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# Microgrids - Large Scale Integration of Microgeneration to Low Voltage Grids

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## SUMMARY

Microgrids comprise Low Voltage distribution systems with distributed energy sources, such as micro-turbines, fuel cells, PVs, etc., together with storage devices, i.e. flywheels, energy capacitors and batteries, and controllable loads, offering considerable control capabilities over the network operation. These systems are interconnected to the Medium Voltage Distribution network, but they can be also operated isolated from the main grid, in case of faults in the upstream network. From the customer point of view, Microgrids provide both thermal and electricity needs, and in addition enhance local reliability, reduce emissions, improve power quality by supporting voltage and reducing voltage dips, and potentially lower costs of energy supply.

This paper outlines selected research findings of the EU funded MICROGRIDS project (Contract ENK-CT-2002-00610). These include:

- Development and enhancement of Microsource controllers to support frequency and voltage based on droops. Application of software agents for secondary control.
- Development of the Microgrid Central Controller (MGCC). Economic Scheduling functions have been developed and integrated in a software package able to simulate the capabilities of the MGCC to place bids to the market operator under various policies and to evaluate the resulting environmental benefits.
- Analysis of the communication requirements of the Microgrids control architecture
- Investigation of alternative market designs for trading energy and ancillary services within a Microgrid. Development of methods for the quantification of reliability and loss reduction.
- Initial measurements from an actual LV installation.

## KEYWORDS

Microgrids; Distributed Generation; Energy Management; Microsource Controllers; Communication requirements

## INTRODUCTION

Microgrids comprise Low Voltage distribution systems with distributed energy sources, such as micro-turbines, fuel cells, PVs, etc., together with storage devices, i.e. flywheels, energy capacitors and batteries, and controllable loads, offering considerable control capabilities over the network operation. These systems are interconnected to the Medium Voltage Distribution network, but they can be also operated isolated from the main grid, in case of faults in the upstream network. From the customer point of view, Microgrids provide both thermal and electricity needs, and in addition enhance local reliability, reduce emissions, improve power quality by supporting voltage and reducing voltage dips, and potentially lower costs of energy supply [1, 2, 3].

Key economic potential of the application of distributed energy sources at customer premises lies in the opportunity to utilise locally the waste heat from conversion of primary fuel to electricity. There has been a significant progress in developing small, kW-scale, CHP applications. These systems are expected to play a very significant role in the microgrids of Northern EU countries. On the other hand, PV systems are anticipated to become increasingly popular in Southern EU countries. The application of micro CHP and PVs potentially increases the overall efficiency of utilising primary energy sources and consequently provides substantial environmental gains regarding carbon emissions, which is another critically important benefit in view of the EU commitments in meeting the Kyoto objectives.

From the Utility point of view, application of distributed energy sources can potentially reduce the demand for distribution and transmission facilities. Clearly, distributed generation located close to loads will reduce flows in transmission and distribution circuits with two important effects: loss reduction and ability to potentially substitute for network assets. Furthermore, the presence of generation close to demand could increase service quality seen by end customers. Microgrids can provide network support in times of stress by relieving congestions and aiding restoration after faults. All this indicates that electricity produced by distributed generation may have a higher value than that produced by central generation.

Technical challenges associated with the operation and control of Microgrids are immense. Effective energy management within micro grids is a key to achieving vital efficiency benefits by optimising production and consumption of heat, gas and electricity. The coordinated control of a large number of distributed sources with probably conflicting requirements and limited communication is a very challenging problem imposing the adoption of distributed intelligence techniques. Furthermore, the management of instantaneous active and reactive power balances, power flow and network voltage profiles imposes unique challenges in the context of Microgrids. Traditionally, power grids are supplied by sources having rotating masses and these are regarded as essential for the inherent stability of the systems. In contrast, Microgrids are dominated by inverter interfaced distributed sources that are inertia-less, but do offer the possibility of a more flexible operation. A further particular problem of Microgrids is the relatively high resistance of the low voltage networks. The amount of voltage drop on any RL circuit is approximately obtained by PR+QX, P and Q being the active and reactive power flow, R and X the resistance and reactance of the circuit. In overhead HV or MV networks, R is much lower than X, so that the injection of reactive power critically affects voltage drops. Active and reactive power effects are reasonably decoupled and this is the basis of several analytical techniques, like the fast decoupled load flow. In underground LV networks on the other hand, R is much higher, it can be 3 times higher or at least equal to X. This results in strong coupling of real and reactive power, and hence the control of voltage and frequency can no longer be considered separately.

