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Advanced Architectures and Control Concepts

for More Microgrids

Specific Targeted Project

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Executive Summary Report
Final Results

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I.Executive summary

The project aimed at the increase of penetration of microgeneration in electrical networks through the exploitation and extension of the Microgrids concept, involving the investigation of alternative microgenerator control strategies and alternative network designs, development of new tools for multi-microgrids management operation (involving Distribution Management System architectures and new software adaptation) and standardization of technical and commercial protocols.

Microgrids are novel distribution network structures offering a number of important advantages. 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. From the Utility point of view, the application of distributed energy sources can potentially reduce the demand for distribution and transmission facilities.

Microgrids operate mostly interconnected to the higher Voltage Distribution network, but they can also be operated isolated from the main grid, in case of faults in the upstream network. The flexibility of microgrids comprises important benefits, but their efficient implementation poses very challenging problems, as listed next:

- The benefits Microgrids provide to power system operation and planning need to be quantified and incorporated into an appropriate commercial and regulatory framework, so that a level playing field for all energy technologies can be established. In order to achieve the full benefits from the operation of Microgrids, it is important that the integration of the distributed resources into the LV grids, and their relation with the Medium Voltage (MV) network upstream, will contribute to optimize the general operation of the system.

- The coordinated control of a large number of distributed sources with probably conflicting requirements and limited communication imposes the adoption of mostly distributed intelligence techniques.

- The design of Micro-source Controllers enhanced with advanced frequency and voltage control capabilities and possessing ride-through capabilities is essential for the stable operation of Microgrids, especially in islanded mode of operation.

- The design of smart Storage and Load Controllers able to face the stringent requirements posed by the islanded operation and especially during transition from interconnected to islanded mode is also crucial.

The first activity at EU level dealing in-depth with Microgrids was the Project "MICROGRIDS: Large Scale Integration of Micro-Generation to Low Voltage Grids", Contract ENK5-CT-2002-00610 (www.microgrids.eu). For a wide deployment of Microgrids however, the following Scientific and Technical Objectives have been set in the "More Microgrids" project, organized in respective Workpackages, as follows:

WPA. Investigation of new micro source, storage and load controllers to provide efficient operation of Microgrids

Transition from interconnected to islanded operation provides challenging frequency control problems. Close coupling of active-reactive power in low voltage (LV) networks complicates voltage control. These have been investigated and solutions proposed and tested in hardware, where appropriate.

WPB. Development of alternative control strategies (centralised versus decentralised)

Several levels of decentralization can be applied, ranging from a fully decentralized approach to a hierarchical control. These approaches have been studied in-depth and comparatively assessed. In particular, the application of decentralized, intelligent techniques has been investigated.

WPC. Alternative Network designs

Inverter dominated Microgrids are not necessarily subject to the same frequency limitations, as traditional power systems. The advantages of operation at variable frequencies including DC operated Microgrids have been investigated together with the application of modern protection philosophies and modern solid state interfaces and other devices.

WPD. Technical and commercial integration of Multi-Microgrids

Integration of multiple Microgrids into the operation of a de-carbonised power system, perhaps with millions of active participants, requires radically new control and management structures and practices to make possible the interface with the upstream DMS and the operation of co-ordinated, but de-centralised markets for energy and services. Specific new software tools and simulation approaches have been studied.

WPE. Standardisation of technical and commercial protocols and hardware

To promote a ***mass scale*** development of Microgrids, it is essential to develop standards of technical and commercial protocols that will allow easy installation of microsources with plug and play capabilities. This objective has been met by building on established IEC standards while taking into account the particular requirements of a Microgrid.

WPF. Field trials of alternative control and management strategies

Evaluation of the control strategies developed and tested in laboratory on actual Microgrids is clearly needed. Islanded operation is a major challenge. In this project field tests on 8 test sites have been undertaken aiming to examine the performance of various aspects of Microgrid operation. The focus has been on technical feasibility rather than large scale demonstration.

WPG. Impact on power system operation

The distinct advantages of Microgrids on power system operation, regarding increase of reliability, reduction of losses, environmental benefits, etc. have been quantified at regional, national and EU level.

WPH. Impact on the development of electricity network infrastructures

Large penetration of Microgrids will have a massive impact on the future operation and development of electricity networks. Microgrids must become a key part of the overall network reinforcement and replacement strategy of the aging EU electricity infrastructure. New tools and simulation approaches have been developed to address this objective and to quantify the benefits of Microgrids.

