	5,7	1,5	7,2
Delivered (peak hours)	kWh/day	3,3	3,7	3,4	3,4	4,6	4,2	4,6	1,5	4,6
Delivered (full hours)	kWh/day	0	0	0	0	2,361	0	1,128	0	2,641
Availlability		100%	100%	100%	100%	100%	100%	100%	100%	100%
€ (total) / year		182,5	193,5	192,2	191,6	226,3	227,5	238,8	219	236,8
Payback term	years	39,8	37,5	37,8	37,9	32,1	31,9	30,4	33,2	30,7
Avoided losses	kWh/year	38,0	39,9	39,5	42,8	50,1	50,1	52,2	47,8	53,0

Table 1 - Analysis of the behaviour of the system for 9 days

Energy price (peak/full hours)	Payback
0.038 / 0.0333 €/kWh	117 years
0.152 / 0.1332 €/kWh	30 years
0.608 / 0.5328 €/kWh	7 years

Table 2 – DG investment payback period for energy different prices

Fig. 5 shows the scheduled and the delivered energy for 9 days, while ***Fig. 6*** shows the time details of the energy delivered and the part that was wasted. ***Fig. 7*** details the SOC behaviour along the period considered.

The system reflects the environmental variations ensuring a 100% availability for the scheduled energy. The wasted energy (back areas of ***Fig. 6***) could be solved by an increase of the storage capacity.

A projection for one year based on energy prices is presented in ***Table 1*** for an investment of 7,000 € (actual market costs, although it is expected a reduction in commercial prices) on the HRES. The payback period for different energy prices is presented in ***Table 2***, the first for current day market prices, the second and third ones for hypothetical subvention prices. The adoption of a subvention similar to the used in photovoltaic energy in 2009 (0.6 €/kWh) would bring the payback period to 7 years. As these subventions tend to decrease in the course of time the payback time obviously increases.

3.2 - Peak hours energy consumption reduction

The objective is to reduce the quantity of purchased energy for a plant (load) in the periods where that energy is more expensive (peak hours).

$$P_{Grid}^{peak} = P_{Load}^{peak} - P_{HRES}^{peak} \quad \textbf{(13)}$$

The role of the HRES is to gather renewable energy when available, store it and deliver it to a local load when the grid energy is more expensive. The management system stores the renewable energy outside peak hours, except when the storage capacity is full or the power gathered is higher than the maximum admissible for the storage system. In these last cases the management allows at reducing the power gathered from the grid diverting the excess to the load. The same method is applied in peak hours when the load power is higher than the maximum combined renewable

power and storage maximum power or storage is depleted. In these cases the management complements the deficit with power from the grid.

3.2.1 - Results and analysis

The results for the peak energy operation mode are presented in ***Fig. 8***, ***Fig. 9*** and ***Table 3***. The energy prices used are retailer commercial prices (0.152, 0.1332 and 0.0742 €/kWh for peak, full and empty hours respectively). The simulations are conducted for a winter day with (case 1 of *Table 3*) and without (case 2 of *Table 3*) wind and a summer day with wind (case 3 of *Table 3*). The reduction in the purchased energy, outside peak hours, when storage is full or renewable gathered power is higher than maximum storage power is also visible. In all days the power reduction in peak hours is attained as can be seen in table 3.

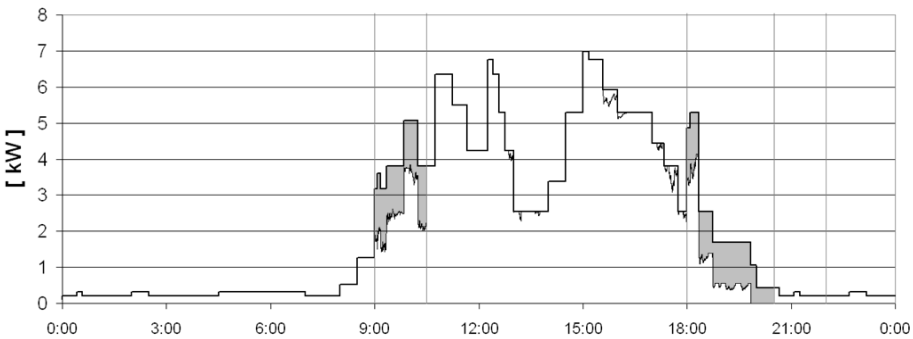

Fig. 8 - Load power profile and avoided grid energy (grey areas) for a winter day with wind (case 1)

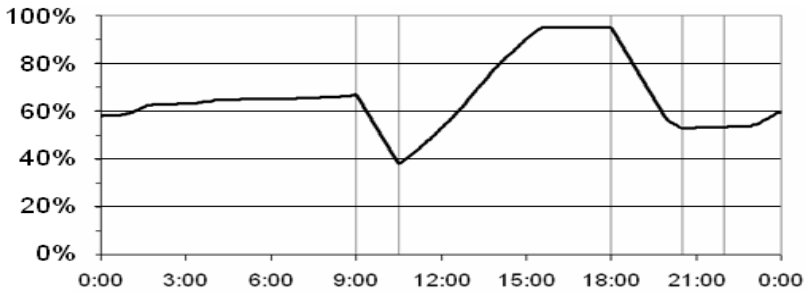

Fig. 9 - SOC of the storage system

	tariff €/kWh	0,152 (peak)	0,1332 (full)	0,0742 (empty)	€ total per day	€ saved per day	€ saved per year	PBP (years)
(Load)	kWh	11,063	36,571	2,501	6,74			
	€	1,68	4,87	0,19				
(Grid) Case 1	kWh	6,152	36,283	2,501	5,96	0,78	187,2	37
	€	0,94	4,83	0,19				
(Grid) Case 2	kWh	6,656	36,570	2,501	6,07	0,67	160,8	44
	€	1,01	4,87	0,19				
(Grid) Case 3	kWh	5,473	35,190	2,501	5,71	1,03	247,2	28
	€	0,83	4,69	0,19				

Table 3 - Saved energy and costs and Payback period (PBP) for the investment in the HRES

The projection shows a payback period ranging from 44 to 28 years, depending on the atmospheric conditions, without subsidized energy prices. The used storage capacity is the minimum (225 Ah) to achieve the objectives. The energy deficits are covered by the grid, although in that period of time the power profile would be fluctuating and therefore not coping with grid power stability. The earning achieved by the reduction of the power demand is therefore conditioned by the storage capacity which is related with the investment and re-investment (operational costs) in storage.

3.3 - Peak hours energy consumption reduction with constant power

The strategy is the same as in 3.2 but with the difference of maintaining the power consumed from the grid at a constant level. The system is therefore responsible to adapt the variable renewable generation and battery power to the difference between the load power and the constant grid power value.

3.3.1 - Results and analysis

Results for the peak energy with constant power are presented in ***Fig. 10***, ***Fig. 11***, ***Fig. 12*** and ***Table 4***. The simulation is performed for the same environmental conditions and the same forecast method as in the energy selling strategy. The storage capacity used is of 600 Ah as the strategy only relates to peak hours. Results show the respect of the planned grid purchase constant power for the 9 simulated days. The payback period is of 136 years at commercial prices and 20 years if the peak hour's energy is paid with a subsidized price of 1.02 €/kWh

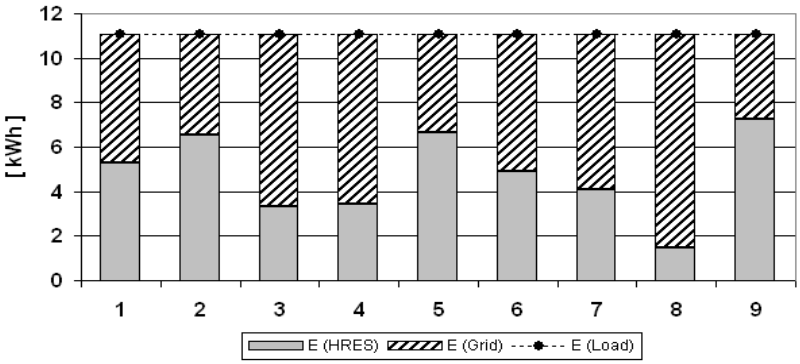

Fig. 10 - Peak load energy profile (dashed line), grid purchased peak power (dashed area) and avoided grid peak energy (grey area) for 9 winter days with variable wind

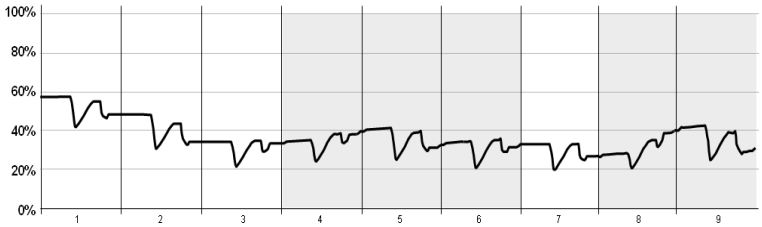

Fig. 11 - SOC of the storage system for the nine days

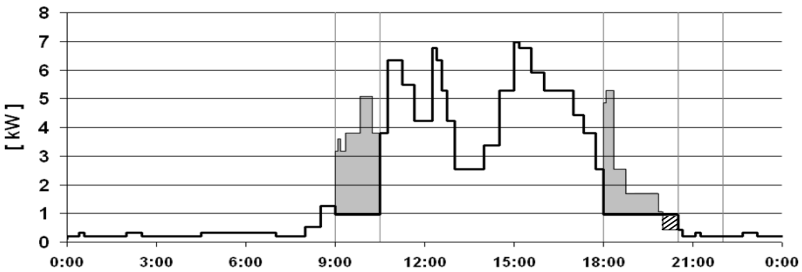

Fig. 12 - Load profile, purchased grid peak energy (solid) and avoided peak energy (grey areas) for one day

Energy price (peak hours)	Payback
0.152 €/kWh	136 years
1.02 €/kWh	20 years

Table 4 - Avoided peak energy and energy costs and Payback period (PBP) for the investment in the HRES

3.4 - Unscheduled grid requests

In this operation mode the HRES uses the previous pre-programmed peak hours selling of energy strategy, coupled with a dynamic management strategy. This means

that besides the capability to deliver the previous day contracted energy the HRES is also available to accept unscheduled power requests from the grid. The power and energy amounts are previously accorded and contracted with the grid operator.

3.4.1 - Results and analysis

The results from the dynamic grid management are presented in Fig. 13, 14 and 15. The used environmental conditions correspond to the winter day with wind. The system is able to respond to the extemporaneous requests of power from the grid while selling peak hour's energy, as programmed in the previous day.

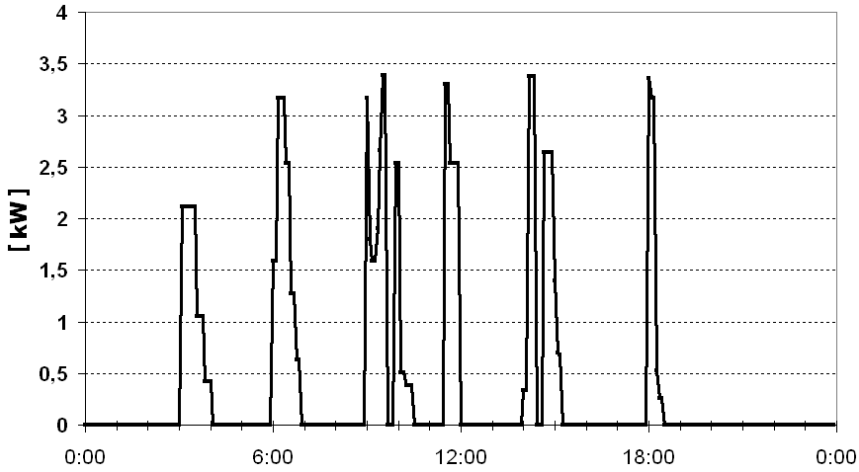

Fig. 13 – Assynchronous grid demands profile

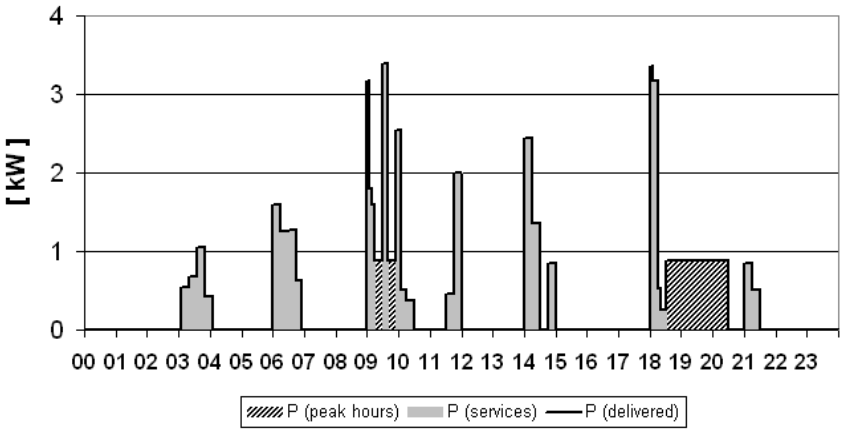

Fig. 14 - Power profile for peak hours energy selling and services

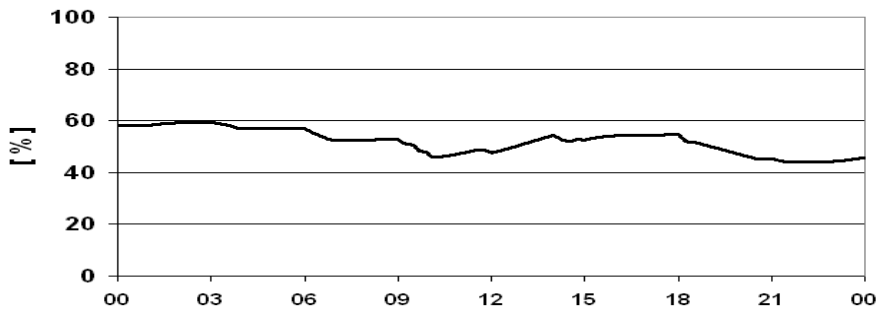

Fig. 15 – Storage SOC

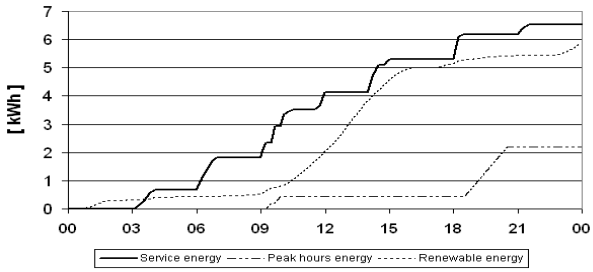

Fig. 16 - Energy profiles for grid energy requests, sold peak hours energy and gathered renewable energy for one day

4 - Results analysis

Performed analysis shows that the system remains controlled, for several different operational modes, presenting a constant power along the periods predefined. It is able to manage the varying power from the stochastic renewable sources while maintaining a constant pre-defined power during the pre-determined time frames.

Carried out results demonstrate that an integration of two different stochastic renewable sources is possible while ensuring the control of the power delivered, not only in value but also in time.

This characteristic allows at adding an economic value that is new in the context of the renewable generation, namely at the micro-generation level. Considering a scenario that generalizes the concept of microgrids at the distribution level, the spread of house based self-generation systems with communication capabilities can be potentially beneficial to all players.

Power exchange between storage and DC bus strongly determines the efficiency of the system. In conditions where the sun radiation is weak and there is no wind available the stress is on the power transfer from the battery to the DC bus the battery having to support all the power to the load. Not only because it obligates the battery to an effort that it has difficulty to cope with but also because the losses increase exponentially. So the best efficiency is attained in conditions of low power exchange and high energy delivered which is not at all the usual case. The use of a deterministic primary energy generator such as CHP could be an alternative. Also the use of hydrogen (by fuel cell form) and supercapacitors, the former to help in energy density the later to help in power capacity, are technologies that could help to improve the system.

Several operation strategies which are believed to have relevance in actual and future electrical environment show that such a system is able to add value to the management of the electrical grids.

These strategies allow the owner to leverage its revenues while providing valuable services to the electrical networks. The first being possible by the transfer of energy to periods where the energy is more expensive, thereby turning is investment more attractive and by that reason aiding to spread generation systems based on renewable energies.

The second one is possible by the transfer of energy to periods when it is necessary in the exact required amount and without raising the issues that have caused problems in the electrical networks management.

The HRES system tests show that its economic viability is strongly dependent on some subvention or on a complementary earning due to the services they can provide.

No considerations are done on some fields related to the economic value of renewable based production such as employment increase, social and environmental value as well as CO2 reduction and others.

Being typically small systems this type of DG units allows their placement anywhere. They therefore contribute not only to solve the usual problem of weak grids but to support an effective contribution to the increase penetration of renewable based

generation. The union of the freedom of placement with the power controllability and the freely primary fuel can make them a powerful instrument to solve electrical networks management and aid to their enhancement.