A key challenge of Microgrids is to ensure stable operation during faults and various network disturbances. Transitions from interconnected to islanding mode of operation are likely to cause large mismatches between generation and loads, posing a severe frequency and voltage control problem. Storage technologies, such as batteries, ultra-capacitors and flywheels may become important components of Microgrids, with the duty to provide stable operation of the network during network disturbances. Maintaining stability and power quality in the islanding mode of operation requires the

development of sophisticated control strategies and needs to include both generation and demand sides.

Considerable research on various aspects of Microgrids is currently carried out in USA [1], Japan and Canada. In Europe a three year Microgrids project (Contract ENK-CT-2002-00610) [2] with 14 partners from 7 countries has concluded its work at the end of 2005. The objectives of this project were:

- To increase the penetration of RES and other micro-sources in order to contribute for the reduction of GHG emissions.
- To study the main issues regarding the operation of Microgrids in parallel with the mains and in islanding conditions that may follow faults;
- To define, develop and demonstrate control strategies that will ensure the most efficient, reliable and economic operation and management of Microgrids;
- To define appropriate protection and grounding policies that will assure safety of operation and capability of fault detection, isolation and islanded operation;
- To identify the needs and develop the telecommunication infrastructures and communication protocols required
- To determine the economic benefits of the Microgrid operation and to propose systematic methods and tools to quantify these benefits and to propose appropriate regulatory measures.

Overall, the project has developed and demonstrated operation, control, protection and telecommunication infrastructures of Microgrids on Laboratory installations and by simulation studies. Methods for determining and quantifying economic and social benefits have been also developed. In this paper selected results of the project focusing on Microgrids control and actual measurements are presented.

## MICROGRIDS CONTROL LEVELS

In order to achieve the full benefits from the operation of Microgrids, as outlined in the Introduction, it is important that the integration of the distributed resources into the LV grids, and their relation with the MV network upstream, will contribute to optimise the general operation of the system. To achieve this goal, a hierarchical system control architecture comprising three control levels, as shown in Figure 1, can be envisaged [1,2].

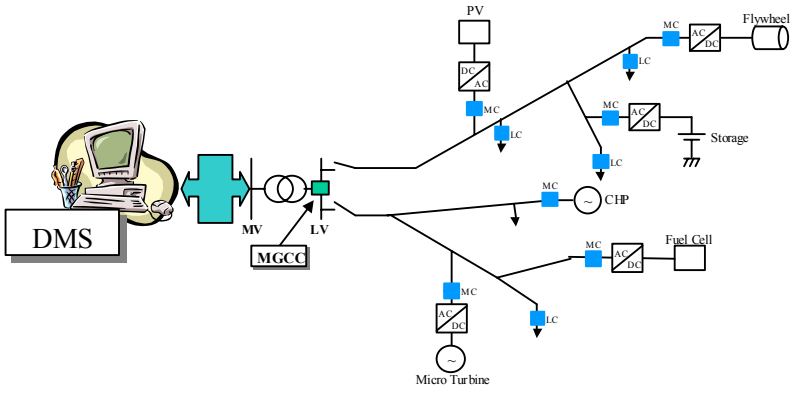



**Figure 1.** Microgrid control architecture

- Local Microgenerator Controllers (MC) and Load Controllers (LC)
- MicroGrid System Central Controller (MGCC)
- Distribution Management System (DMS).