The Consortium comprised major European manufacturers, power utilities and potential Microgrid operators and research teams with complementary, high quality expertise. Participants of the proposal have cooperated effectively in the previous EU Microgrids project acquiring significant know-how and gaining world-wide recognition in this field.

II.Major Achievements of the Project

1) Investigation of new micro source, storage and load controllers to provide efficient operation of Microgrids

- A template for data collection for DG sources, storage and controllable loads in order to allow the seamless transition between isolated and interconnected operation has been completed and a data structure suitable for implementation into a data base.
- Microgrid stability was studied and a special control system was proposed.
- Different approaches of the problem caused by reactive and active power flow in meshed low voltage Microgrids with long lines has been investigated and tested by laboratory prototypes.
- An Intelligent Load Controller which allows the implementation of Intelligent Agents' Technology has been designed and laboratory tested.
- Inverter performance for ancillary services and Fault Ride Through (FRT) capabilities has been investigated.
- The islanding detection method for inverter dominated low voltage networks has been developed and evaluated.

2) Development of alternative control strategies (centralised versus decentralised)

- Control strategies were developed for both centralized and decentralized approach. In the Centralized approach the work focused in the development of online security and forecast modules as well the adaptation of scheduling functions for laboratory needs.
- In the Decentralized approach the Multi- Agent system (MAS) concept was adopted. For the Decentralized Control system, algorithms and general implementation structures were developed based on common used platforms (Jade).
- The MAS software developed was installed in Kythnos island and in Wallstadt.
- Centralized and decentralized strategies were implemented and tested in Laboratory environment.

3) Alternative Network designs

- In-depth analysis of the radial vs. meshed configuration regarding power losses, voltage profiles, short circuit current levels, etc. has been performed.
- The use of fault current limiting (FCL) devices has been examined including economic analysis.
- A micro-grid protection concept based on low voltage circuit breakers with adjustable settings based on Microgrid's operating mode has been developed.
- Novel self-adjusting protection schemes, combining real time data (Microgrid topology, loads and generation) and off-line data available e.g. from energy management systems have been investigated.
- Research on "Active Islanding Detection" (AID) methods, with special regard to SELFSYNC™ controlled inverters, has been carried out and a suitable AID method has been developed.
- Implementation of a robust protection strategy for a Microgrid in islanded mode was made, wrt the automatic isolation in case of a fault on the feeder and a storage system capable of providing adequate fault current.

- A prototype single phase inverter Fault Current Source (FCS) has been developed.
- A demonstrator 20kVA ride-through grid linked inverter intended to connect energy storage and renewable energy sources to the utility grid with the additional possibility of supplying a local load when running in islanded mode has been designed.
- The possibility of adapting standard industrial converters for Microgrid applications have been studied and ways of modularizing the converter system so as to achieve flexibility and low cost have been analyzed.
- A study on the possibilities and advantages of DC Microgrids has been conducted, including load sharing among grid forming units.

4) Technical and commercial integration of Multi-Microgrids

A detailed definition of possible Microgrid operating modes has been made for both normal and emergency operation and a control and communication scheme has been proposed in order to achieve efficient multi-Microgrid operation. Also, the main functions for a new control and management structure - the Central Autonomous Management Controller (CAMC) - have been identified.

Derivation of Microgrid dynamic equivalents has been performed using: a) classical system identification techniques for a physical model, which was derived from the behaviour of the different components of a Microgrid, and b) neural networks (such as TDNNs).

New algorithms for distributed state estimation have been developed and tested, as well as fuzzy state estimation routines were applied to electrical distribution systems.

Tools for the coordination of Voltage VAR control for multi-Microgrids (MV and LV) have been developed based on conventional approaches and on optimization procedures that meta-heuristic approaches (using Particle Swarm Optimization techniques).

A complete simulation platform was developed and implemented, which involved the design of several dynamic models for DG units. The simulation platform developed allows the study of decentralised control strategies including coordination with load curtailment.