The weak point is the storage due primarily to its cost and life span. Batteries that are subjected to extreme conditions, in order to reduce their investment weigh in the system cost, do not survive much time. This characteristic has an important impact in maintenance cost (batteries replacement) and therefore in the ROI. Their limited energy density furthermore subjected to the current limitations calls for another technology either replacing them either aiding them.

To optimize charging/discharging operations and to improve battery management system is out of the scope of this work as the technology in the field is moving fast and new technological approaches show some kind of complete changes, reducing costs, increasing charge/discharge cycling and so on.

The improvement of the forecasting capabilities, namely ultra-short forecasting, could also improve the system efficiency as it can reduce the variability of the excursion of the energy stored.

The use of two complementary stochastic energy sources is relevant as they allow relieving some of the energy weight from the battery.

5 - Conclusions

The present chapter is focused in the analysis of the improvements brought by the evolution from uncontrolled renewable generation systems to hybrid renewable sources with storage capacity. The focus is at technical issues, mainly safety and availability of power what means control services for grid operators, as well as economic consequences through the increase of the added value of generated power. The capability of using the HRES in different modes of operation is undoubtedly beneficial for the grid operators.

The next chapter deals with the description of the experimental HRES designed to validate this work as well as to analyse its behaviour in real conditions of use.

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Chap. V – Experimental platform

The experimental validation of the results carried out with the computational analysis performed in previous chapter requires the design and implementation of a hybrid generation system. So a small but scalable experimental platform was built based on two primary energy sources, wind and photovoltaic, and a DC bus provided with a storage system. The system architecture is according to the analyzed one.

According to previous chapters, renewable based distributed power systems connected to a grid must namely be able of controlling the power they deliver and to be economically efficient. That allows this type of systems to be accepted as a grid power generator and to be attractive to investors.

The controllability of the generation system can be analysed through dynamics of the controlled DC bus supplying an AC load, based on integrated operation of an inverter and load. The grid interconnection is not realized as it is not important for analysis in the context of this thesis, as the main issue is to control the DC bus voltage with dynamic conditions similar to those adopted in power electronics based systems interconnected to the grid.

The integration of the different energy sources is architected through the DC bus. Its controlled operation demands for monitoring a set of variables needed for system control as well as for results demonstration proposals. The layout of the experimental system is shown in ***Fig. 1***. It depicts generation, storage and conditioning elements as well as data gathering points.

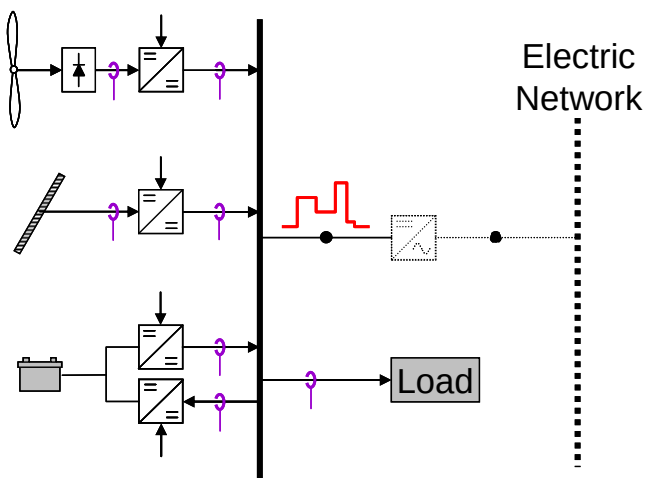

Fig. 1 - Layout of the system with data collection points

1 - Experimental platform description

The hybrid system is based on a 1.1 kW Bergey XL.1 wind generator , two BP polycrystalline (80 Wp) and one BP monocrystalline photovoltaic (PV) panels (85 Wp) parallel coupled, and a 195 Ah lead acid battery. Detailed characteristics of each component are presented in Annex 1. Each unit is coupled to a 20 mF DC bus through DC-DC converters: three Booster converters for interconnection of the two renewable sources and the battery, in delivering power mode, to the DC bus and a Buck converter to store the excessive power in the DC bus in the battery.

These system elements are very similar to the ones used in the computational analysis and are scalable to larger power with minor changes.

The use of four independent DC-DC converters allows at validating the all operating conditions, with none, one or the both generators and with charging or discharging modes for storage subsystem. Appropriated and managed scheduling of operating subsystems increases the service availability of the generation system in delivering power mode and therefore its economic value.

The control platform is implemented over a digital signal processor (DSP), through a Spectrum Digital evaluation module eZdsp f2812 (***Fig. 2***) running at 150 MHz.

This clock speed ensures that the processor has the capability of taking care of the dynamics of the electrical quantities involved in the control of the system. The module incorporates a 12 bit ADC with a maximum clock speed of 25 MHz, two sample and hold units allowing the acquisition of two simultaneous values (voltage and current usually) and sixteen input channels available. The ADC clock speed used was nevertheless inferior – 9.38 MHz which features 5.76 us for a burst of 8x2 consecutive channels conversion – in order to reduce conversion noise. The eZdsp module includes four independently modulated PWM signals used to control the DC/DC converters of the system and several I/O digital lines necessary to be used either as specific peripheral I/O signals (as for instance the serial communication interface (SCI) used to send and receive data from a RS232) or programmed as digital general input or output lines.

DSP/BIOS[1] is a built-in operating system that allows to use a real time operating system features, providing an visual programming interface for task scheduling, interrupts and periodic functions as well as other capabilities. It is an alternative to the interrupt driven code programming and was used to program the various tasks controlling the present hybrid power system. Several periodic timed tasks were defined in the DSP/BIOS each one taking care of a specific function as bus voltage control and MPPT computation along with support tasks as serial communication and system state conditions.

The capture of the maximum power of the renewable sources is accomplished in a continuous mode not restricted by power control requirements such as DC bus voltage control. A fuzzy based maximum power point tracking (MPPT) is selected to implement this capability as it is well adapted to non linear systems like the photovoltaic and wind sources. As the implementation of the fuzzy controllers (namely the rules) occupies a large memory space, related computation is transferred to an additional computer running Visual C++ under Windows XP. The communication between the DSP and this computer is implemented through a serial connection (SCI with 16 byte FIFO capability) with a custom board to convert the DSP to the RS232 voltage levels. The use of the FIFO further relieves the DSP from the task of directly controlling the communication bit to bit.

The acquisition of voltage is made with voltage dividers as well as the acquisition of currents is performed with 50 A Hall effect transducers (LEM has 50). A custom board to adapt their output voltages to the voltage level of the DSP is adopted. The current transducers were adapted to each particular current level case through several turns in order to raise the measurement accuracy. The current measurements were taken at the output of the generators for maximum power point tracking computation and between each unit and the DC bus for DC-DC converters control. The data gathering points are depicted in ***Fig. 1*** with small open circles.

[1] Built In Operating System

An additional analog interface (push buttons for commands and led's to view current state - see ***Fig. 2***) is used to avoid interruption of the processor control tasks[1] as the experimental operating conditions could need on-time change of parameters values. This interface encompasses manual controls – system initialization, parameters of MPPT manual/fuzzy computation, serial communication reset – and viewing of the main current state of the system – system on/off, manual/fuzzy MPPT, charging/discharging mode, serial connection malfunction and reset, bus voltage levels. The interface is implemented through several general purpose digital I/O (GPIO) lines of the DSP.

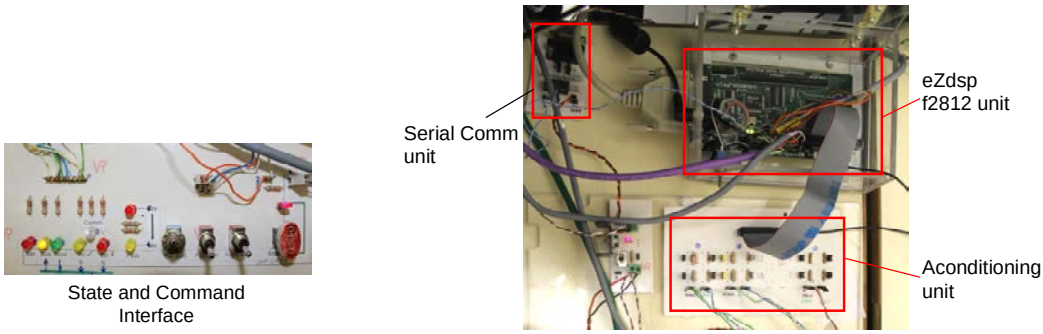

Fig. 2 – Control and interface units of the hybrid system

A National Instruments (NI) data acquisition board (low cost NI 6024E) with an interface implemented in Labview was also developed (***Fig. 3***). This interface allows at tracing the general short term as well as the long time behavior of the global system. It captures and displays the values of voltages in the battery, photovoltaic and wind generators and the DC bus, currents flowing in and out the DC bus, shows the activation of the converters in use and their eventual malfunction and implements a input/output battery current counting in order to display an assessment of the state of charge (SOC) of the battery. It also implements the saving of runtime values for pos-processing and an external command of the system load. The acquisition frequency in this interface is 10 HZ and results are saved with a frequency of 1 Hz. These frequencies are much lower than the 10 kHz frequency of the PWM control signals and the dynamic variations that they cause, but the averaged values are well suited to the long term behavior display. The faster dynamic characteristics are taken with digital oscilloscopes.

[1] These interrupts to transfer data from the dsp to the host control computer can even lead to the damage the electronic switches if the transfer happens during a high level switch state (short circuiting). This is dependant of the communication transfer type and the protection schemes used in the switch.

The interface is also used to command system loading either manually – as in the case of asynchronous requests of load power (referred in chapter IV as dynamic grid control strategy) or through a pre-programmed schedule – as in the case of peak shaving, with power control. This allows the simulation of various forms of system loading for experimental tests.

It should be noticed that the reduced power of load combinations are directly related with the maximum power capacity of the battery element. The battery is a 12 V 195 Ah unit with approximately 20 A safe maximum (C/10) which represents a current of 5 A on the 48 V bus side, that is around 250 W. Although the system is theoretically able to deliver more power regarding the battery limitations it would only be possible when renewable power is sufficient to ensure that increment. This however would be contradictory with the constant power objective and thus not considered.

The use of a common internet connection also allows not only to view the present behavior of the system but also to command the loading from a remote location (see ***Fig. 3***). This capability allows at simulating the control of the system by a network manager which is one of the requirements of grid services offering.

Fig. 4 depicts the power electronics converters.

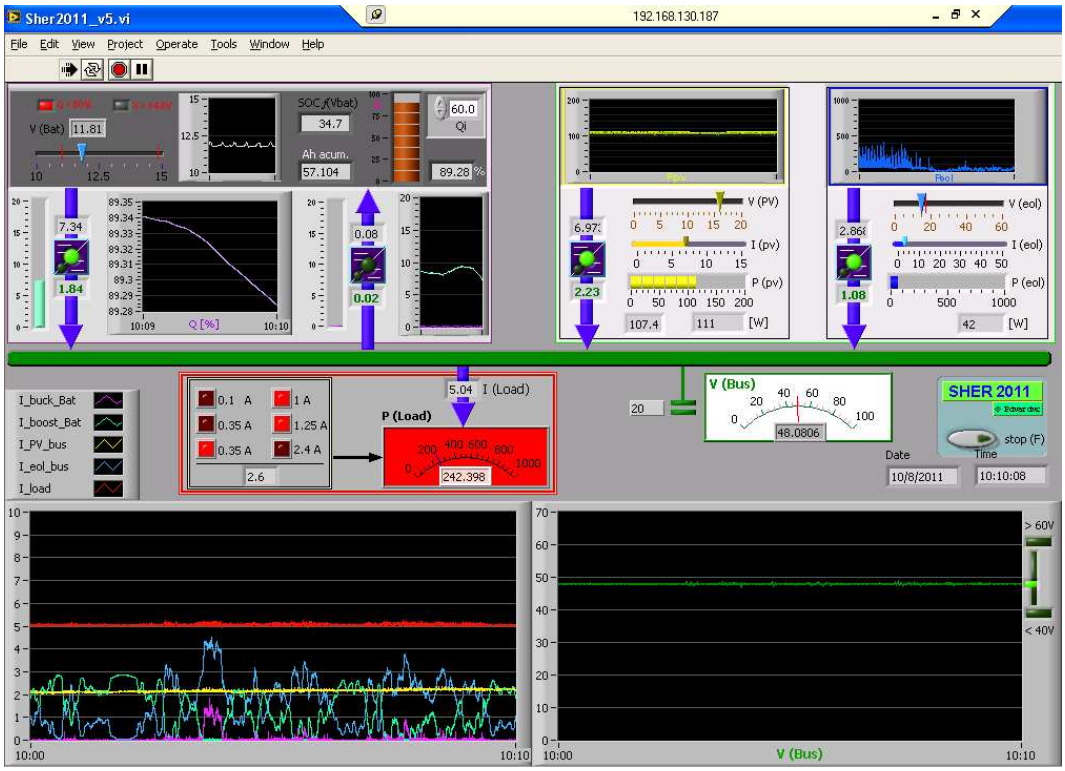

Fig. 3 – Hybrid system Labview interface

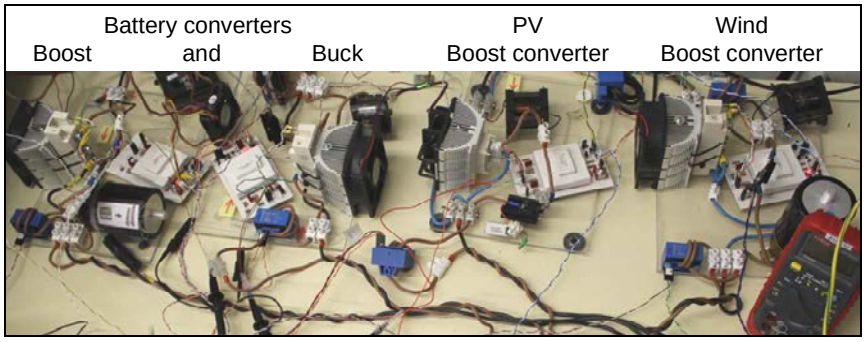

Fig. 4 - Overview of the four DC-DC converters

2 - Dynamic and control characteristics

2.1 - DC-DC converters

According to output characteristics of the wind and photovoltaic sources and battery voltage as well as the regulated voltage of the DC bus the system requires the operation of four DC-DC converters, three of them operating in stepping up and the fourth in stepping down mode. ***Table 1*** displays the main electrical characteristics.

Element	P [W]	V [V]	I [A]	Vbus [V]	Ibus [A]
Wind generator	1100	20	55,0	48	22,9
Photovoltaic	245	17	14,4		5,1
Battery	1345	12	112,1		28,0

Table 1 – Hybrid power elements characteristics

The converters are built with switches from Semikron, 1200 V IGBT's with current capacity of 100 A for the battery converters, 50 A for the wind converter and of 40 A for the photovoltaic panels. These ratings are adequate to the currents expected – ***Table 1***.

Converters include output filters: the Booster DC-DC converters use LC filters where C is the DC bus capacity; for the Buck DC-DC converter a LCL filter is adopted in order to improve dynamical behaviour.

As the stepping up action of the Booster converters is based on its operation as a current source at the input, inductances are key elements in power transfer from unregulated input to regulated output. Considering the frequency operation

of the converter some attention has to be paid to conditions of low power in the sources, which is the common condition of the average wind power as well as the case of winter and cloudy periods for the photovoltaic source.

Consequently it implies a focus on the battery contribution. In those cases to be able to transfer power to the bus it is necessary to have a high duty factor due to the voltage ratio between the battery (12 V) and the bus (48 V) voltages. Therefore to achieve the necessary gain to transfer energy from the battery to the bus within the converter frequency the Booster converter inductance has to be as small as possible in order to regulate the bus voltage with good dynamics. This implies a larger ripple in the current delivered to the DC bus as well as high commutation spikes present in it. That behaviour can be observed in ***Fig. 5*** where the IGBT's commutation spikes due to the compressed time span used in the Laview displays appear as a continuous variation of load current. This subject is detailed in the following sections.

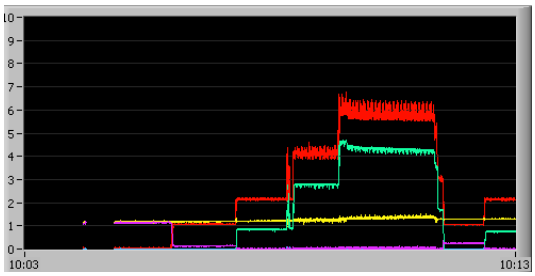

Fig. 5 – Labview currents – load (red), battery charge (light green), discharge (magenta) and photovoltaic (yellow) display

In the case of the charge converter (Buck) of the battery and in view of its current limitations as also to preserve as much as possible its life span – as the lead-acid battery is the element which degrades faster and has a relatively high cost (replacement) over the overall system – an LCL filter was implemented. The charge voltage behaviour is presented in ***Fig. 6***.