The ***Microgenerator Controller*** (MC) takes advantage of the power electronic interface of the micro source and can be enhanced with various degrees of intelligence. It uses local information to control the voltage and the frequency of the microgrid in transient conditions. MCs have to be adapted to each type of micro source (PV, fuel cell, micro turbine, etc.) Local *Load Controllers* (LC) are also installed at the controllable loads to provide load control capabilities.
The ***Microgrid Central Controller*** (MGCC) functions can range from monitoring the actual active and reactive power of the distributed resources to assuming full responsibility of optimizing the Microgrid operation by sending control signal settings to the distributed resources and controllable loads.
The ***Distribution Management Systems*** (DMS) to whom multiple MGCCS are interfaced need to be enhanced with new features related to the operation of Microgrids. Microgrids connected on their feeders should ideally look like concentrated loads. The issues of autonomous-non-autonomous operation of the Microgrids and the related exchange of information are new important issues. Disconnection and re-synchronization of Microgrids during and post-fault periods need to be evaluated.

It is clear that in order to operate a Microgrid in a coordinated manner it is important to provide a more or less decentralized decision making process in order to balance demand and supply coming both from the distributed resources and the MV distribution feeder. There are several levels of decentralization that can be possibly applied ranging from a fully decentralized approach to a basically centralized control depending on the share of responsibilities assumed by the MGCC and the MCs and LCs.

## DEVELOPMENT OF LOCAL MICRO SOURCE CONTROLLERS

In order to achieve the steady state operation of large numbers of micro sources with their individual control and synchronization, but with a communication of set points and parameters, the basic local functions are based on the simple control real and reactive power by means of droops. This way, the voltage and frequency control of the Microgrid can be dealt with at a primary level by the time uncritical setting of the droops [4].

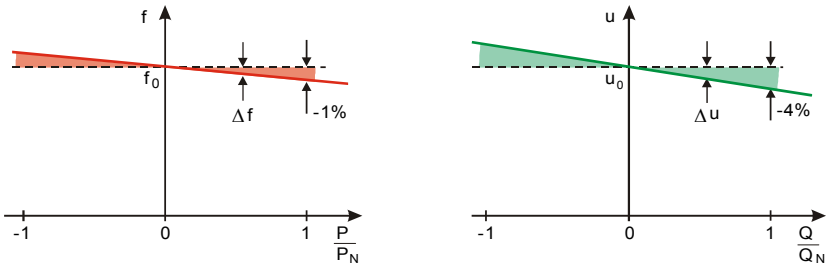



**Figure 2.** The concept of frequency and voltage droops

The solution suggested for the local micro source controllers is shown in the following figure.

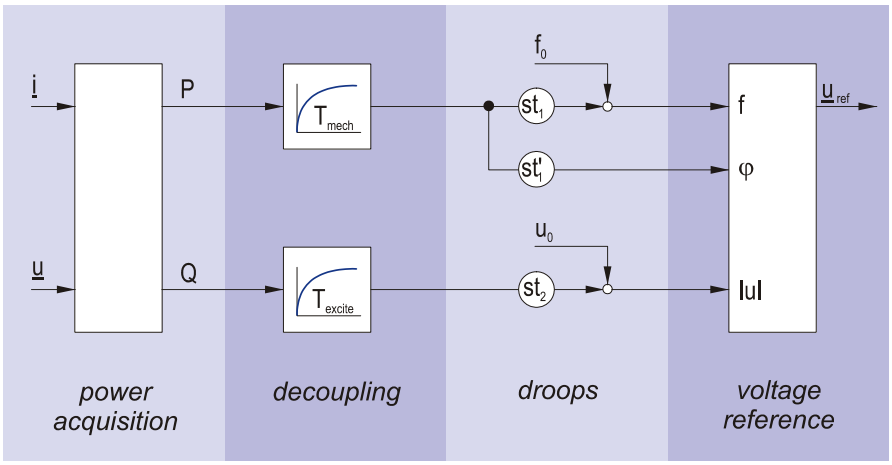



**Figure 3.** *Droop control based on power acquisition*

The impact of the high resistance over reactance ratio of LV-lines on the droop control was also investigated. It was shown that despite contradicting line parameters the conventional droop concept can be used at the low voltage level, as shown in figure 4. Improvements of the voltage control can be achieved by compensating for the lines.

