DERri
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PROPOSAL UNDER DERRI

User-Project Proposal:

User-Project Acronym	MASGrid
User-Project Title	Multi-Agent System for Self-Optimizing Power Distribution Grids
Main-scientific field	Smart Grids
Specific-Discipline	Control and Regulation

Lead User of the Proposing Team:

Name	DI Alexander Prostejovsky
Phone	+43 (1) 58801 376852
E-mail	prostejovsky@acin.tuwien.ac.at
Nationality	Austria
Organization name, web site and address	Automation and Control Institute (ACIN) / Vienna University of Technology (http://www.acin.tuwien.ac.at/)
Activity type and legal status* of Organization	1
Position in Organization	Research Assistant

* Higher Education Institution (1) – Public research organization (2) – Private not-for-profit research organization (3) – Small or Medium size private enterprise (4) – Large private enterprise (5) – other (specify)

Additional Users in the Proposing Team:

Name	Dr.techn. Munir Merdan
Phone	+43 (1) 5880137656
E-mail	merdan@acin.tuwien.ac.at
Nationality	Austria
Organization name, web site and address	Automation and Control Institute (ACIN) / Vienna University of Technology (http://www.acin.tuwien.ac.at/)
Activity type and legal status* of Organization	1
Position in Organization	Post-Doc / group leader

* Higher Education Institution (1) – Public research organization (2) – Private not-for-profit research organization (3) – Small or Medium size private enterprise (4) – Large private enterprise (5) – other (specify)

Date of submission	30.11.2012
Re-submission	YES_______ NO___x___
Proposed Host TA Facility	ICCS-NTUA, RISOE, TECNALIA
Starting date (proposed)	April 2013

Summary of proposed research (about ½ page)

The MASGrid project is a co-operative project between the Vienna University of Technology and AIT Austrian Institute of Technology with the aim of developing a novel control system approach using Multi-Agent Systems (MAS) for energy distribution grids (commonly referred to as Smart Grids). Given the on-going change away from energy production solely performed by bulk power plants towards an increasing number of small distributed energy resources (DERs), current control concepts do not suffice any longer. MASGrid methodically addresses the problems of autonomous grid behaviour, grid optimization and interoperability with legacy systems. MAS are a promising technology to cope with complex networks consisting of a large number of different interconnected devices and hence overcome the deficiencies of current control concepts. The proposed control approach assigns each DER a so-called Automation Agent that takes appropriate actions based on observation of its device and environment as well as negotiations with other agents in order to provide the necessary grid functionality. The approach consequently makes use of the decentralized nature of MAS in order to eradicate single-points-of-failure due to ICT malfunctions. As MASGrid also aims to stay aligned with IEC 61850, the use of OPC UA is enforced for its flexibility and data model support.

The original project proposal included the verification of the developed control design in a real physical environment in AIT's SimTech laboratory. Since the design is supposed to be universally applicable, gaining experience and experimental data with different hardware in other environments is crucial for MASGrid. The proposed test cases involve the verification of the autonomous behaviour of the developed agent system both in normal and island operation mode, as well as its ability to optimize and reconfigure the electric network. The DERri transnational access (TA) opportunity could provide vital data for successfully completing the project.

State-of-the-Art (about 1 ½ page)

The continuous growth of electric energy consumption as well as the upcoming large-scale integration of distributed energy production units, based on renewable energy resources (photovoltaic systems, wind turbines, etc.) result in an increasingly complex electric network [1]. However, today's grids form a vertically integrated scheme with centralized generation, distributed consumption, limited inter-connection capabilities between the control areas, and commercial and regulatory frameworks that are not harmonized for mutual advantage [2]. The current control approach of using a centralized Supervisory Control and Data Acquisition (SCADA) system – also known as Energy Management System (EMS) for the transmission domain and Distribution Management System (DMS) for distribution grids – has deficiencies in flexibility and adaptability and is no longer sufficient for certain control operations [3]. Conventionally, energy management is ensured by a central facilitator whose program is based on long series of conditional branches. Even if this solution achieves a constant supply of the load, it cannot fulfil other objectives such as fault tolerance of an element [4]. Consequently, the search for a control strategy gets more and more difficult with increasing system size. Besides, in present power system networks, a single fault can lead to massive cascading effects affecting power supply and power quality [5]. Moreover, applied monitoring, analysis, and control technologies are sometimes too slow, limited to protecting only specific components. The process of system restoration is mainly based upon the operators' experience and results from offline studies [6].