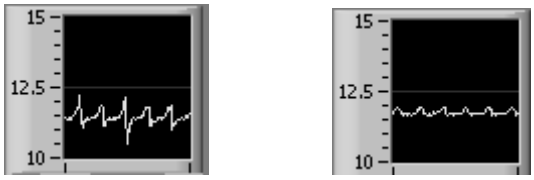

Fig. 6 – Battery charge voltage without and with LCL filter (Labview display)

Values of 20 uH for battery Boost; 48 uH, 220 uF, 170 uH for battery Buck, 25 uH for photovoltaic Booster and 50 uH for wind Booster were used in the DC-DC converters.

Converter stability can be analysed through the Bode plot for its transfer function and considering phase and gain margins.

It is only analysed the booster converter as well as related filter as the design and consequently the stability characteristic can be established by the same method.

The Bode plot for the PV booster and its filter are displayed in ***Fig. 7*** and ***Fig. 8***. The converter stability and so the dynamic behaviour is good enough as the phase and gain margins present good figures.

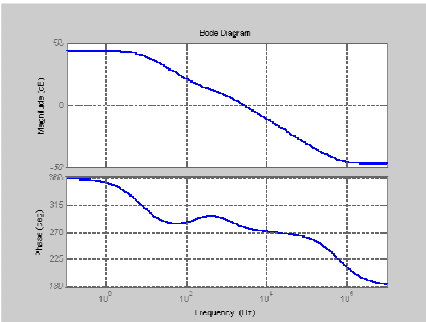

Fig. 7 – Bode plot of the converter and filter used in the PV booster (light load)

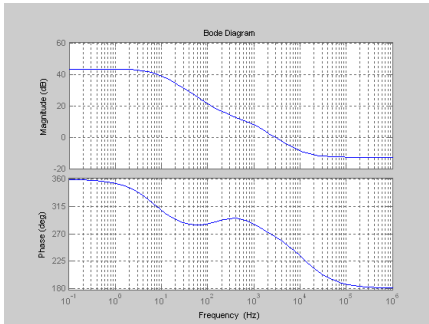

Fig. 8 - Bode plot of the converter and filter used in the PV booster

Converters are controlled by a PWM signal generated by the DSP system, based on TI TMS320F2812 microcontroller. The control is accomplished through the command of the generators converters, their duty factor established by the MPPT algorithms, as well as the DC bus voltage regulation and delivery of the pre-programmed load balancing the power flow among the different elements in operation.

A custom board to match the voltage levels of the DSP PWM outputs (0/3.3 V) with those of the IGBT drivers (Semikron SKHI22A) input (0/15 V) had to be built. It also includes switch short circuit protection as well as its error information transmission.

The following figures show the PWM waveforms that control the DC-DC booster converters interfacing the PV array (yellow) and the wind generator

(blue) to the DC bus. The current exchanged by the bus with the battery converters (negative: to the battery; positive: from the battery) is also shown (violet) as well as the load current (green).

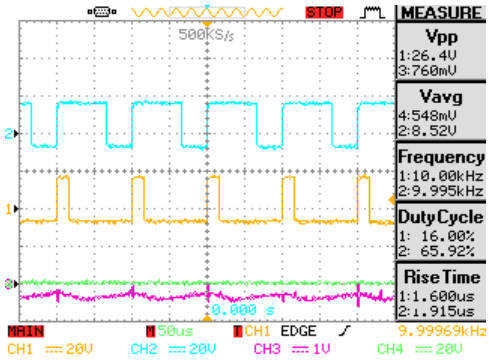

Fig. 9 – Wind and sun generation with no load

Fig. 9 shows a low duty cycle for the PV indicating its reduced generation and a load current of zero. Although the duty factor of the wind generator is high (for the reasons pointed in chapter III and related with the MePPT controller) there was no wind and therefore no power from that source. The excess of power in the DC bus is transferred to the battery. As the charging converter uses a LCL filter the current has a fairly stable behavior. The electronic switches commutation spikes are also visible in the battery current.

Fig.10 depicts the same situation type excepting that the load is now higher than the photovoltaic generated power. The power imbalance in the bus has lead to the deactivation of the previous converter and to the activation of the one that injects battery power in the bus. The voltage level difference between the battery and the bus, which led to the use of a small inductance, reflects in the delivered current that has now a more sharp profile. As it can be seen the commutation spikes reflects in the load current with a relatively higher amplitude.

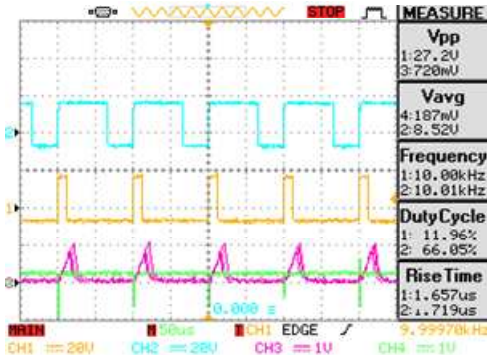

Fig.10 – Wind and sun generation power lower than loading

Fig.11 depicts the same case but now with a photovoltaic generated power approximately equal to the load power. As in the last case the spikes in the load are still exists with relatively high amplitude.

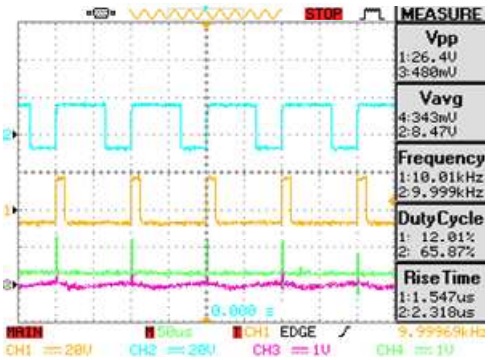

Fig.11 – Wind and sun generation slightly higher than loading

Fig.12 shows the case where the load was increased and higher than PV generation. The figure now reveals spikes in the load current for two situations: the commutation of the switch of the PV converter and of the battery booster converter.

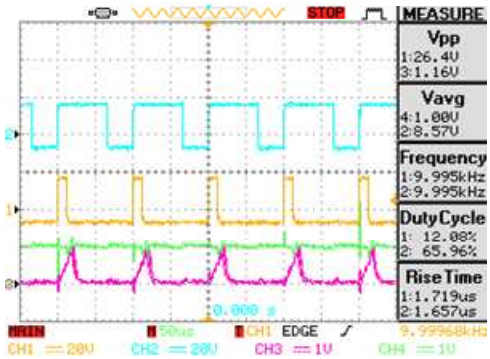

Fig.12 – Wind and sun generation lower than loading

2.2 - DC bus voltage control

The DC bus is the key element of the system performing the role of integrating all the energy sources and load ensuring the power flows demanded in the different generating conditions. This role implies to operate with regulated voltage.

If the DC bus delivers energy to a grid the bus voltage is regulated by the DC-AC converter as the grid is a regulated voltage source. In hybrid generation systems each source as well as the storage element are required to inject power into the DC bus operating at that controlled output voltage.

In the experimental platform a DC bus with regulated voltage is therefore adopted. The output voltage regulation is achieved by the battery DC-DC controllers compensated with a proportional-integral (PI) block. It controls each of the two battery connected DC-DC converters in order to deliver/extract the difference between generated and delivered power to/of the DC bus. The controllers measure the actual bus voltage at a 1 kHz frequency and through the error to the 48 V reference computes the duty factor needed to maintain the power controlled, choosing the stepping up or stepping down operation.

The computation of the necessary duty factor of the battery converters for the bus power compensation is accomplished by digital PI controllers that follow the expression:

$$D^n = D^{n-1} - \left(\left(K_1 \times error^n\right) + \left(K_2 \times error^{n-1}\right)\right) \tag{1}$$

where D is the duty factor that controls the converters and the exponent is the discretized time: n for the actual sampling and $n-1$ for the former sampling. *error* is the difference between reference voltage and actual voltage as define below. The expression is derived from the continuous PID general equation [1], without the derivative component.

The two constants K1 and K2 are computed as:

$$K_1 = K_P + \left(T_S \frac{K_I}{2}\right) \tag{2}$$

$$K_2 = -K_P + \left(T_S \frac{K_I}{2}\right) \tag{3}$$

where K_I and K_P are the integrative and proportional gains respectively and T_S is the sampling period.

The error is determined by:

$$error = V_{Ref} - V_{bus} \tag{4}$$

where V_{Ref} is the reference voltage (48 V) and V_{bus} the measured actual bus voltage.

The proportional and integral constants are 0.2 and 20.0 for Boost converter and 0.01 and 1.0 for Buck converter respectively. These gains are the values that allows to achieve a good dynamics for the bus voltage compensation in relation with the converters inductances values used.

Fig. 13 presents the DC bus voltage in a condition of null generation and null load. As it can be seen the voltage is constant regulated by the battery booster converter. ***Fig. 14*** shows the DC bus voltage behavior in response to a load step from 0 W to 300 W also without renewable generation contribution (storage response only). Bus voltage experiences a decrease of about 2 V while not compensated by the response of the battery controller. Although with a slight decrease the bus voltage remains constant around the 48 V.

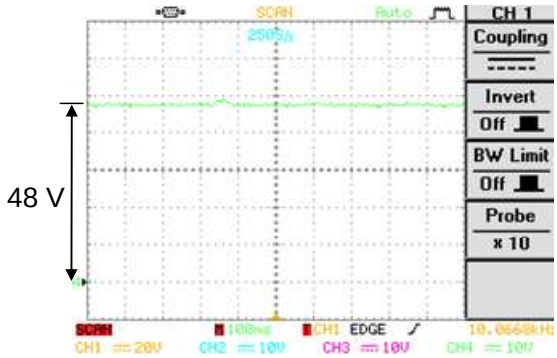

Fig. 13 - DC bus voltage in steady operation (no load change)

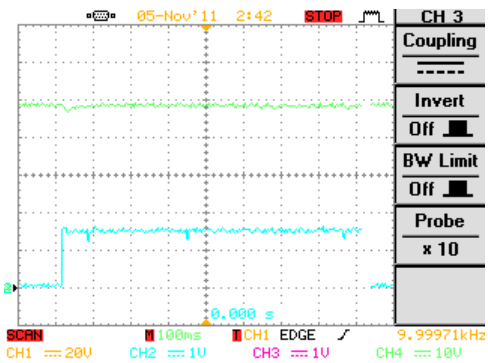

Fig. 14 – DC bus voltage (green) behavior to a load (blue) change from 0Wto 300W without renewable generation contribution

Using the Labview larger time frame capabilities ***Fig. 15*** and ***Fig. 16*** presents the DC bus voltage values for one hour. The system was not loaded and was capturing sun and/or wind energy which was transferred to the battery. The voltage has an average value of 48.01 V with a standard deviation of 0.19 V and even with the spikes the values are inside an acceptable value (-0.5 V to +1.5V) corresponding to an error of -1.0% to 3.1% in the case of ***Fig. 15***, which is the worst of the two cases.

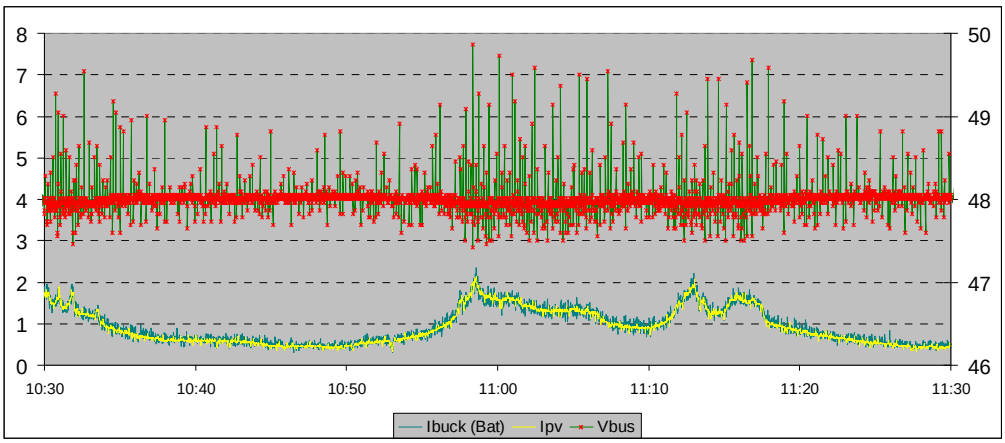

Fig. 15 – One hour display of DC bus voltage (green with red dots) and currents from PV (yellow) to battery (teal)

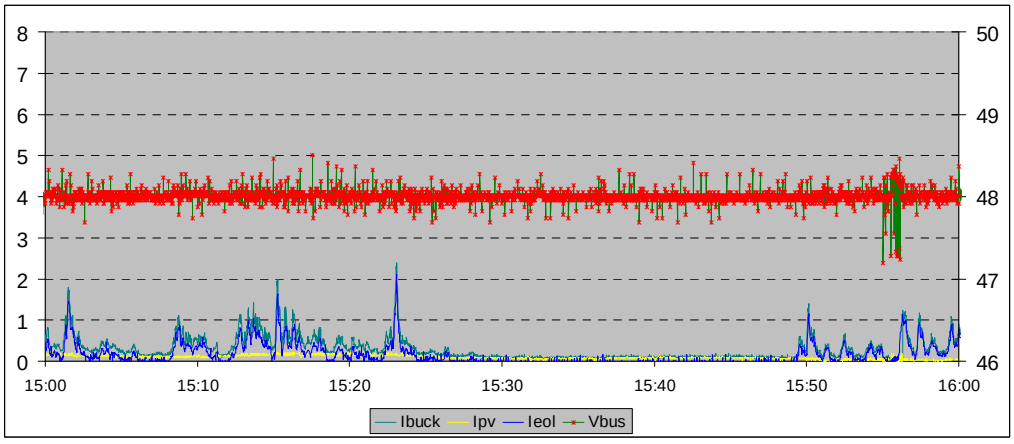

Fig. 16 – One hour display of DC bus voltage (green with red dots) and current from the wind (blue) and PV (yellow) to battery (teal)

2.3 - Generated power control

As pointed before the renewable sources are stochastic in nature. Therefore their variability introduces changes in the generators operating conditions. So the system must take care of them to maximize the gathered renewable power.

The use of a MPPT schemes allows at maximizing the extracted power from the renewable sources. As analyzed before, there are different algorithms performing the role. In the present system fuzzy controllers are adopted.

Due to the relatively high number of rules that must be coded as permanent variables, demanding for a large memory space, decision to transfer the fuzzy controller from the DSP to a secondary computer was taken. As the sun conditions vary slowly and the wind generator inertia also implies a time constant in the order of several seconds the solution has a reduced effect on tracking the maximum power.

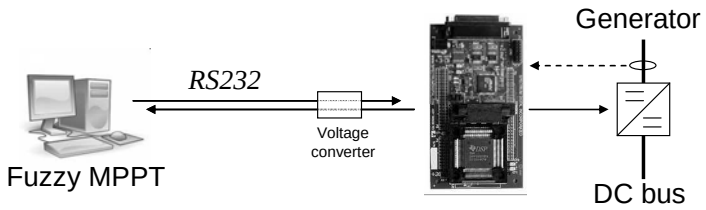

Fig. 17 – Generators Fuzzy power control decentralization

A custom board with an integrated circuit (MAX3232) was built to allow the interconnection of the serial interface of the DSP (SCI) to a running Windows computer, through a standard RS232 connection (see ***Fig. 17***). The used transfer speed used is 34200 baud in order to reduce the communication time while maintaining the error of clock differences in 0.06% (not covering errors due to noise and other factors).

The fuzzy MPPT algorithm is worked out with a period of one second for the photovoltaic and five seconds for the wind generator. The 'long' five seconds update period of the MPPT of the wind generator is related with the time constant of the generator and the algorithm used to implement it – MePPT. Due to the high wind turbulence at the generator site[1] – presented in ***Fig. 19*** and ***Fig. 20*** – and large turbine inertia, for most of the experiments a fixed duty factor for the wind generator is used.