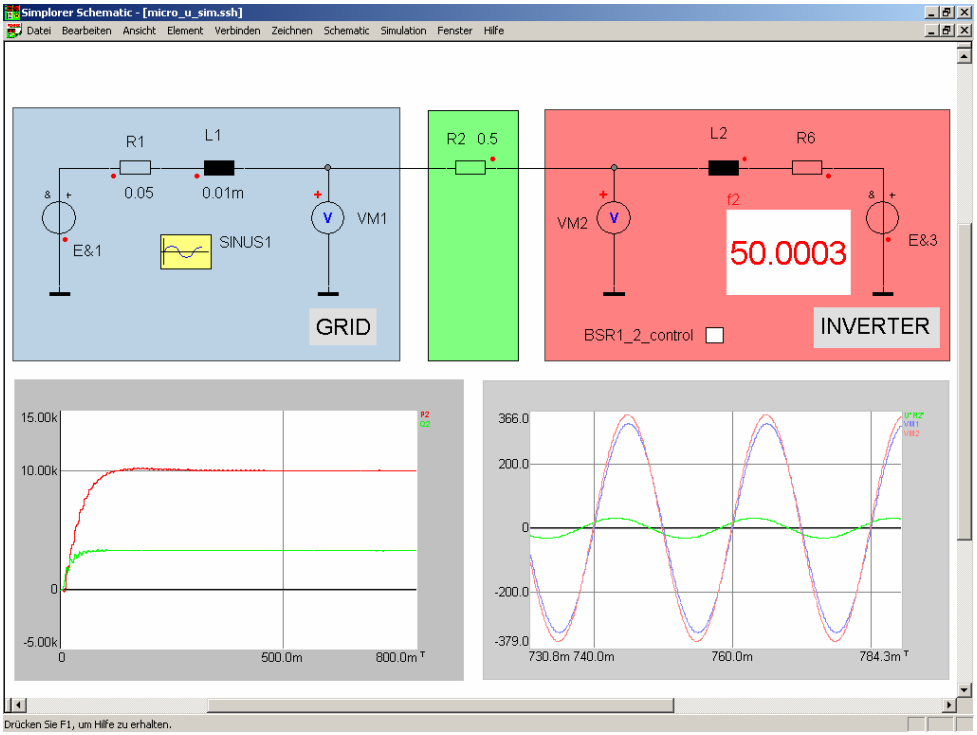



**Figure 4:** Droop controlled inverter coupled via a resistive line to the main grid

***Fully Decentralized Control***

According to the fully decentralized approach, the main responsibility is given to the ***Microgenerator Controllers*** (MCs) that compete to maximize their production in order to satisfy the demand and probably provide the maximum possible export to the grid taking into account current market prices. This approach can be based on distributed multi-agent technology. The use of Multi Agent Systems (MAS) in controlling a Microgrid solves a number of specific operational problems [5]. First of all,

microgenerators can have different owners, in which case several decisions should be taken locally, making centralized control very difficult. Furthermore, Microgrids operating in a market environment require that the actions of the controller of each unit participating in the market should have a certain degree of intelligence. Finally, local DG units next to selling power to the network might have also other tasks, like producing heat for local installations, keeping the voltage locally at a certain level or providing a backup system for local critical loads in case of main system failure. These tasks suggest the importance of distributed control and autonomous operation.

In the Microgrid MAS the ***Microgrid Central Controller*** is implemented by an extra supervisory Agent whose primary job is to record the bids of the distributed resources and the power flow. A transaction is valid only if it is registered in the supervisory agent and this is vital in order to avoid double offers to separate loads. In Market Operation the job of the supervisory Agent is to create the final bill for each load or unit.

## DEVELOPMENT OF MICROGRID CENTRAL CONTROLLER

### *Centralized Control*

In hierarchical control, the ***Micro Source Controllers*** (MC) follow the orders of the MGCC, when connected to the power grid, and have the autonomy to perform local optimization of the micro source active and reactive power production, and fast load tracking following an islanding situation.

The main responsibility for the maximization of the Microgrid value and the optimization of its operation lies to the ***MicroGrid Central Controller***. The MGCC uses the market prices of electricity and gas costs and probably grid security concerns and DSM requests to determine the amount of power that the Microgrid should draw from the distribution system, optimizing the local production capabilities. It might use simple load forecasts (electric and possibly heat) and forecasts of power production capabilities. The defined optimized operating scenario is achieved by controlling the micro-sources and controllable loads within the Microgrid by sending control signals to the field. In this framework, non-critical, controllable loads can be shed, when necessary. Furthermore, it is necessary to monitor the actual active and reactive power of the components. These techniques can be considered equivalent to the secondary control of the interconnected grid [6-8].