Results of actual research and demonstration projects show that the realization of active distribution networks, also referred to as Smart Grids, is a promising way to overcome the deficiencies of current implementations. Realizing a Smart Grid requires the establishment of an innovative system architecture in order to provide coordinated monitoring and control capabilities in the heterogonous grid environment. The system architecture defines how well the system components are utilized and in what manner the application's functionalities are integrated and the services are delivered. The changed demands on distribution grids require the application of intelligent methods to keep the system state within legal bounds at any time. Multi-Agent Systems (MAS) are considered as an approach able to realize and implement the above described functionalities and services for intelligent devices in a Smart Grid [7]. MAS offer a convenient way to cope with the dynamics in large complex systems, making the control of the system decentralized and thereby reducing the complexity, increasing flexibility, as well as enhancing fault tolerance [8]. Agents have the ability to coordinate several different devices like sources, loads or switches in a decentralized manner and are capable of finding a technically and economically (local) optimal operation point under consideration of all kinds of constraints [9]. In this context, a distributed system architecture enables local data processing and minimizes the need for massive data exchanges (e.g. capable of providing local fail proof, feeder level forecasts aggregated at substation level). A distributed system can enable the high performance needed for preventing or containing rapidly evolving adverse events [8]. In electric power systems, the agents can be utilized e.g. for controlling, communication and protection of the grid [10], as well as monitoring, visualizing and coordinating energy use within the home [11]. The issue of fault diagnosis and reconfiguration is addressed in [12]. In this context, Li Liu et al. [13] have described the need for fault detection in naval shipboard power systems; Huang et al. [14] have presented a multi agent approach for fault detection using nonlinear parameter identification techniques. Solanki et al. [7] propose different approaches for restoration of the power system by distributed reconfiguration. Chouhan et al. have presented a multi-agent based system for distribution network reconfiguration [15]. Among several projects dealing with MAS, one has already successfully implemented a MAS control in a pilot microgrid on Kythnos island, Greece [16]. However, despite the growing awareness and the on-going research activities of MAS technology in the power distribution area, there are still some requirements that remain to be considered, such as

- the interaction between distinct conceptual entities, the ability to locally undertake analysis and decisions without a central facilitator,
- the adaptability of the system to easily integrate new elements, and
- the ability to provide self-corrective reconfiguration and restoration as well as to handle randomness of loads and market participants in real-time [4, 17].

Preliminarily, a MAS architecture was developed and recently successfully implemented at the ACIN's laboratory palette-transfer system showing valuable advantages in self-diagnostics [18], robustness [19] and self-reconfiguration [20].

At present, the proposed MAS architecture based on the palette-transfer system has been adapted and enhanced for the electricity distribution domain and results of early development stages have been published [21,22,23].

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Detailed Description of proposed project : Objectives – Expected Outcome – Fundamental Scientific and Technical value and interest (2-3 pages)

Starting Point

In the frame of an earlier project, the Automation and Control Institute (ACIN) developed an automation agent architecture which was recently successfully tested on the "Testbed for Distributed Holonic Control". The architecture clearly separates the control software of physical components into two layers: the High Level Control (HLC) and the Low Level Control (LLC). The HLC incorporates an ontology-based world model that provides an explicit representation of the agent's immediate environment and supports reasoning about its state, diagnostic activities and the coordination with other agents. The application of the ontology will enable the systematic integration of different functionalities and activities within the electrical power system, integrating on the one side data and notifications that require real-time attention and on the other side data associated with networks, their configuration, condition, and other operational and business data. The subjacent LLC manages the physical component by using a limited set of reactive behaviours thereby meeting required real-time constraints. In the present project the LLC is based on the standard IEC 61499, which is well-suited for distributed applications due to its event-driven execution model and offers a framework for the integration of run-time control and diagnosis applications. Besides, the IEC 61499 can be used as an integration, extension and verification mechanism for the systems based on IEC 61850, which defines information and information exchange models for substation automation functions and primary equipment. This approach forms a very flexible, scalable and interoperable architecture which is capable to master the above described complexity of the Smart Grid.

Main Project Objectives

MASGrid aims at realizing automated power distribution grids able to monitor and reconfigure themselves. It considers a distributed management and control approach which is able to master the upcoming high penetration of distributed energy resources as well as the upcoming integration of electro-vehicles in a very complex distribution system, especially in areas of high population.

The MASGrid project will methodically target, research and develop a Multi-Agent System framework for the self-optimization of power distribution grids. Therefore, the main target of the project is to radically improve the operation of power distribution grids through a fully distributed management, control and diagnostics approach.

Scientific and Technological Objectives

MASGrid aims to create several scientific and technological innovations, which will be the door-openers for the development of future intelligent power distribution grids with a Multi-Agent System approach. **To realize these aims the following objectives have to be achieved, with the hindmost point being the most relevant for the transnational access:**

- Multi-Agent System architecture of power distribution grids

  Research and development of a MAS system architecture for power distribution grids which supports self-reconfiguration and self-diagnostics.