[1] Near tall trees of a military compound in a small valley field

Fig. 18 – Wind generator location (perspective erroneous shows wind generator higher than trees)

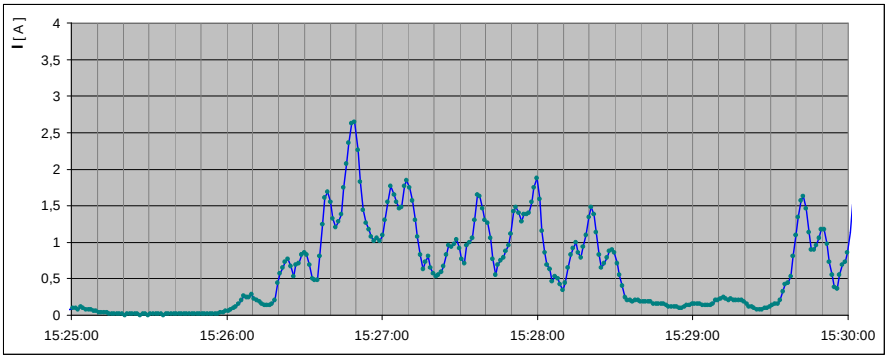

Fig. 19 – Local wind dynamics

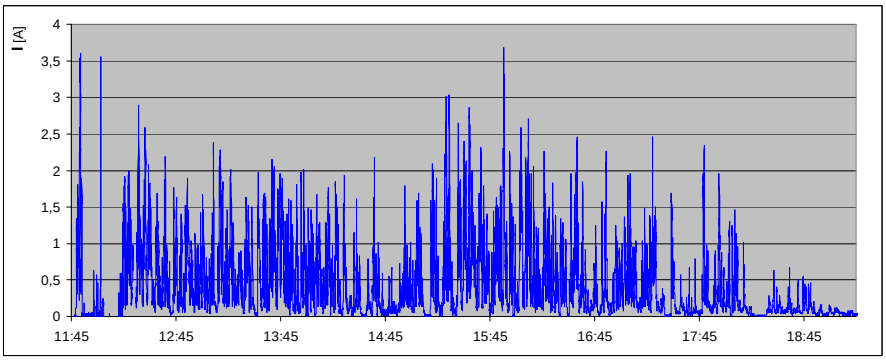

Fig. 20 – Local wind dynamics (several hours)

To avoid the commutation glitches on the voltage/current values caused by the DC-DC converter commutation a delay before sampling of voltage and current, necessary to compute the duty cycle of the converters to achieve the maximum power, is implemented. A measure of the time to settle is taken and this value transformed in a dummy delay before the actual ADC sampling and conversion.

```
for (i=0; i<N; i++) {;}
get_adc_values();
```

With each iteration taking approximately 133 ns, N was defined as 15 giving a delay of 2 us.

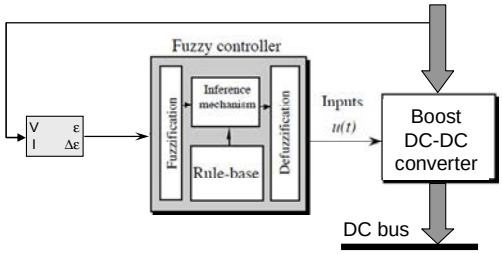

Fig. 21 – Fuzzy MPPT controller

The fuzzy algorithm takes the error ($\varepsilon_k = \dfrac{P_k - P_{k-1}}{V_k - V_{k-1}}$) and change of error ($\Delta\varepsilon_k = \varepsilon_k - \varepsilon_{k-1}$) of the PV power using five membership functions for each input and five memberships for coding of the output – the duty factor for the converter. The fuzzy controller (***Fig. 21***) seeks to reach an null error (MPP where *d*P/*d*V = 0 – see ***Fig. 22***) with the sign of error defining the right or left side from the MPP and with the sign of change of error defining if the iteration is approaching or moving away the operating point from the MPP.

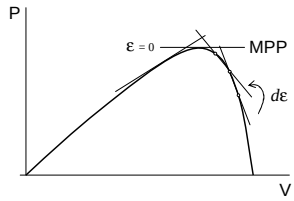

Fig. 22 – PV power curve and fuzzy inputs

The fuzzyfication of the inputs is made through 5 triangular shape membership functions, from left to right: NB, NS, Z, PS, PB, for both the inputs and the output. N means negative, P means positive, B means big, S means small and Z means zero.

		dε				
		NB	NS	Z	PS	PB
ε	NB	Z	Z	PB	PB	PB
	NS	Z	Z	PS	PS	PS
	Z	PS	Z	Z	Z	NS
	PS	NS	NS	NS	Z	Z
	PB	NB	NB	NB	Z	Z

Fig.23 – Fuzzy rule base

The table of ***Fig.23*** implements the inference between the inputs and the outputs driving the operating point to move towards the MPP. For instance, if the operating point is in the right side of the power curve and is moving to the right – ε(t) = Nx and *d*ε(t) = Nx (where x means either B or S) – then the output is Z, that is the operating point tend to stop near the last point. This condition makes ε(t) to stay Nx but now *d*ε(t) tends to be Z. This present condition makes the output to be Px, which implies an increase of the duty factor that, applied to the booster converter, makes the operating point to move to the left towards a increase of the power (reducing the voltage and increasing the current).

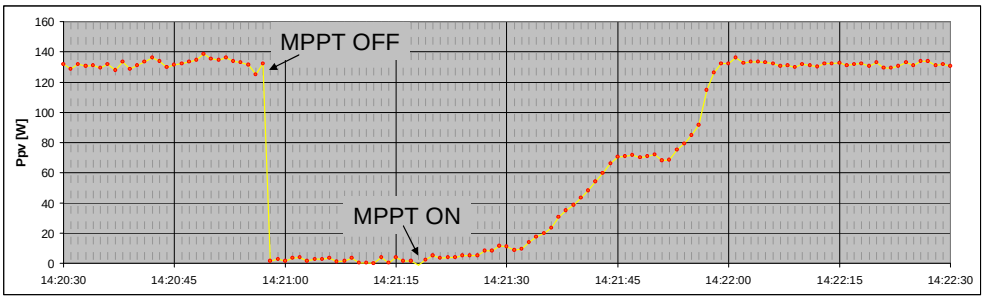

Fig. 24 – Fuzzy MPPT operation

Fig. 24 shows that the PV MPPT tracks correctly the maximum power operating point increasing the power until returning to the maximum power level. The results were taken turning off the MPPT and turning it on again to observe the behavior of the fuzzy controller. The display is made in Excel based on the values stored in file by the Labview interface since it is a relatively slow process.

Individual PV power-voltage characteristics are showed in ***Fig. 25*** and the parallel connection power voltage characteristic curve in ***Fig. 26***. These results are obtained varying linearly the duty factor from 0% to 85% (allowed maximum for switch protection) and obtained from the data saved on file by the Labview interface and created with Excel.

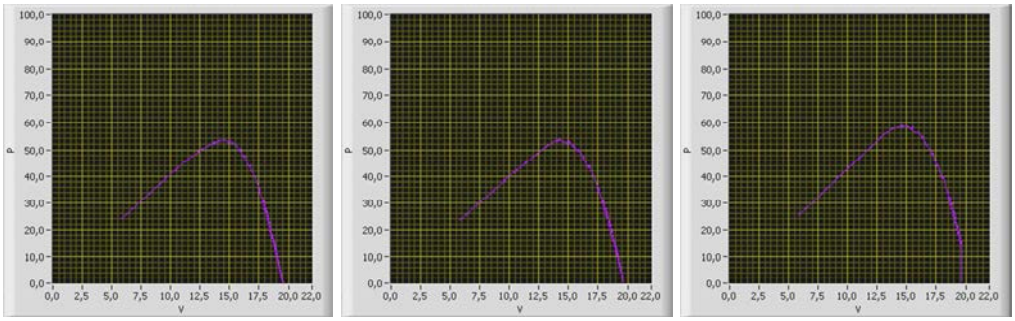

Fig. 25 – Power vs Voltage characteristic curves for each of the three PV panels used – displays taken with Labview interface for consecutive duty cycle variation from 0 through 0.85.

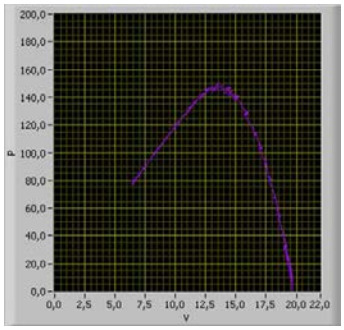

Fig. 26 - Power vs Voltage characteristic curve for the three parallel connected PV panels used

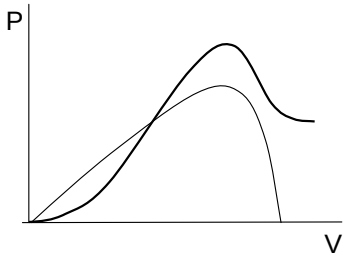

Fig. 27 – Power versus Voltage curves shapes for PV and wind generator

The MPPT controller for the wind generator uses the same fuzzy controller with different membership values since the shape of the power curve is approximately the same as can be seen in ***Fig. 27***. The difference would be the triggering time: fixed in 1 second for the PV and a function of the DC power for the wind power. The wind MPPT mechanism is presented in chapter 3 and is based on the wind generator DC power output. A new duty factor is computed when the power produced following the previous duty factor change settles in a constant value. Tests on the wind generator showed a delay between the change of operating conditions (converter duty factor change) and the settle of the new

generated power governed by the generator inertia in the order of the 5 seconds. The MePPT mechanism changes the operating conditions increasing or decreasing the duty factor and waits for the DC power generated to be stable to move to the next MPPT iteration. This scheme is operational if the time constant of the wind speed change is larger than the inertia time constant.

Experiments with the MePPT are presented in a Code Composer Studio display (TI DSP programming environment) for a time frame of 45 seconds - ***Fig. 28***. The wind speed was taken from a wind sensor, located in the mast of the wind generator for test purposes. It can be seen the increase of power in response to the variation of the power converter duty cycle, but only when the wind speed is relatively constant otherwise the dynamics of the wind change overcomes the MePPT control. While the particular location of the wind generator does not favour the operation, a less turbulent wind location makes the MePPT a contributor to the maximization of the gathered wind.

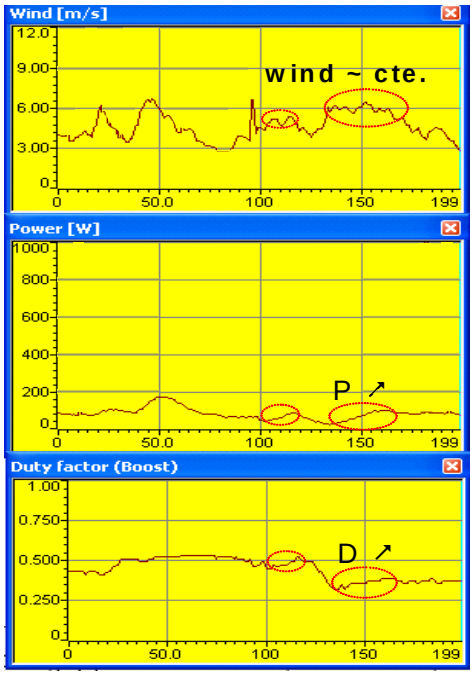

Fig. 28 – Experiment results with DC MPPT

3 - Validation of the system operation

In order to attenuate the effects of the oscillating over-voltages caused by semiconductors commutation, a secondary bus with a capacitance of 6.9 mF connected to the primary bus through a low inductance is used. The voltage wave form from both buses is shown below along with the PWM pattern (yellow) controlling the PV array generating about 100 W and without loading the system.

As it can be seen the secondary bus attenuates the turn-on and turn-off gradient spikes of the PV generator presenting a more stable voltage to the load. Average behaviour of the secondary bus voltage is depicted in ***Fig. 29*** and ***Fig. 30***. The bus voltage presents oscillating over-voltages related to semiconductors switching transitions and a ripple in the order of 0.4 V.

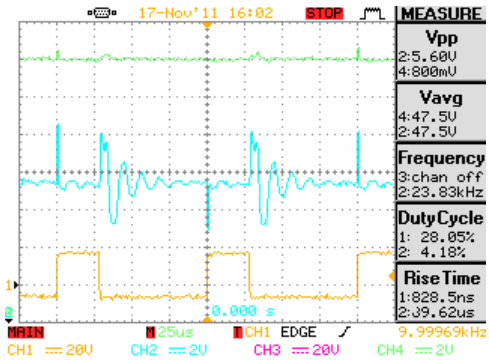

Fig. 29 – Primary (blue) and secondary (green) bus voltages with PV generation

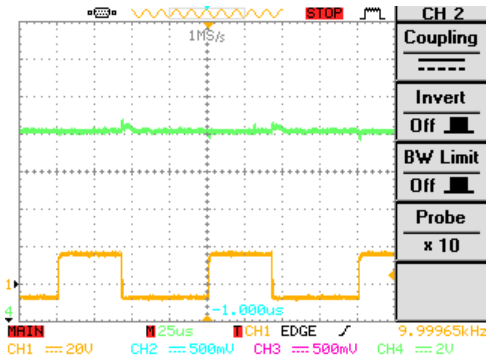

Fig. 30 – Secondary bus voltage (green) and PV PWM switching signal (yellow)

The IGBT turn on and turn off effects on the bus voltage can be observed in more detail in ***Fig. 31***.

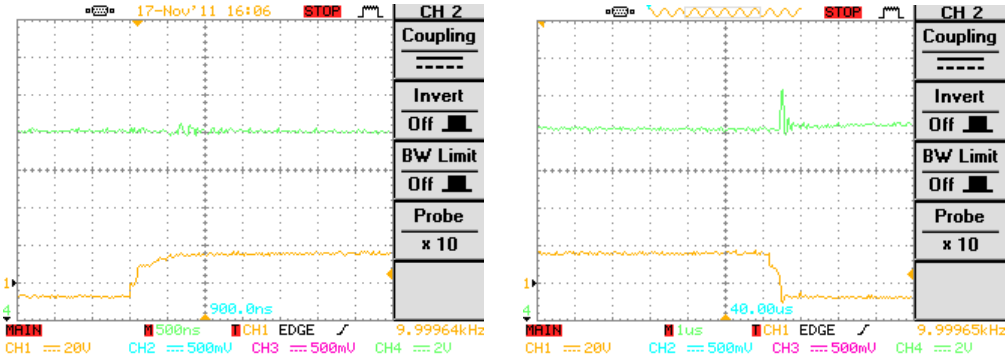

Fig. 31 – Switch turn-on/off effect on the bus voltage (green)

The effect on the bus voltage (green) and on the PV array current generated (blue) is depicted in ***Fig. 32***

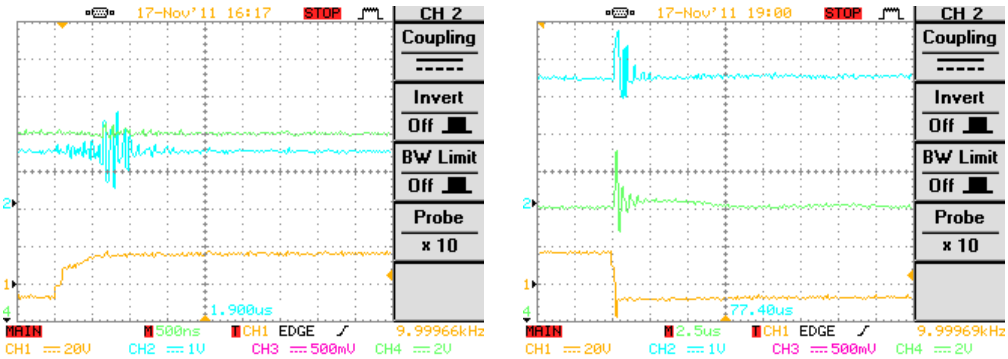

Fig. 32 – Turn-on/off effect on the bus voltage (green) and PV current (blue)

From these displays it can be observed that the turn-on/off of the switch generates glitches that must be taken in consideration at the sampling/conversion of voltage/current values for the MPPT and power control to avoid obtaining erroneous values. The analysis of the displays shows a relatively longer effect off the turn-off – about 2 us (***Fig. 33***) – and therefore that is this time that will be taken in consideration. This time is integrated in the control of the system by adding a software delay of approximately 2 us before actual sampling and conversion.