### *Controller Functions*

This Section considers controller functions in order to achieve optimal operation of the Microgrid in interconnected mode of operation. Islanded operation is expected to happen very few times in a year and it is obvious that in such periods, the main concern is to “Keep the lights on”. In interconnected mode, the following functions adopted from EMS systems controlling large interconnected systems need to be considered:

### *Operational Planning functions*

The economics of Microgrids operation are driven by market conditions of the system. The local distributed energy sources either acting as individual market players or as one coordinated market player will provide energy and ancillary services bidding on energy and ancillary markets based on the prices provided by the system. Two market policies can be distinguished: In the first case, the Microgrid serves its own needs only, displacing as much as economically optimal energy from the grid. In the second case, the Microgrid participates in the market probably through an Energy Service Provider or Aggregator. Due to its size and the uncontrollability of the microsources it is unlikely that the Microgrid bids will concern longer term horizons. It is conceivable however to have Microgrid bids covering a short time ahead, say the next 15 to 30 minutes.

It is assumed that the MGCC takes decisions about the Microgrid operation at m-minutes interval, e.g. 15 minutes for the next hour or hours. The Generator LCs, based on the market prices and possible limitations to their production, place bids to the MGCC regarding their level of production. Similarly, the Load LCs place similar bids regarding the amount of energy requested depending on their priority.

Based on the market policy, the MGCC optimizes the Microgrid operation taking into account:

- The bids of the DG-sources and loads
- The energy market prices
- Network security restrictions
- Demand forecasts and renewable production forecasts, if needed

Based on its optimization routines, the MGCC sends to the LCs:

1. Set-points for DG productions
2. Set-points for loads to be served or to be shed.
3. Energy market prices for the next optimization period, so that LCs can place effective bids.

Based on these signals, the LCs adjust their levels of production or load and prepare bids for the next period. The functions implemented, in order to perform centralized control of Microgrids are:

1. Load forecasting. Since the optimization horizon is couple of hours, persistent methods or simple time-series methods can be used. The load forecasting error is expected to be higher than in the case of larger networks, where the smoothing effect ameliorates individual load behaviors.
2. Renewable production forecasting. Since several DG sources are RES based, estimation of their output is needed. Due to the short prediction horizon, persistent methods and simple methods based on time-series can be used.
3. Heat forecasting. This is necessary in Combined Heat and Power (CHP) dominated Microgrids driven by thermal needs. Similar forecasting methods for electrical load can be used.
4. Unit Commitment functions. These functions define which units should run in order to meet the demand and, if necessary or financially beneficial, to exchange active power with the main grid. A simple method that can be used is the priority list method according to their bids.
5. Economic Dispatch functions. These functions define the output of the units whose output can be regulated. For those whose output cannot be regulated, their set point is zero, if not committed, or nominal or forecasted, if committed.
6. Security functions. A key issue for the operation of the Microgrids is the ability of seamless transition from interconnected operation to island operation with minimum load shedding. Security functions can define which units or storage should run or which loads should be shed, so that critical load continues to be served in case of islanding.

A prototype software incorporating the above functions, capable to simulate the operation of a Microgrid in energy markets has been developed in the project. As an example, Figure 5 displays the daily economic scheduling of a 400 kW Microgrid comprising one 100 kW Microturbine, one 100 kW Fuel Cell, one 40 kW Wind Turbine and two PVs of 10 kW, assuming DG bids reflecting fuel costs and investment pay-back and characteristic market prices of the Amsterdam Power Exchange (ApX).