- In black start conditions, the sequence to be followed that minimizes loss of supplied energy has been identified, considering the controllability of the DG units installed at the MV level and having in mind the type of control existing in the different Microgrid cells.
- The development of Ancillary Services Markets has been studied, namely scheduling of secondary voltage and frequency reserves that individual Microgrid could offer to the system, taking full participation of demand side.
- Models for Economic Scheduling have been developed including models for adjustment markets in order to identify changes of generated or demand powers from agents in the Microgrids.

5) Standardisation of technical and commercial protocols and hardware

- The available and under work DG standardization efforts on technical and commercial (market integration) issues have been reviewed.
- The specification of the operation of Microgrids and Multi-Microgrids in terms of data communications has been covered. A comparison with the Advanced Metering Interface case has been used as reference for the establishment of the communication infrastructure.
- Two implementations of the IEC 61850-7-420 standard have been applied. The first one includes several extensions to incorporate other equipment not included in the standard (namely controllable loads and measuring devices) and an alternative communication protocol (XML-RPC). The second one forces the

standard data model into mapping each particular variable of one commercial PV inverter while adhering to the original MMS communication protocol.

6) Field trials of alternative control and management strategies

The functionalities tested in 8 pilot sites have been defined and several tests have been performed. It should be noted that the aim of these tests was mainly to prove the technical feasibility rather than performing large scale demonstration to investigate economic or social benefits. More specifically:

- Testing of the interconnected mode has been conducted and experiment results outlined though real time measurements and system evolution of variables in Labein's laboratory installation.
- Experimental validation of islanding mode of operation at the Gaidouromantra (Kythnos) pilot site. Options for the expansion of the Kythnos Microgrid were studied. Smart load controllers have been installed along with an appropriate communication solution.
- Field tests of the transfer from interconnected to isolated mode of Microgrids operation & vice versa at the **EDP**'s study case - Microturbine serving Ilhavo municipal swimming-pool loads. Power quality was also analysed.
- Experimental validation of islanded Microgrids by means of smart storage performed at the Bronsbergen holiday park of Alliander. Parallel operation of the inverters was demonstrated to full satisfaction, as well as the lifetime optimization functions of the storage system.
- Field test on the transfer between interconnected and islanding mode at the ecological settlement in Mannheim-Wallstadt (MVV). Agent technologies for decentralized control have been installed and tested.
- Experimental validation of islanding mode of operation at CESI RICERCA test facility. A Power Ride-Through Inverter (RTI) has been used to control Microgrid parameters (V, f, etc.) and to test the transition of operation from "Microgrid directly connected to the main grid" to "microgrid connected to the main grid with the interposition of the inverter" and reverse, under active and reactive power flow conditions.
- Field test on MV islanding at the island of Bornholm operated by OSTKRAFT. Several experiments were performed including demonstration of "drop of a 2 MW generator", "passage to island mode" and "passage to emergency mode". A Fuzzy State Estimator has been developed and tested.
- Field tests on Microgrids fed by biogas power plant, were undertaken by **INCO** partners. Optimal conditions for higher biogas production were defined and tests on its quality have been performed. Transfer to island mode has been tested.

7) Impact on power system operation

- Typical rural and urban distribution networks have been identified for different European countries (Portugal, Germany, United Kingdom, Denmark, the Netherlands, Poland, Italy, Macedonia and Greece) for Low Voltage (LV), Medium Voltage (MV) and High Voltage (HV) levels, in order to quantify technical, environmental and economical benefits of Microgrids (i.e. regarding power quality and security of supply, reduction of losses, economics of operation).
- A set of general and technical indices was defined, such as different scenarios for DER Penetration Level, Active Power Loss reduction in transmission and distribution networks, amount and the value of upstream network capacity released, CO2 emissions according to

different DG penetration scenarios and various reliability indices to quantify the benefits that can be provided by Microgrids.

- The potential of Microgrids for enhancing the quality of supply seen by the end customers for a number of real (typical) distribution networks taking into account their operation conditions has been investigated.
- The environmental benefits of Microgrids based on the economic Microgrid scheduling algorithms have been calculated. It turned out that highest benefits for Microgrids operation can be achieved if Microsources are scheduled according to a combined optimization strategy where both interests of system operators and of Microsource operators are considered to achieve most economic and environmentally friendly operation meeting all technical constraints.
- The social benefits of Microgrids have been identified.