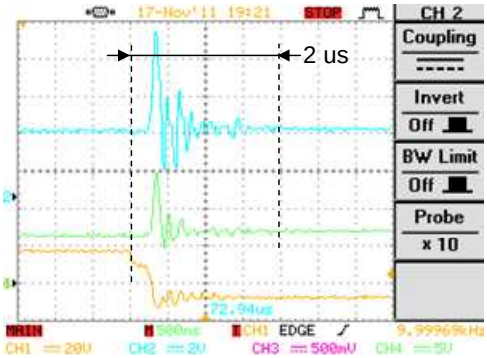

Fig. 33 – Turn-off effect on the voltage and current from the PV (both quantities taken from the PV side of the converter)

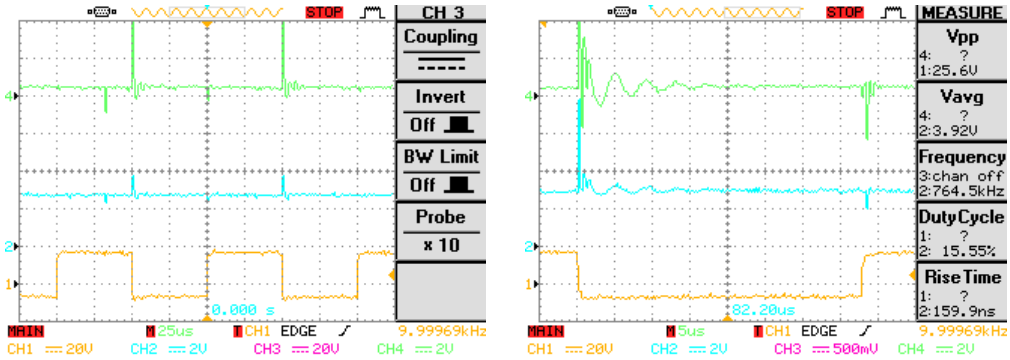

Fig. 34 – Currents from the PV array – PV side (blue) and bus side (green)

Fig. 34 shows the currents of the PV array at the PV side (blue) and at the bus side of the converter (green). The bus side has a relation of 1 V to 2.5 A which means a glitch in the order of 5A at the moment of turn off and of 1 A in the turn on and a negligible DC ripple. The PV side has a relation of 1V to 16.7 A which means a glitch in the order of 10 A at turn off and 3.33 A at turn on also with a negligible DC ripple. The smaller glitches appearing at a ratio of approximately 32% are due to the turn off of the battery buck converter working to transfer the excess of power from the bus to the storage unit. This PWM wave is not showed in the display due to the used converters topology and system architecture which would cause a short circuit since the voltage references of the oscilloscope are all the same.

The switching effects by the generating (PV) and storage units also appear in non working units as the load current as can be observed in ***Fig. 35*** and with more detail in ***Fig. 36***.

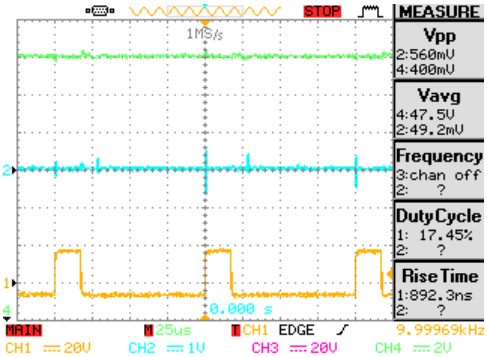

Fig. 35 – Switch commutation effect on null load current (blue) and bus voltage (green)

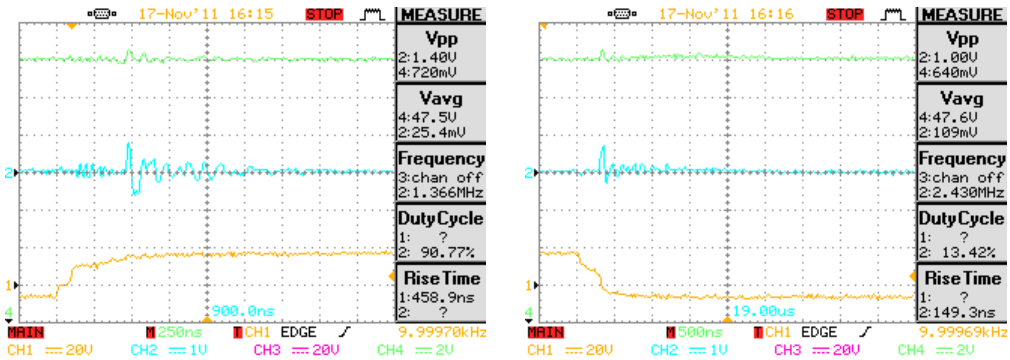

Fig. 36 – Switching effects on load current (blue) and bus voltage (green)

The spikes in the load current correspond to a current variation of 3.5 A

Fig. 37, ***Fig. 38*** and ***Fig. 39*** show the system response to three different loads, respectively 50, 115 and 173 W. Bus voltage remains at steady-state regimen with a ripple from 0.1 V to 0.2 V in the first and third case respectively. The load current presents a DC ripple of 0.15 A to 0.2 A in the case of 50 W and 173 W respectively.

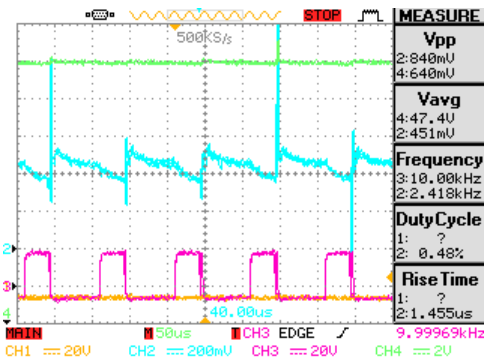

Fig. 37 – System with 50 W load (blue), without renewable generation (yellow) and storage (magenta) operating to deliver the power to the load through the DC bus (green)

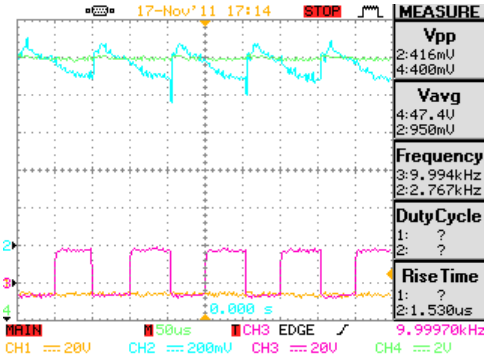

Fig. 38 – System with 115 W load (blue), without renewable generation (yellow) and storage (magenta) operating to deliver the power to the load through the DC bus (green)

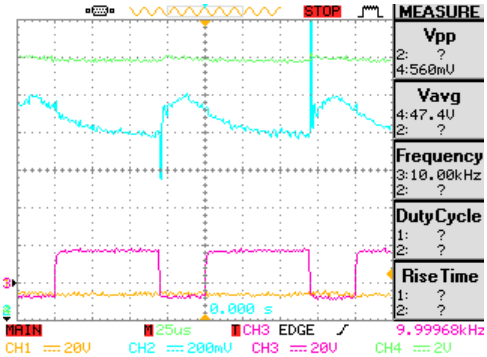

Fig. 39 – System with 173 W load (blue), without renewable generation (yellow) and storage (magenta) operating to deliver the power to the load through the DC bus (green)

While in fact existing, the fast spikes caused by the physical commutation of the switches (IGBT and diodes) are not a major obstacle to the correct functioning of the system as the DC components demonstrates. They could nevertheless be controlled by appropriate snubbers but as the present work is not fundamentally related with the electronics particularities it was not treated. They nevertheless appear in the long term displays as the used in the Labview interface that could lead to erroneous interpretation of the behaviour of the hybrid power system. Therefore "hiding" those spikes through filters shows a system that behaves correctly managing the input and output energy and maintaining the system controlled in the presence of renewable generation fluctuations.

The dynamic characteristics of the system with both generators producing and with a load consuming are presented in the following displays (***Fig. 40*** to ***Fig. 42***).

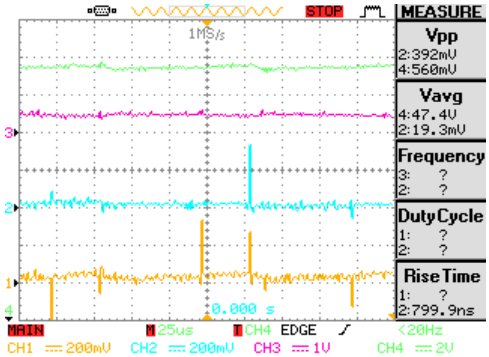

Fig. 40 – System with reduced renewable generation (PV and wind) supplying a 50 W load. Bus voltage (green), load current (magenta), wind current (blue) and PV current (yellow)

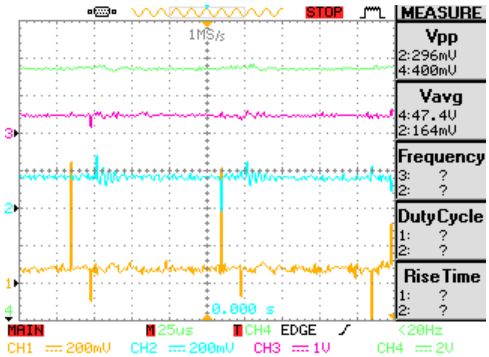

Fig.41 – System with PV and wind production supplying a load with 50 W (1.1 A). Bus voltage (green), load current (magenta), wind current (blue) and PV current (yellow)

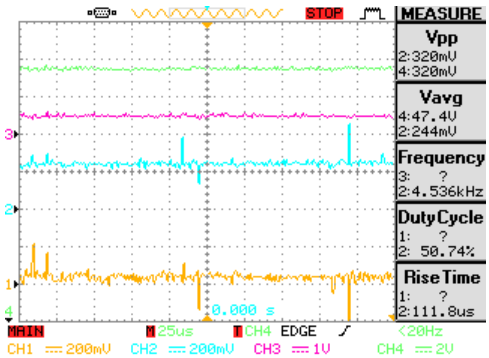

Fig. 42 – System with PV reduced production and wind supplying a 50 W load. Bus voltage (green), load current (magenta), wind current (blue) and PV current (yellow)

The previous displays show the voltage in the DC bus and the current to a load which remain constant for different values of renewable generation.

Fig. 43 shows the behaviour of the system with renewable generation – wind and photovoltaic – and loading for a time of 7 minutes. Data collected in the Labview interface (1 second period) and the display created in Excel. Load consisted in two constant values 225 W and 115 W respectively higher and lower

than the sum of PV and wind generation. As referred before, data was filtered at the input of the Labview interface to hide the spikes showing therefore only the DC value. The change of load was accomplished through the interface at 14:55:05. Consistent with the former displays taken with the oscilloscope the bus voltage and the power delivered to the load remains constant while the wind variation caused renewable generation to fluctuate causing either excess either deficit of power in the bus. The battery controllers take care of that difference with the battery delivering the deficit and storing the excess. The change from charge (DC bus excess power) to discharge (DC bus power deficit) appears in a smooth way not reflecting it in the bus voltage neither in the load power. ***Fig. 44*** shows about the same context but with continuous load stepping in order to demonstrate the storage control capabilities to follow continuous differences of load.

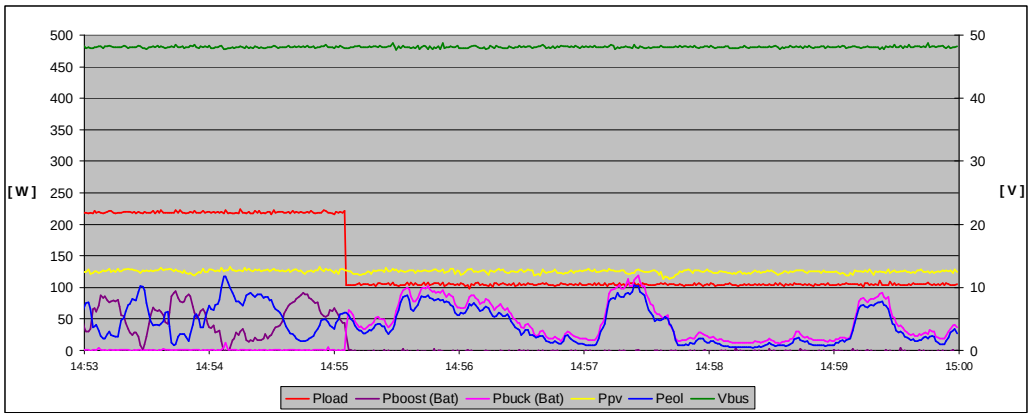

Fig. 43 – Long term behaviour of the system with timed constant loading and renewable generation

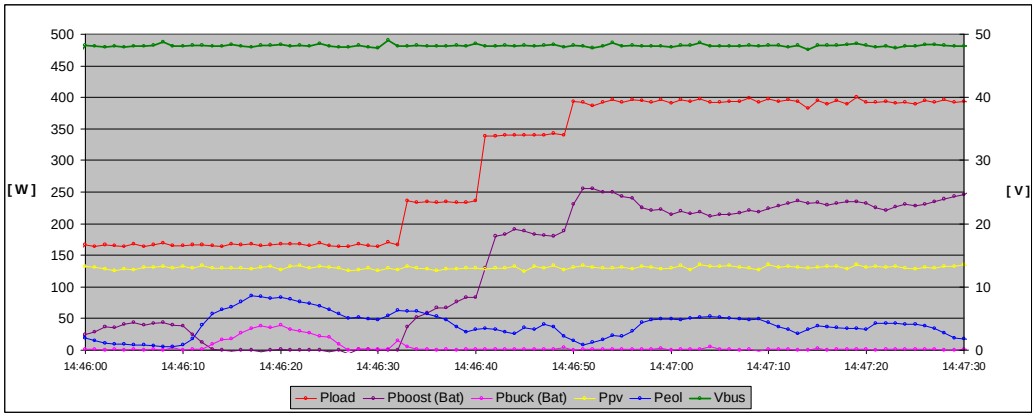

Fig. 44 – Long term behavior of the system with step loading and renewable generation

The analysis of the former waveforms demonstrates the ability of the system to solve the two renewable inputs floating generation through the control of the DC bus voltage associated with the two battery converters in maintaining a constant power delivered to the load.

The system also responds adequately beside the input fluctuations to changes in the load power therefore showing the characteristics needed to become a controlled and controllable generation unit.

The present analysis allows accepting the experimental platform as adequate to validate a controlled power generator. The next chapter is directed to test the system under several operation conditions and strategies related to its performance as a controlled power generator.

References

[1] J. Murphree, B. Brzezinski, J. Parker, “Using a Fixed-Point Digital Signal Processor as a PID Controller”, Proceedings of the 2002 American Society for Engineering Education Annual Conference & Exposition, 2002

Chap. VI – System performance

As stated in previous chapters modern hybrid power systems are intended to be able of transforming stochastic power in deterministic power and energy. This capability aims at increasing the grid power quality and enlarging the potential of offering grid services. Both characteristics leverage the economic value of distributed generation systems not only because they can present stable and known power delivering but also because they allow an owner to be free to deliver power when he considers it beneficial. A renewable sources based hybrid power system which is controllable is well fit to political trends toward energy independence and to the environmental concerns while providing an answer to technical concerns from the grid operators.

Considering this framework several operation strategies are possible with the present hybrid system. These strategies have already been presented in chapter IV and are recalled briefly here:

- The selling of renewable energy in a constant power format (day ahead market energy selling with constant power delivering).
- The reduction of the energy acquired from the grid in a constant/not constant amount format, the hybrid system providing the difference from the local necessity (peak hour's energy shaving).
- Satisfying extemporaneous requests of energy from the grid (spin reserve service like).

The referred operating strategies can be tested through:

- The ability to provide a constant power over a pre-defined period even when the renewable sources are floating.
- The ability to change delivered constant power without affecting its quality.
- The ability to manage renewable gathered energy so that it is available when needed.
- The ability to forecast the inaptitude to maintain the expected deliverable power.
- The ability to satisfy extemporaneous power requests in unscheduled times (although with previously agreed maximum energy).

Tests to assess these capabilities are conducted with real meteorological conditions and controlled load changes. The load changes are performed in a pre-programmed form in order to simulate real operating conditions of external and/or previously agreed (contracted) load requests. The loading is applied, when applicable, following the commercial conditions of tariffs and correspondent timing: higher power at peak hours followed by medium power over full hours. In all delivering periods the power is intended to remain constant and equal to the pre-defined value. The deliverable load power amounts encompass several possible associations of 5, 17, 48, 115 and 173 W the maximum attainable power being the sum of all (374 W). This last value is conditioned by the actual lead-acid battery capabilities.

Displays shown are built in Excel and are based on results acquired and saved by the Labview data acquisition interface. Because these displays have a large time frame the resultant time compression shows the spikes mentioned in chapter V as a large value ripple. This note is evidenced in ***Fig. 1*** for the photovoltaic case and analogous to other variables shown in displays.