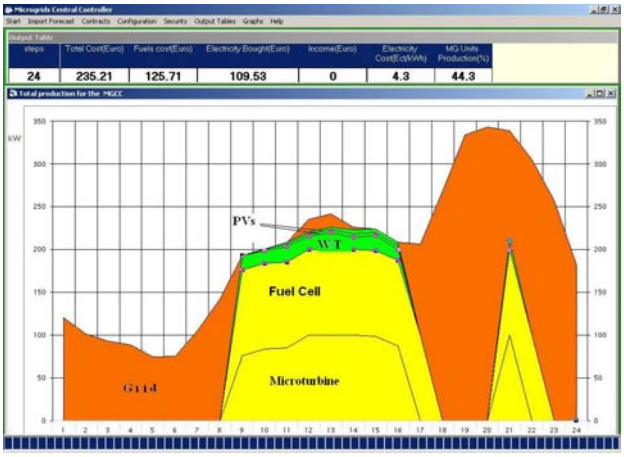



**Figure 5.** Display of DG dispatch and energy bought from the Grid

## TELECOMMUNICATION INFRASTRUCTURES & COMMUNICATION PROTOCOLS

The communications platform necessary for supporting the MICROGRIDS control architecture, which requires interaction between a Micro Grid Central Controller (MGCC) and local Micro Source Controllers (MC) and Load Controllers (LC) as well as communications with a Distributed Management System (DMS) has been investigated.

Although a simple architecture (based on running the control application over a data link layer protocol) would probably fulfil the basic requirements, it was concluded that many advantages could be gained by using standard network and transport protocols, which, at present, means using the TCP/IP family:

- independence of subnetwork technology;
- possibility of sharing a physical subnetwork with other services and applications;
- global or local addressing schemes at network level (logical, not physical);
- integration within a wider IP network (internetworking support);
- provision of standard transport services (TCP or UDP);
- exploitation of TCP reliability mechanism;
- use of existing or new services that run on top of TCP or UDP and that may benefit from the widespread use of application protocols like HTTP.

Thus, using TCP/IP as the intermediate layers in the Microgrids architecture provides extra functionality, flexibility and scalability, especially in what concerns future evolutions, such as the exploitation of more complex scenarios (for example, multiple micro-grids) or the use of a variety of physical communication services (depending on the actual offer by network operators).
In what concerns the physical infrastructure, the adoption of IP for the internetwork layer means that any subnetwork technology can be adopted and the choice would depend on a number of factors, especially availability, ease of deployment and cost. At present, a number of access solutions are available, such as ISDN, xDSL, WiMax, cable, Wi-Fi (IEEE 802.11) or Ethernet in the First Mile (EFM); Power Line Communications (PLC) is also emerging as a new last mile access technology for broadband Internet access.

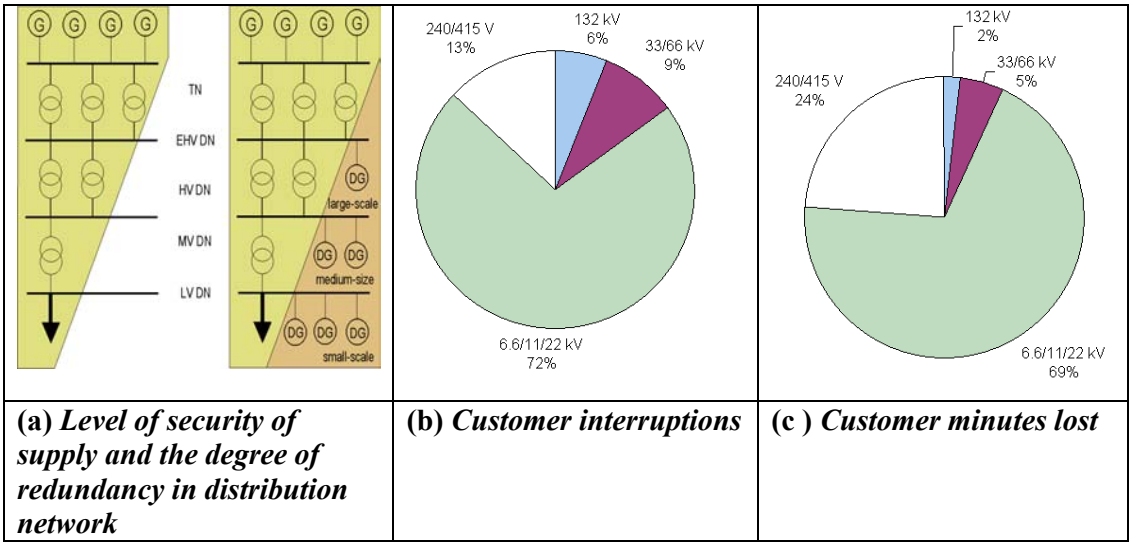
In spite of the complex nature of the communications channels and the many challenging technical problems that must be solved (distortion, attenuation, interference, variable channel conditions, electromagnetic compatibility, etc.), the result of the study allows to conclude that PLC is already a well established broadband last mile technology. Therefore, from the technical point of view, it constitutes a feasible solution for Microgrids, although, as mentioned before, other factors need to be considered when selecting the access technology, in particular the availability of off-the-shelf components fully compliant with open standards, both at the physical and the medium access control (MAC) protocol layers.