8) Impact on the development of electricity network infrastructures

- Typical network models for different voltage levels in Europe, identified according to established criteria in collaboration with WPG, have been developed. Different specific tools have been developed to assess the system-level impact of Microgrids on generic distribution networks, regardless of the specific applications. Southern and Northern network scenarios have then been studied and the relevant impact of Microgrids on European distribution networks has been quantified.
- Transmission network studies have been carried out to identify the Microgrids impact owing to the possibility of controlling transmission flows through dispatchable micro-DG and controllable loads.
- A novel methodology has been outlined in order to assess the system-level technical, energy and environmental benefits brought by microgrids, also considering their impact on centralized generation. Specific focus has been set on cogeneration-based Microgrids, thus extending the analyses to include also the heat generation issue, which is becoming of prominent interest in the latest years.
- In terms of impact on conventional generation, the capacity credit of micro-DG technologies and controllable loads has been quantified. In addition, the potential of Microgrids to provide load balancing and frequency support services and to delay conventional generation capacity expansion has been assessed.
- A Microgrid roadmap has been formulated with the aim of identifying the potential evolution of Microgrids and their future role within power systems in order to carry out sensible long-term decisions.
- Different business scenario models within Microgrids have been formulated and studied, with the specific aim of allocating the benefits created by Microgrids among the different subjects involved. These business models have also addressed environmental aspects.
- Investigations based on a multi-criteria assessment framework, aimed to address the impact of Microgrids in terms of network investment and operational benefits, and to capture complex decision maker preferences in the presence of uncertainties by exploiting decision theory tools, have been carried out.
- Environmental and upstream network impacts/benefits have been framed within an external cost approach, with the objective of carrying out comprehensive economic assessment of Microgrid solutions.

- The need for a suitable commercial and regulatory framework to enable Microgrids development has been pointed out along with the gaps in the status quo, and the main characteristics of such a framework have been outlined from a high level perspective.
- The results obtained show great potential of Microgrid solutions to improve energy efficiency and security of supply, reduce the carbon footprint of the energy system operation, and maximize the deployment and defer the update of current and future network infrastructures.

The scientific and technical work carried out in the framework of the project leads to the development of new hardware prototypes, models, algorithms and processes, whose knowledge resides in the partners in charge of each specific development. All the associated information is shared among the partners, through the technical reports that constitute deliverables of the project, but also by internal reports, direct contacts and visits. The partners of the project have decided to release all deliverables to external dissemination via the project web-site http://www.microgrids.eu

III.Project Partners

	Participant name	Short name	Country
1	Institute of Communication and Computer Systems – National Technical University of Athens	ICCS/NTUA	Greece
2	ABB Schweiz AG, Corporate Research	ABB	Switzerland
3	SIEMENS AG	SIEMENS	Germany
4	SMA Solar Technology AG	SMA	Germany
5	SYSTEMS SUNLIGHT S.A.	SYSTEMS SUNLIGHT	Greece
6	ANCO S.A.	ANCO	Greece
7	Emforce B.V.	EMforce	The Netherlands
8	EDP – ENERGIAS DE PORTUGAL S.A.	EDP	Portugal
9	N.V. Continuon Netbeheer	Continuon	The Netherlands
10	MVV Energie AG	MVV	Germany
11	Technical University of Denmark	DTU	Denmark
12	CESI RICERCA S.p.A.	CESI RICERCA	Italy
13	Lodz-Region Power Distribution Company	LRPD	Poland
14	Centre for Renewable Energy Sources	CRES	Greece
15	Fundacion LABEIN	LABEIN	Spain
16	The University of Manchester	UM	UK
17	INESC Porto – Institute de Engenharia de Sistemas e Computadores do Porto	INESC Porto	Portugal
18	Fraunhofer IWES	IWES	Germany
19	Association pour la Recherche et le Développement des Méthodes et Processus Industriels	ARMINES	France
20	ZIV PmasC S.L.	ZIV	Spain
21	Intelligent Power Systems a division of Turbo Genset Co Ltd.	I-Power	UK
22	University of Lodz	UL	Poland
23	Sts Cyril and Methodius University, Faculty of Electrical Engineering	UKIM	FYROM
24	Research Center for Energy, Informatics and Materials of the FYROM's Academy of Sciences and Arts	ICEIM-MANU	FYROM
25	Bioengineering DOO	BIG	FYROM
26	IMPERIAL COLLEGE	IMPERIAL	UK
27	ABB AB	ABB AB	SWEDEN