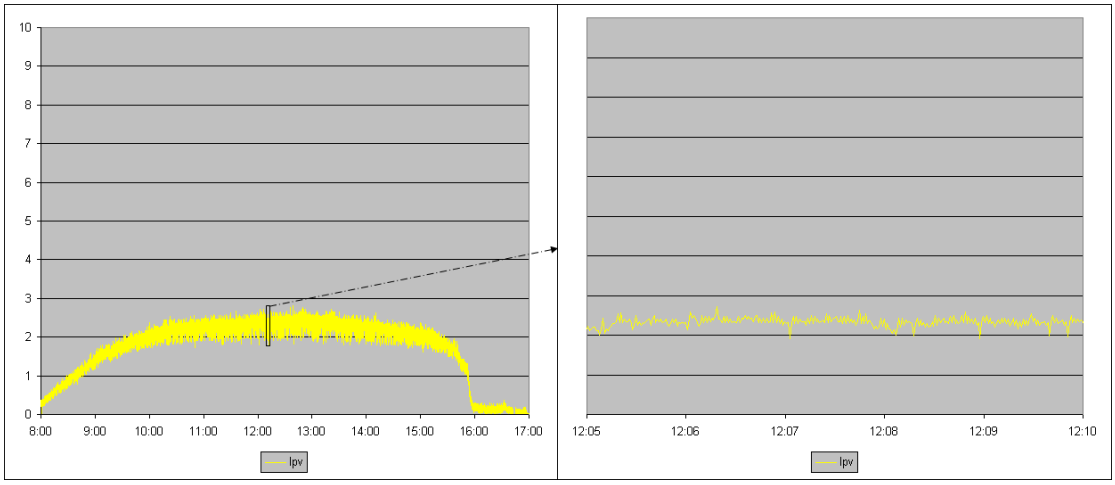

Fig. 1 – Commutation spikes and the large ripple resultant of time compression and detail for a narrower time frame

1 - Pre-programmed stepped load

The present experiment consists in supplying two hours with a constant power of 160 W and twelve hours with a constant power of 50 W. The rest of the time the loading is zero. The first value is related with peak hours and is further divided in two periods of

time: from 09:00 to 10:30 and from 18:00 to 20:30. The second value is related with full hours and is further divided in three periods: from 08:00 to 09:00, from 10:30 to 18:00 and from 20:30 to 22:00. These values, both pre-programmed and delivered, are depicted in ***Fig. 2***. The period initial capacity of the battery is 92% (Q_N = 195 Ah) thereafter allowing to deliver a higher energy amount value than the pre-programmed value for the experiment day.

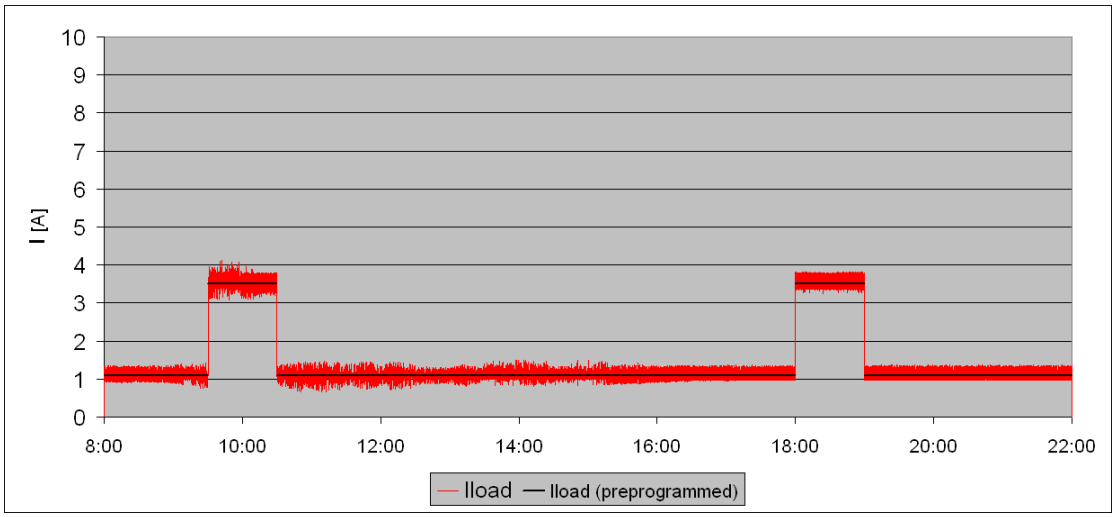

Fig. 2 - Pre-programmed (black) and delivered (red) load

The aggregated results of all relevant values are presented in ***Fig. 3***. The experiment is performed in late fall in a windless and cloudy sky day. The renewable sources gathered power and the behaviour of the battery power transfer are depicted in ***Fig. 4***. Several relevant details of the running operation of the HRES are displayed in ***Fig. 5*** through ***Fig. 8***.

Without accounting for the spikes, the delivered power that was scheduled is respected (see also ***Fig. 3***). The floating PV power behaviour is followed by the battery controllers/converters with the battery charging and discharging as needed to maintain the bus voltage and load power constant. The constancy of the bus voltage and load current during the power excursions of the PV, the changes from charging to discharging of battery power and changes of load power is evidenced in ***Fig. 5*** to ***Fig. 8***.

As the scheduled load energy has revealed to be higher than the actual gathered renewable energy the charge of the battery decreases to 66%.

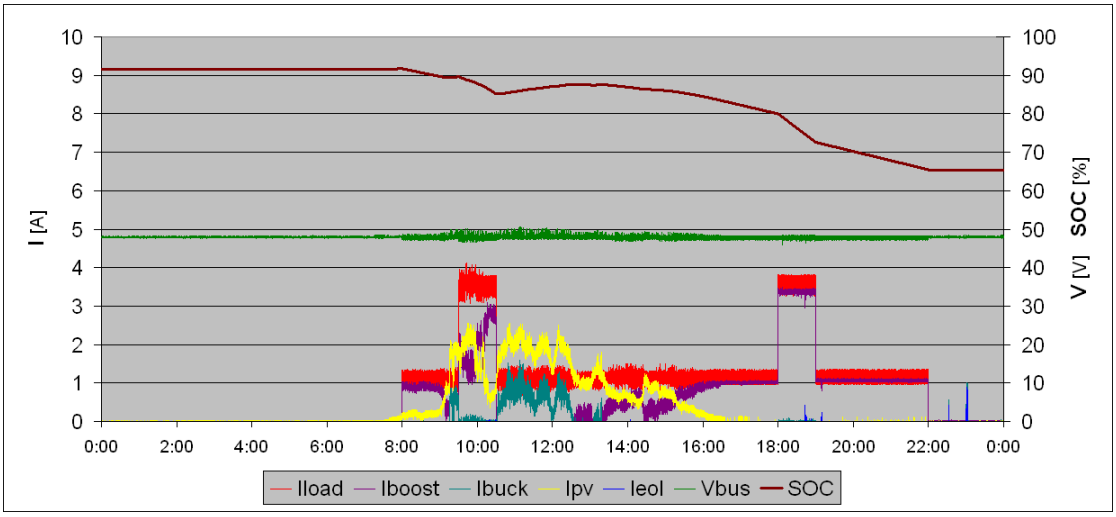

Fig. 3 - One day with preprogrammed load (red) of 50W from 8:00 to 9:30, 10:30 to 18:00 and 19:00 to 22:00 and 160W from 9:30 to 10:30 and from 18:00 to 19:00 with varying sun (yellow) and wind (blue) current generation. Battery current compensation with charge (teal) and discharge(violet), battery state of charge (brown) and DC bus voltage (green) are also diplayed..

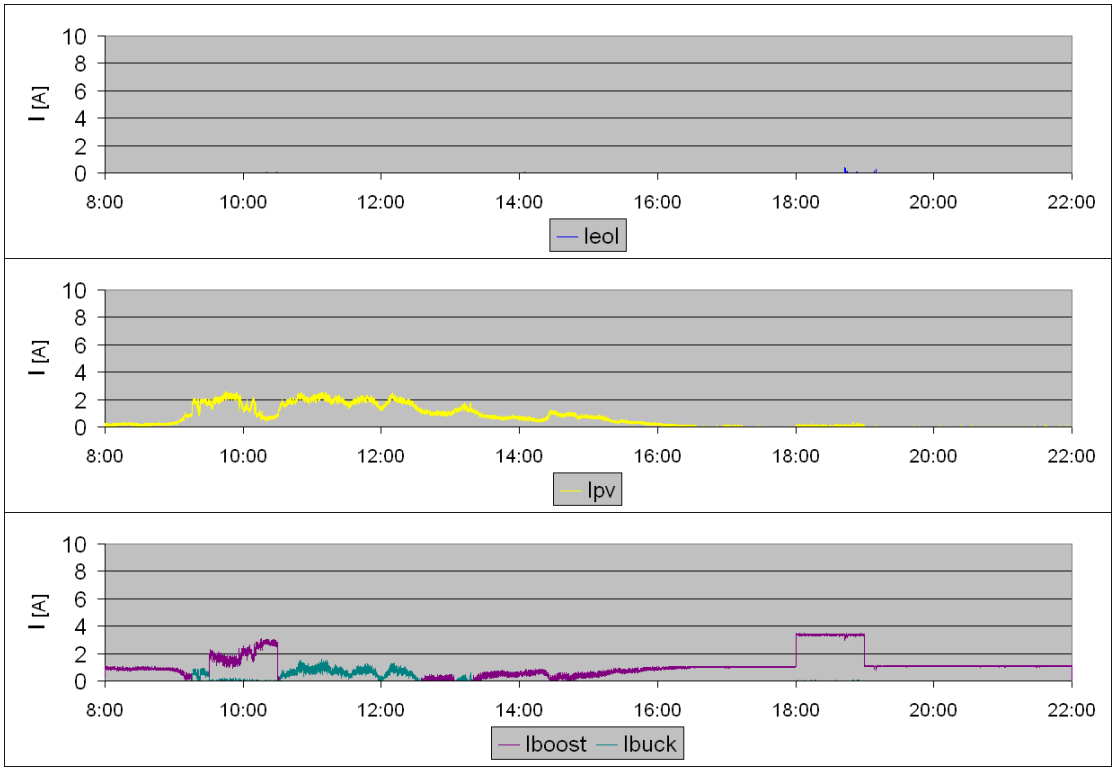

Fig. 4 – Windless, photovoltaic and battery currents for the time frame related with the load supply

The experiment demonstrates that a hybrid controlled power system is able to manage the stochastic inputs and to present a controlled and known pre-defined power to a load. The power and energy objectives are therefore attained.

Also, while reducing its charge more than expected – the optimum being the renewable equal to the load energy – the battery is able to fulfil an important technical/quality requirement that is to avoid unexpected supply disruption (in the sense of interrupting the expected scheduled power). This last type of situation has been one of the characteristics of uncontrolled renewable based power generators and one of the obstacles to the spreading of this type of systems. The effect of this decrease in the storage charge would be a lowering of the energy available for the next supply period.

Any way, a good balance in battery SOC at the end of day, allowing charge during the night with wind energy, is the key issue for this approach. It is always possible to forecast the energy available for the day after, the approaching being improved if it is performed by a good very short-term forecast technique for the wind and sun in next day.

Nevertheless, this situation has the advantage of the HRES being able to notify in advance the load/grid manager of that condition and allowing him to take adequate measures.

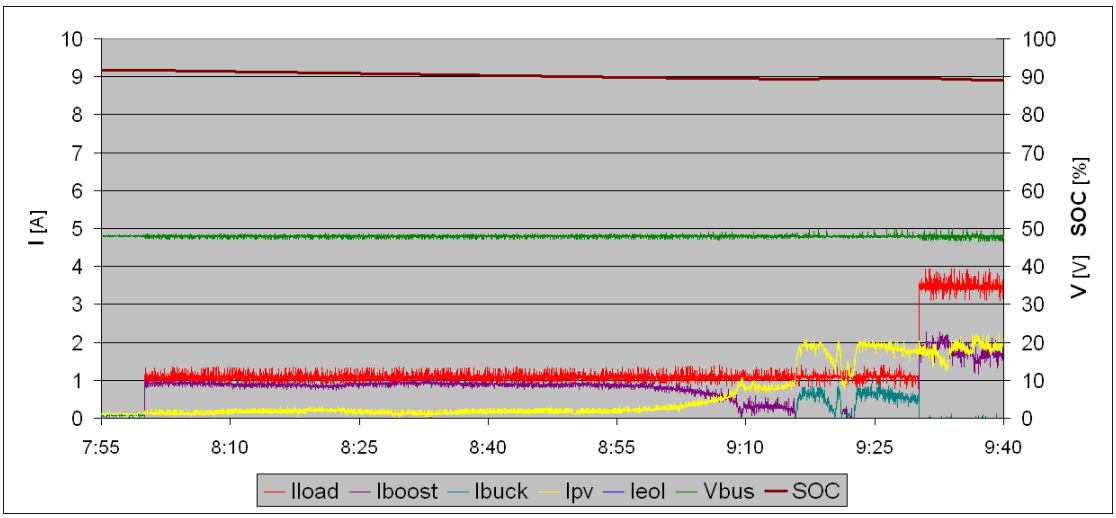

Fig. 5 – Details of an increase in step load (red) with battery charge (teal) to discharge (violet) changing in function of photovoltaic generation (yellow). DC bus voltage (green) and SOC (brown) of the battery also shown

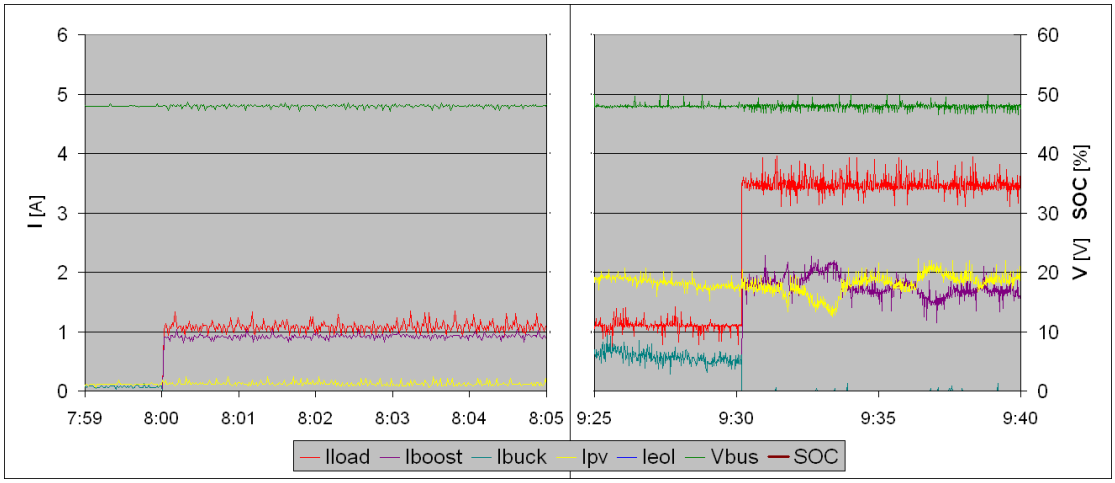

Fig. 6 – Detail of the average and spikes values. Bus voltage (green), charge (teal), discharge (violet) and photovoltaic generation (yellow) for a load (red) step increase

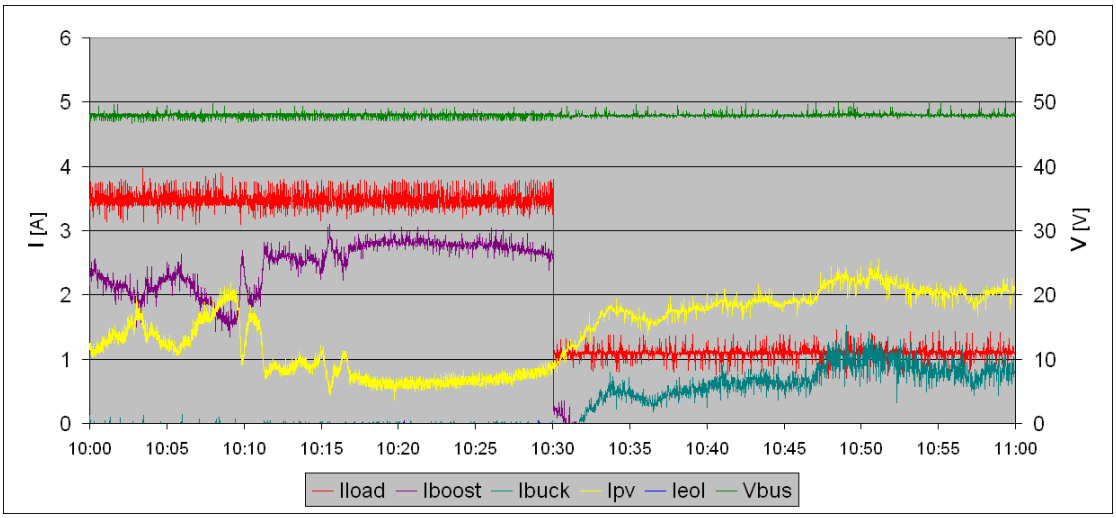

Fig. 7 – Detail of a decrease step load (red) with change of the battery discharge (violet) to charge (teal). Photovoltaic generation (yellow) and bus voltage (green) also displayed

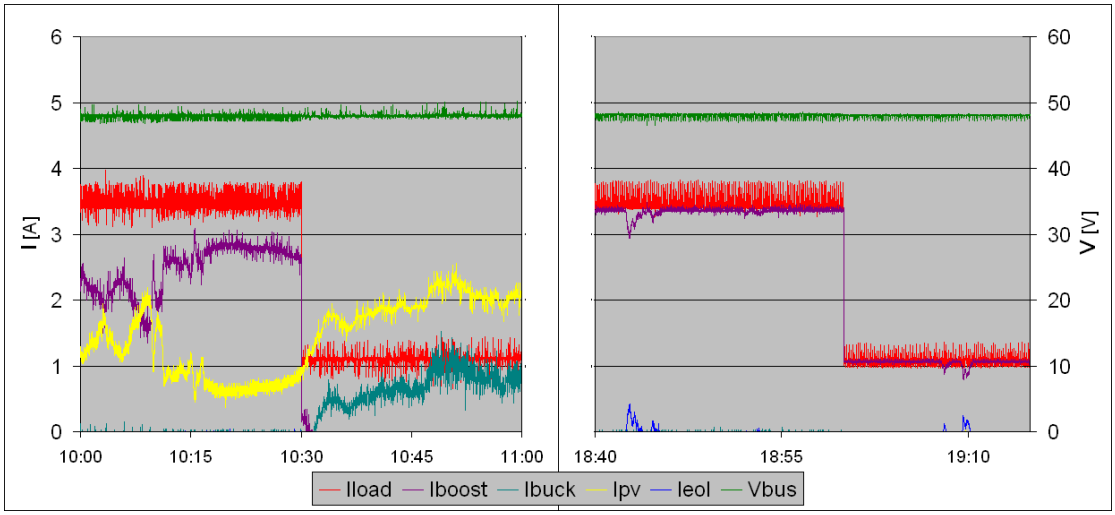

Fig. 8 – Detail of the average and spikes values. Bus voltage (green), charge (teal), discharge (violet) and photovoltaic generation (yellow) for a load (red) step decrease

In order to be able to satisfy the preprogrammed load and taking in consideration that it was not expected wind in the day, the previous day was dedicated to store enough energy in the battery – ***Fig. 9***. Load was activated only to avoid the lead acid battery voltage rise higher than the manufacturer recommended values.