## COMMERCIAL, ECONOMIC AND ENVIRONMENTAL ISSUES

In addition to environment and security of supply related benefits, a number of tangible benefits can be derived from Microgrids. Within the project the benefits of Microrrids wrt (i) increased service and power quality (ii) reduced connection cost for micro generation (iii) increased efficiency of entire system operation including loss reduction, (iv) reduced investment in system reinforcement and last but least (v) reduced price and increased choice for end customers have been investigated. Methods to quantify these benefits have been developed [9].

In particular, the issue of reliability of the electricity supply has become a key factor for economic wealth. In the left diagram of figure 6, the level of security of supply and the degree of redundancy in current power systems is illustrated. While the right diagram shows the potential contribution of Microgrids islanding. The Microgrids concept has the highest potential to improve the security and

quality of supply at the low voltage levels. Interestingly, a large amount of micro generation is expected to connect to these voltage levels. The next figures show the distribution of customer interruption and customer minute lost for each voltage level in distribution network. It is shown that the majority of the interruption occurs in the LV and MV networks where the applications of Microgrids will take in place.




| (a) *Level of security of supply and the degree of redundancy in distribution network* | (b) *Customer interruptions* | (c ) *Customer minutes lost* |
|---|---|---|

**Figure 6.** Effect of Microgrids on Service Quality

***Frielas Study Case***

In the following, measurements from a Low Voltage (LV) grid that supplies a semi-urban area in Portugal, are reported [10]. One of the few industrial installations is a Natural Gas (NG) station used to provide natural gas to a regional distributor. In order to distribute natural gas, it is necessary to reduce the pressure, from the transmission network to the distribution network and as a consequence, the temperature of the gas decreases strongly. To compensate this phenomenon, it is necessary to pre-heat the gas before the reduction of pressure, normally using boilers. However, considering the regularity of the heat demand, a micro-cogeneration system was installed, in a pilot station to supply the required heat substituting one boiler by a micro turbine. In this specific situation, the micro-cogeneration system produces the main part of the required heat by the NG station and generates electricity for local consumption and exportation to the Medium Voltage (MV) and LV public grids.

During the initial five operation months (from December 2003 until May 2004), the micro-turbine performance was measured and recorded. The micro-turbine was electrically connected to a MV substation where the exceeding produced power was injected after feeding the local loads consisting of the control system of the NG station. With some reconfigurations of the micro-turbine's protections and at the level of the LV public feeder it would be possible to supply a group of fifteen Customer by this micro generation system, through the LV public grid, and to implement a real LV Microgrid with a single micro-source. This simplified scheme (**Error! Reference source not found.**) emphasizes the efficiency achieved with the micro turbine (85%) compared to the efficiency achieved in centralized generation (71%).

As result of the efficiency improvement, the Microgrid can make a major contribution in the reduction of Green House Gas (GHG) emissions and the global pollution and at the same time, it can improve the reliability of the LV grid, supplying the Customers during MV voltage interruptions. In fact, the main causes of voltage interruption are related with MV network. Regarding power quality, in steady state, the micro-sources can contribute to voltage control and frequency stability, reducing the severity of voltage dips, voltage droops and swells. Simultaneously, the Microgrid would provide some ancillary services to the distribution operator, such as power factor control and harmonics mitigation.

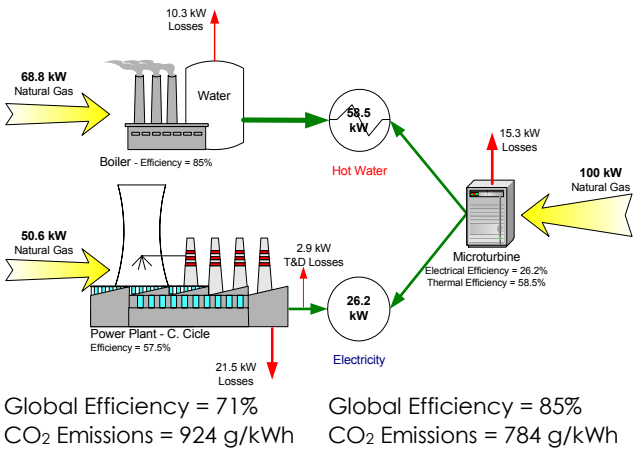



**Figure 7***:* Power flow in centralized / distributed power and heat generation

The small-scale investments in micro-sources, closely matching the demand of the Microgrid loads, reduce the risk and capital exposure. In a distribution perspective, these micro-sources can prevent bulk investments on the reinforcement of the T&D systems. In natural preserved areas, the Microgrid and particularly the micro-sources can also contribute definitely to reduce the proliferation of MV and HV distribution infrastructures. The following **Error! Reference source not found.**presents a comparison between two possible scenarios – "Customers supplied by typical Distribution System" or "Customers supplied in MicroGrid", based on the data collected during the year of 2004. In order to analyse the two scenarios, it was considered that two MV interruptions and one LV interruption in the Distribution System that supplies these Customers occurred in 2004.

**Table.** Analysis of Scenarios with and without LV Micro Turbine

| | **Customers Supplied by Typical Distribution System** | **Customers Supplied by the Possible Microgrid** |
|---|---|---|
| Yearly Number of Voltage Interruptions | 3 | 1 |
| Yearly Interruption Time (min) | 153 | 60 |
| Yearly ENS (kWh) | 33 | 13 |
| Yearly ENS by LV Maintenance (kWh) | 1,3 | 1,3 |
| Yearly Energy Generation (kWh) | 238.388 | 219.554 |
| Yearly Losses (kWh) | 21.455 | 5.446 |

*ENS Expected Energy Not Served*

The yearly losses in the scenario of "Customers supplied by typical Distribution System" (21.455 kWh) include the losses in the LV feeder (5.707 kWh) and the losses in the T&D systems; from the centralized power plant (15.748 kWh). In a Microgrid scenario, the yearly losses are only referred to the reconfigured LV circuit, from the local micro-generation installation (NG station) to the local of consumption (Customers installations). In this analysis it was assumed that the micro-turbine system is always available to supply the loads when a MV network interruption occurs. Consequently, the LV Customers are not disturbed by MV interruptions.

With the integration of the micro-turbine system in this LV grid the following potential improvements are expected:

- Reduction of the number of voltage interruptions from 3 to 1 interruption per year – **(66,6%)**;
- Reduction of the interruption time from 153 minutes to 60 minutes per year – **(61%)**;
- Reduction of the ENS from 64 kWh to 13 kWh per year – **(80%)**

## CONCLUSIONS

In this paper key results from the EC funded research project Microgrids are briefly presented. These are:

- Development and enhancement of microsource controllers to support frequency and voltage based on droops. It is shown that the droop concept can work equally well in the LV high resistance case. In addition, decentralized secondary control of Microgrids based on agents has shown promising results.
- Several functions of the Microgrid Central Controller (MGCC) have been developed and integrated in a software package able to simulate the capabilities of the MGCC to place bids to the market operator under various policies. DSM functions including load curtailment have also been developed.
- Analysis of the communication system requirements of the Microgrids control architecture (both general as well as application related), specification of the communications architecture (with selection of protocols and interfaces) capable of fulfilling these requirements and choice of an adequate platform to support the execution of the Microgrids control applications. The suitability of the Power Line Communications (PLC) as a communications infrastructure, considering its complex channel characteristics as well as the available solutions in the market has been assessed.
- The improvement in the quality of service due to islanding operation has been discussed. The environmental and reliability benefits obtained by the operation of an actual microturbine installation feeding local loads in Microgrid operation have been calculated showing distinct benefits.

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