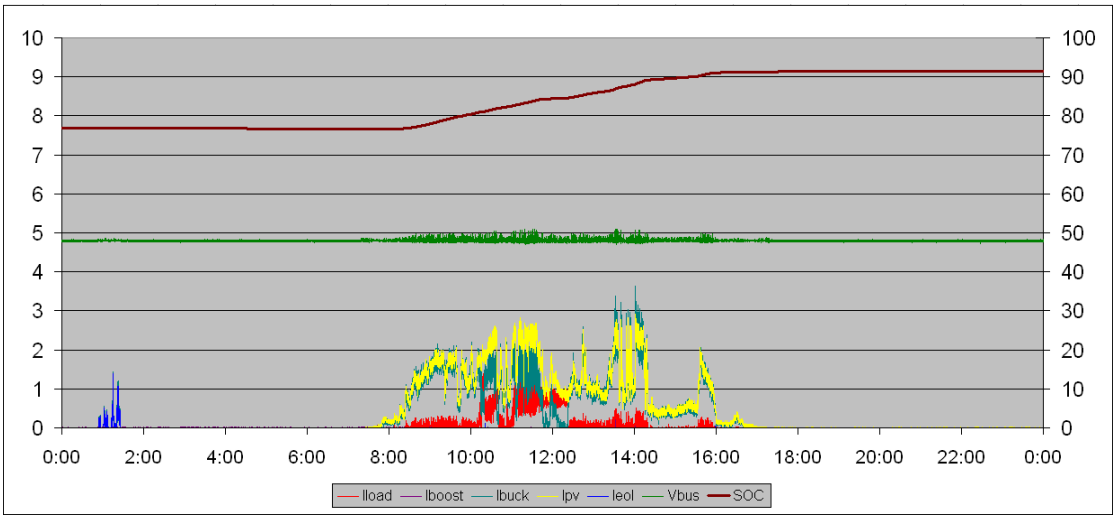

Fig. 9 – On day charging only to store enough energy for next day pre-programmed load

In order to show system behaviour with both renewable sources active another experiment is performed. ***Fig. 10*** shows the system behaviour in a day with wind and clouds and ***Fig. 11*** shows the details of the wind and sun currents generation and the charge and discharge currents of the battery.

Load was activated during the day with the following characteristics: 9:00 to 10:00 with a light load then with a fast and brief load at 10:15 then with a very light load until 15:15 and again with stepped load from until 16:45 (see ***Fig. 12***). This loading is performed in order to analyze the HRES reacting to changing in both renewable inputs along with load changes. ***Fig. 13*** shows system behaviour faced to a relatively intense and highly variable wind and sun variation by clouds. In this time frame there is no load active and the battery controller is taking care of the highly fluctuating generated power, charging the battery. The DC bus voltage remains constant as the battery controller takes care of the power generated.

The behaviour of the system with both the power sources generating and a load being supplied is presented in ***Fig. 14***. While with a less intense but still variable wind and sun the system maintains the bus voltage and therefore the load current stable.

Changes from battery charge to discharge can be observed without any appreciable effect on system stability which is a determinant condition to the power quality of controlled systems.

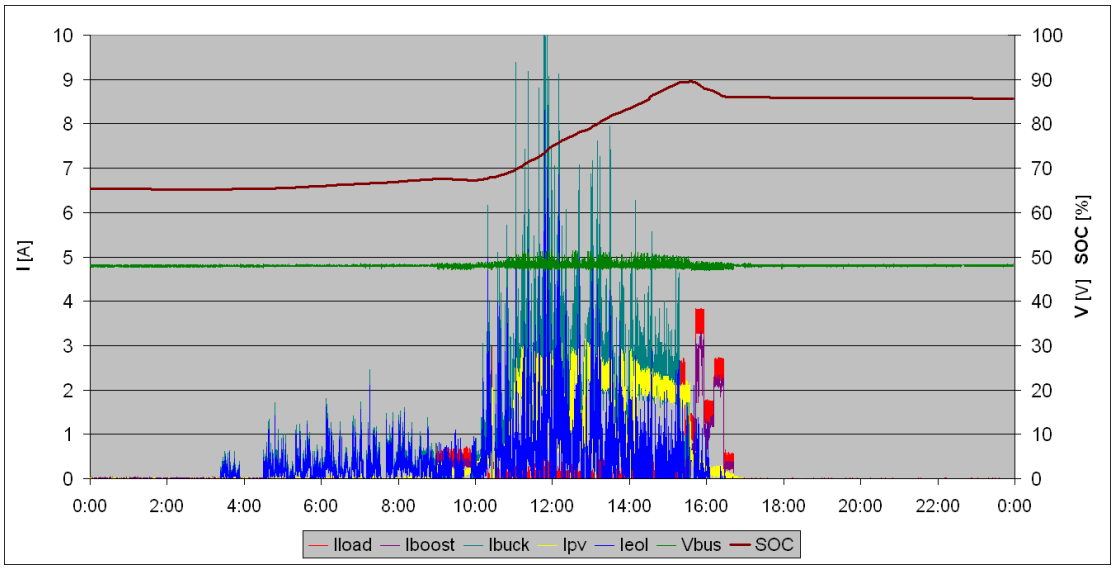

Fig. 10 – One day with wind and cloudy sun

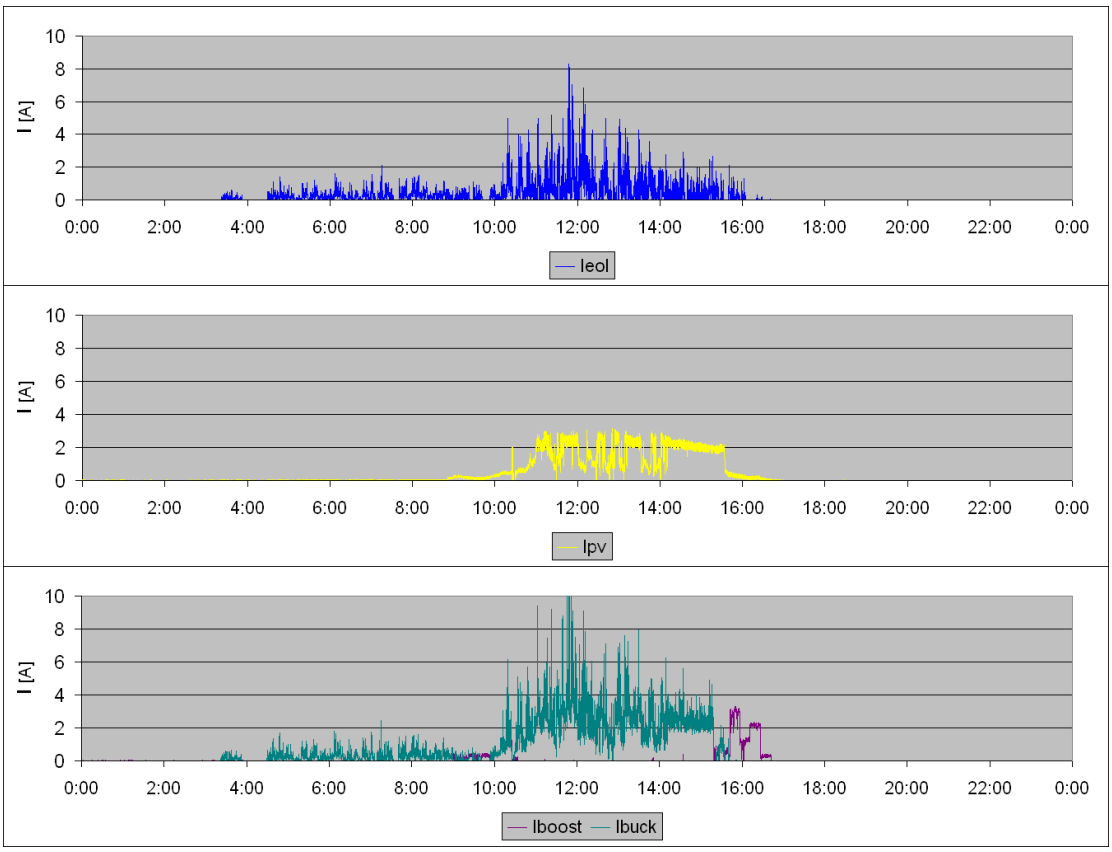

Fig. 11 – Wind, sun and battery waveforms

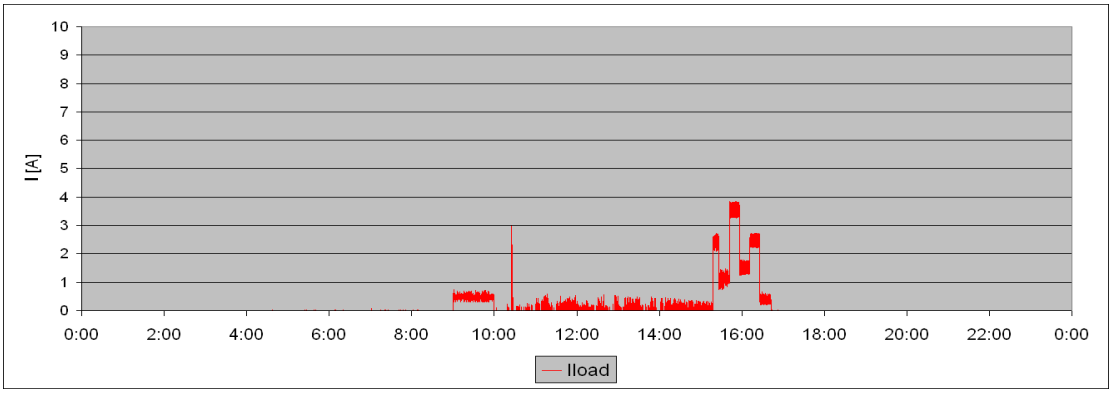

Fig. 12 – Step loading used in the test

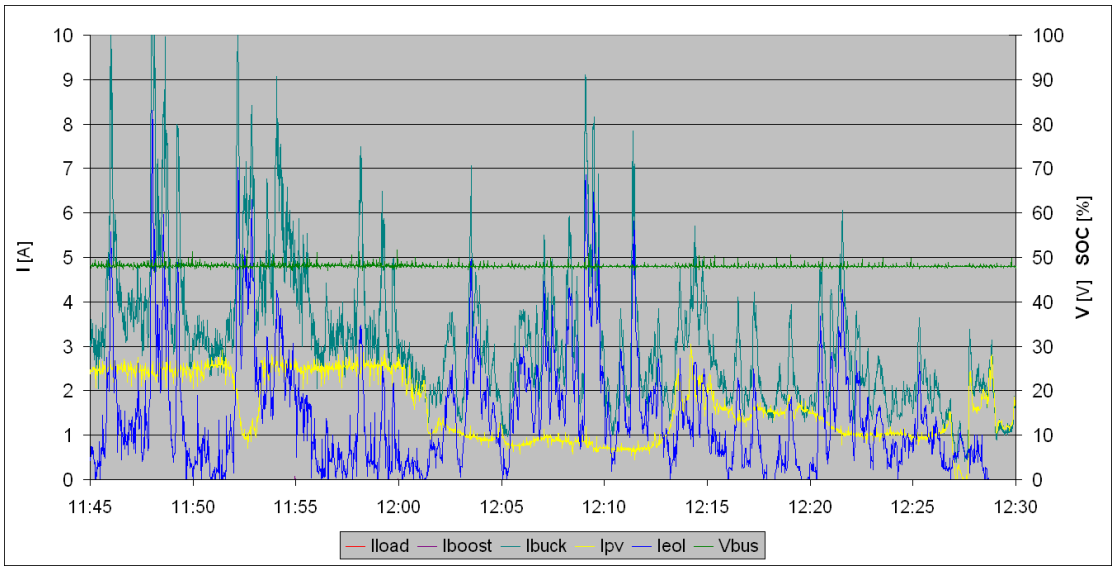

Fig. 13 – Loadless system with highly variable and relatively strong wind and photovoltaic power

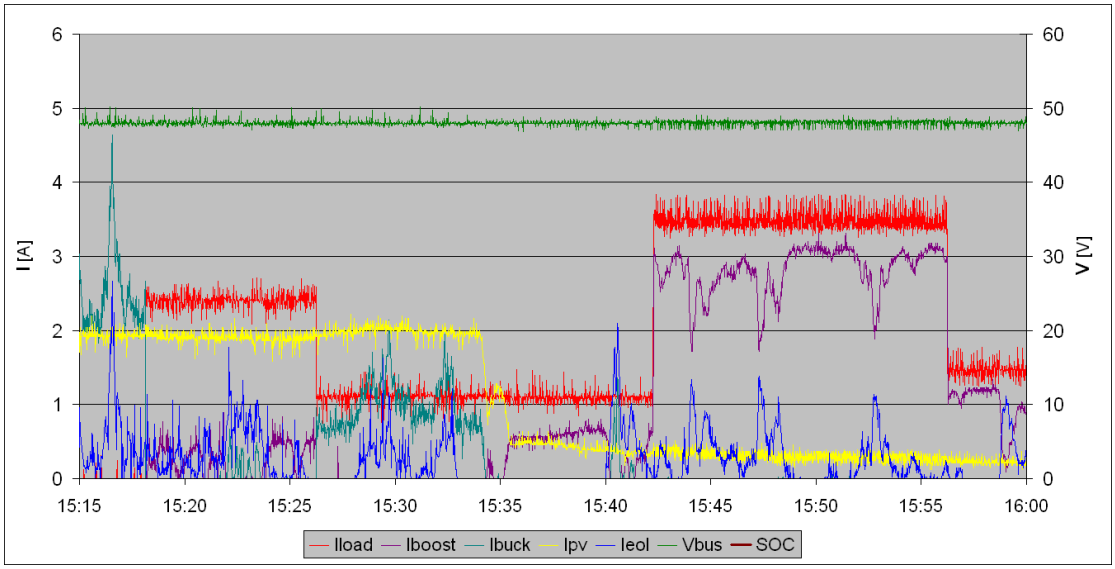

Fig. 14 - System with variable wind and sun as well as step loading for a 45 minutes period

2 - Unscheduled power requests

The present experiment assesses the system capability for power availability in the event of an unknown power and time external request. The experiment considers a time frame of 15 minutes during which the power requested is constant to adapt to general energy counting practice. Although the unscheduled power is unknown it is supposed a restriction to a maximum deliverable power related with the maximum battery discharge current capability.

The experiment is conducted in a cloudless day with relatively high intensity and also very variable wind regime.

The loading that somehow follows the characteristic curve of grids power consumption is presented in ***Fig. 15***. It means to mimic a somehow 'spinning reserve' although the power remains constant for 15 minutes period. It is nevertheless possible to implement another, more narrowed, time frame to adapt the system response to other type of load/grid needs.

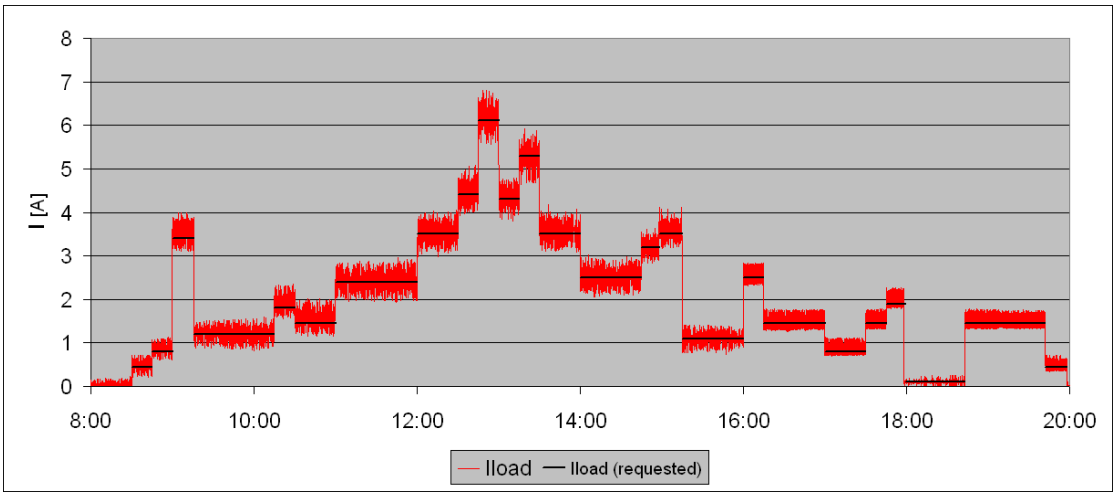

Fig. 15 – System extemporaneous load requests (black) constant in 15 minutes interval and delivered load current (red)

Aggregated behaviour of all quantities involved in the system is depicted in ***Fig. 16*** and the correspondent two renewable sources generation and battery charge and discharge are presented in ***Fig. 17***.

With higher dynamics than the previous experiment the system is still able to control and regulate the various quantities in order to maintain bus voltage and load constant during the required periods. The unscheduled power requests are satisfied as required the system maintaining its stability. ***Fig. 18*** depicts a 40 minutes interval where

despite the sharp variations of the wind power the system remains stable and the load constant for the periods defined to.

It can also be noticed the merits of the hybridization by the storage SOC behaviour. This one floats around a mean value of 85% without charging or discharging deeply. This not only ensures that energy is available to the next period but also that is lifetime can be enlarged.

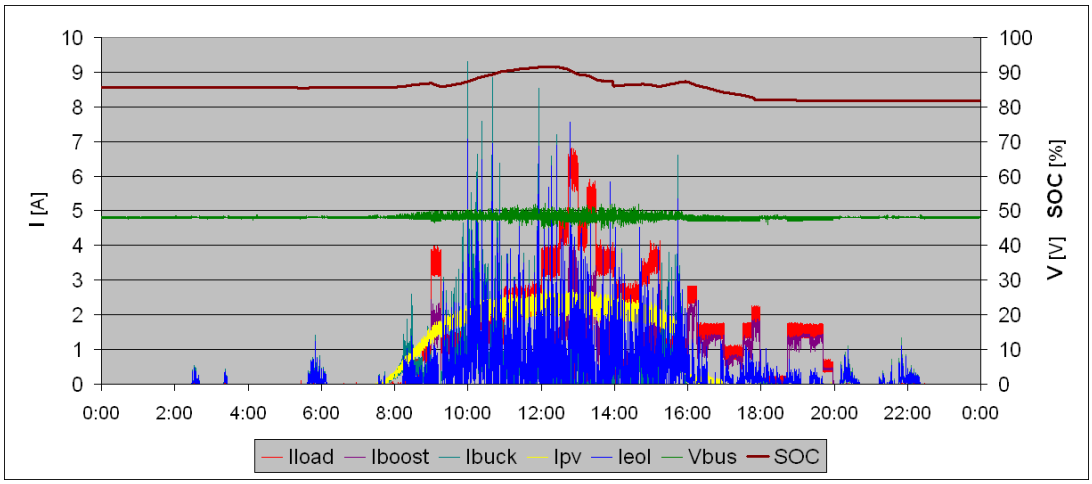

Fig. 16 – System behavior overview with extemporaneous external power requests for 15 minutes time frames. Wind (blue) and sun (yellow) generation, battery SOC (brown), charge (teal) and discharge (violet), load (red) and Dc bus voltage (green)

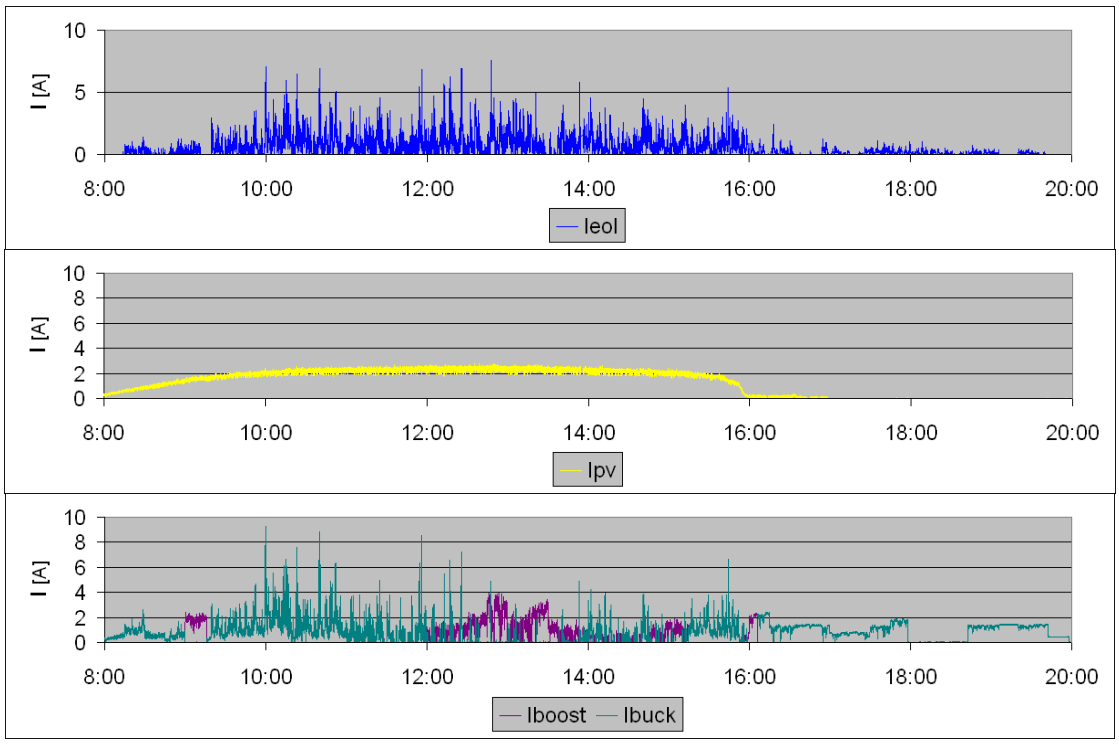

Fig. 17 - Wind and sun generation and battery charge (teal) and discharge (violet) currents

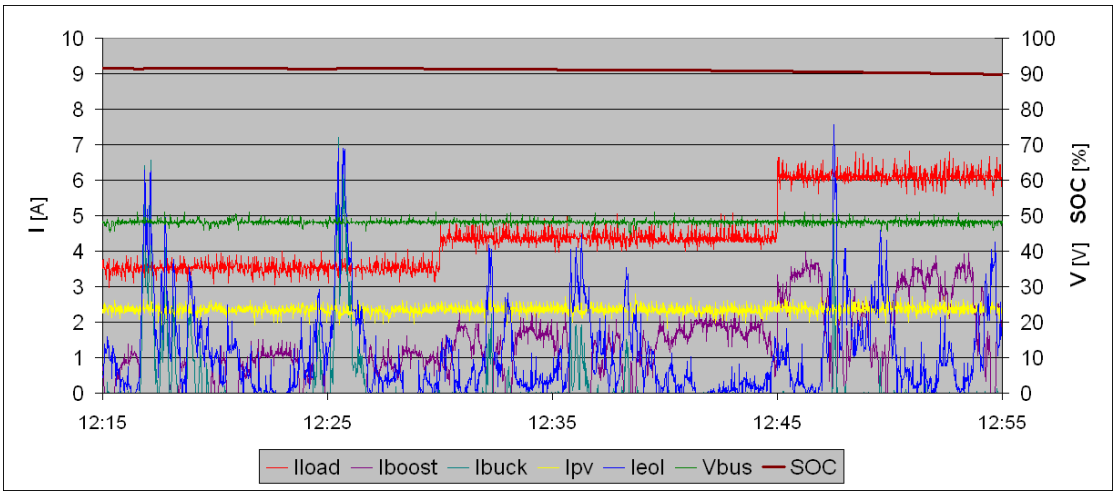

Fig. 18 – Details of the various quantities variations during 40 minutes

3 - Conclusions

The experimental HRES was tested for the fundamental operating conditions which represent the main system operating states, in order to validate it as a controllable generation system based on renewable sources.

Tests with conditions of real variable input conditions were performed with the HRES maintaining its stability while managing efficiently the power flows among its inputs and the battery. The transitions between charge and discharge are also presented without interfering with the HRES stability.

Accompanying the inputs variations, two types of loading were performed. The first type corresponds to the pre-programmed one, either in time or in value, and the second one corresponds to an unscheduled, also either in time or in value. For the both cases the HRES is able to maintain its stability and to comply with the required pre-programmed load.

The battery unit is able to fulfil its requirements charging and discharging as needed to ensure the availability of power namely in the more demanding case of one complete day with peak and full tariff hours. Tests demonstrate the viability of the energy transfer from one period to other which is one of the objectives established for such type of

systems and therefore the viability of an economic management for the renewable energy.

Finally the power control of the sources is able of keeping on extracting the maximum power of the sources.

Chap. VII – Conclusions and future research

As stated in chapter I distributed generation benefits encompass the possibility of using small systems with the advantages of possessing the following characteristics:

- reduced power – adaptable to the local needs
- fast installation time
- locatable near the loads
- isolated or grid interconnected operated
- able of offering grid services
- allow the deferment of grid investments due to delaying of grid expansion
- embrace renewable generation sources

In the other side, issues like the non-dispatch ability of renewable based generation, causing grid quality degradation and the incapability of services provision (namely system services), are concerns that must be addressed to ensure the spread of such type of systems.

Part of the system services, regarding DG electronically interconnected to the grid, are presently a function of the inverter control characteristics. But they are dependent on their own input power availability to be addressable.

Availability of power over certain periods is a central issue for power quality and leverages the merits of controllable power units. Considering new grid architectures like microgrids and their capability to operate in islanded mode, the existence of renewable based generation units which are controllable further reinforces their role as energy generation systems.

For renewable based sources generation units the controllability along with external control, made possible through communication capabilities, are base requirements for what is perceived as the future of electrical grids.

Being able to provide constant power over the renewable power variations and over the load changing is one of the main objectives of the hybrid renewable based power system - HRES. As showed in chapter 5 and 6 this objective is accomplished as the services provision is possible.

The ability of the system to gather continuously the sources maximum power regardless of the environment dynamics along with the stability of the delivered load power also demonstrates the economic potential of the present HRES.

Finally the successful energy transfer from lower to higher profitable time periods also evidences that the possibility of taking advantage of the price tariffs is attainable although being dependant of the energy characteristics of the storage technology.

This energy transfer also reflects on technical possibilities for grid operators to move energy between low and high consumption periods. This operational objective can be accomplished either directly through the injection of stored energy plus renewable controlled generation or by some agreement established with consumers where the power gathered from the grid in those periods is limited, the remaining being delivered by the controlled HRES (peak shaving concept).

In all the cases the system allows the user to be notified, in advance, of eventual change of operating conditions (for instance the depletion of storage along with low renewable power generation), giving him time to take preventive measures.

The applied hybridization (photovoltaic and wind) lowers the dependence on each of the sources and, consequently, on the storage. The last one is a weak link of the system, not only technically – it is a highly nonlinear dynamic element – but also financially. The type of charging/discharging in such type of systems is not favourable to a large life cycle thus increasing their cost (replacement).

The bus voltage being controlled by the battery converters, allows at freeing the control of the sources for continuous extraction of their maximum available renewable energy. This characteristic leverages the ratio that relates energy value to investment made in the renewable technology, by the increase of the gathered energy amount by period of time. It nevertheless is conditioned by the storage characteristics.

The last issue calls for further research in storage technologies. Namely capacitor based technology to cope with fast power density and hydrogen to cope with energy density. These are two storage technologies that are relatively mature actually although the latter one suffering from hydrogen generation issues. The use of different, more performing, electrochemical technologies is also a possible immediate improvement. The storage of energy in a kinetic form, as in free-wheels, is another particular technology that has been applied in specific applications.

The effect of the decrease in the storage charge would be a lowering of the energy available for the next supply period. Nevertheless, this situation has the advantage of being able of notifying in advance the load/grid manager of that eventuality and allowing him to take adequate measures such as to provide an alternative supplier. This last consequence, which has commercial and financial repercussions for the energy producer, stresses a strong need for a more effective forecasting, namely for very short-term conditions.

Being digitally controlled opens additional possibilities such communication and consequently external control from, as an example, a grid operator interested in controlling the power injected not only in an energy perspective but also in a power perspective. Also interesting is the possibility of programming the system to accomplish pre-defined different strategies.

The present system implements those perspectives in a satisfactorily way justifying the deepening of research and development of renewable based power systems with some connection to the electric grids. It responds affirmatively to the requirements of controllability, flexibility and economic needs as well as to environmental concerns. Beside the very small scale involved in the present platform, although scalable to higher power, the dissemination of such a type of systems – similar to the V2G strategy of using already existent but temporarily not used capacity – has potential to join environmental concerns with grid operators concerns in a single system.

The strategy of selling and avoiding buying can lower the need for measures to ensure power quality and for the expansion of generation capacity, specially in cases dictated by short peak power needs and not by steady consumption growth. In a more private home owner perspective such type of system also has an importance in the reduction of the local grid consumption in high tariff periods which reflects in a bill reduction and in a lowering of the grids peak power. The last component should be considered as a service to the grids and as such to be the object of a rewarding value.

Therefore it can be concluded that:

- The integration of different renewable energy sources into a unique electric energy generation system (HRES) improves generated energy quality as

well as it increases the generation system economic value, as it allows to provide power and energy according to well defined rules;

- An appropriate power balancing strategy of the HRES allows at controlling the power injected in the grid, while its different sources are always operating at maximum power point;
- A good energy management strategy, defining operation modes for the HRES, ensures energy and power availability to the generation system;
- A reinforcement of the economic value for hybrid generation units based on renewable sources is obtained through the attribution of control services to grid operators;

Nevertheless some improvements in the researched system are desirable:

- Accurate ultra-short term forecasting method in order to be able to ensure a higher supply security of a pre-planned amount of energy (day ahead strategy);
- A system supervisor, aggregating the functions of monitoring the operational states of the system – as the SOC and ultra-short term forecasting – in order to enlarge the system capability of accomplishing generation services for scheduled loads;
- More adequate storage technology that permits to achieve higher power and a better life span would bring a more technically as well as economically efficiency – the use of other storage technologies as Li-Ion and hydrogen could improve the overall system;
- Integration with other existing storage (such as automobile batteries and other forms of storage such as heat) that can lower the weight of this component in the overall cost of the system;
- Improvement of the control capabilities namely integrating an inverter in the system;
- Study of the perspective of spreading such type of system and its collective management and control over a well defined geographic region, integrating different types of renewable sources and some storage capacity.

Anex 1

Wind turbine

Manufacturer: Bergey
Model XL.1
Nominal power : 1 kW (max: 1.3 kW)
Rotor diameter: 2.5 m
Start-up Wind Speed: 3 m/s
Cut-in Wind Speed: 2.5 m/s
Rated Wind Speed: 11 m/s
Furling Wind Speed: 13 m/s
Max. Design Wind Speed: 54 m/s
Type: 3 Blade
Permanent Magnet Alternator
In nacelle diode rectification
Overspeed Protection: AUTOFURL

Photovoltaic panels

Manufacturer: BP
Model: 380U
Multicrystalline
Peak power: 80 W
VMPP: 17.6 V
IMPP: 4.55 A
Short circuit current: 4.8 A
Open circuit voltage: 22.1 V
Temperature coefficient of short circuit current: (0.065±0.015)%/ºC
Temperature coefficient of voltage: -(80±0.05)mV/ºC

Manufacturer: BP
Model: 585U
Monocrystalline
Peak power: 85 W
VMPP: 18 V
IMPP: 4.72 A
Short circuit current: 5 A
Open circuit voltage: 22.1 V
Temperature coefficient of short circuit current: (0.065±0.015)%/ºC
Temperature coefficient of voltage: -(80±10)mV/ºC

Lead acid battery

Manufacturer: Autosil
Model: E series, E12-195
Voltage: 12 V
Capacity: 195 Ah