- Algorithms and methods for power distribution grids topology self-reconfiguration

  Plug-and-play self-reconfiguration of power distribution components (e.g. PV devices, storage units) based on automatically detected changes (e.g. generation/load peaks, faults). The MASGrid system should be able to master the “unpredictable” nature of renewable energy sources and mobile consumers (i.e. electric vehicles) in the power distribution network.

- Distributed and adaptive MAS-based control strategy

  Agents have the ability to coordinate several different devices like sources, loads or switches in a decentralized manner and are capable of finding a technically and economically optimal operation point under consideration of various constraints. Single-points-of-failure should be eradicated in order to allow basic operation of the grid even under partial failure of the ICT technology.

- Advanced monitoring capabilities of power distribution components

  The distributed MAS-based monitoring capabilities provide the basis for advanced diagnostics services.

- Legacy system integration

  Integration of the MAS system into existing legacy systems like SCADA and distribution management systems for power distribution grids is necessary in order to allow an integration of the proposed distribution management and control approach.

- **Proof-of-concept demonstration**

  The demonstration will show the applicability of the developed MAS technology in the AIT SimTech laboratory for testing advanced Smart Grids services. Controller-Hardware-in-the-Loop (CHIL) and Power-Hardware-in-the-Loop (PHIL) methodologies, provided at AIT, will be used to test the capabilities of the MASGrid system in a realistic environment. **To keep the design easily adoptable for other systems, the control approach preferably is tested in other laboratories as well.**

As stated before, the original project proposal already included the verification of the MAS control design in a real power distribution environment at AIT’s SimTech laboratory. In order to avoid the design to become too customized for specific hardware, **the utilization of other testing facilities (i.e. Research Infrastructures) is essential for gaining experimental values**. The proposed activities are:

- Evaluation of the transnational access (TA) infrastructure and its relevance for testing the control approach in order to derive a set of representative test cases, which will later be carried out on-site.
- Adaption of the developed design to the selected testing facility. The majority of this part will already be done at the home institution after receiving details of the TA laboratory setup, but in close co-operation with the receiving RI.
- Testing of the autonomous behaviour of the agent systems. As the control approach is

designed to be truly decentralized in order to avoid single-points-of-failure, scenarios like the islanding test case described in [21-23] help to understand and improve the agent behaviours.

- Testing the global reconfiguration algorithms. A singleton special purpose agent, the so-called System Agent, observes the complete grid state during normal operation and calculates the optimal operational point for given criteria (i.e. the power loss with respect to available production and line capacities).
- Recording of measured data for further evaluation and dissemination.

Proposed TA infrastructure

The laboratory has to offer a low- to medium voltage distribution grid with a selection of DERs and other grid devices. In more detail, the following items are of importance:

- A representative set of devices including some or all of the following categories:
    - Loads (e.g. RLC bank),
    - Supplies (e.g. PV, Diesel generator),
    - Storages (e.g. battery),
    - Switching devices (e.g. circuit breaker),
    - Measurement devices,
- an interconnection to an external grid,
- the ability of changing the grid topology using switches and breakers.

For implementing the developed control design, the following information system features are necessary:

- All energy devices should be controllable via a common communication infrastructure (e.g. an open SCADA interface), preferably using OPC UA / OPC Classic.
- A Microsoft Windows workstation capable of running the JADE agent platform and the OPC tools simultaneously. To demonstrate the decentralized character of the MAS, distributed controllers running JADE would be preferable.

In accordance to the proposed activities in this section, the following test cases are going to be performed. As the tests mainly depend on the available equipment and infrastructure, this part is subject to change.

- Normal operation mode with external grid connection:
    - Constant loads and supplies;
    - Variable loads.
- Islanding test case:
    - Normal operation without external grid connection with constant and/or variable loads;
    - Sudden disconnection from external grid;
    - Seamless reconnection to external grid.
- Grid reconfiguration and optimization:
    - Calculation of optimal grid configuration for several given load and supply scenarios and verification, if results are feasible;
    - Manual reconfiguration of the grid according to the previous optimization results and verification, if the optimum was actually hit;
    - Autonomous reconfiguration according to the previous results.

- Evaluation and revision of the control concept:
    - The tests will be repeated several times in order to iteratively enhance the control concept by tweaking and adapting parameters and algorithms as necessary.

Originality and Innovation of proposed research – Broader Impact (1-2 pages)

Considering the widely conjured paradigm change of distributed energy generation and its impact on energy control systems, promising technologies able to meet those new requirements have yet to emerge into practical applications. A considerable number of Smart Grid field trials are being currently executed or have already been completed, each dealing with certain aspects of the whole issue. With the numerous proposed and implemented control approaches, the future development will most likely be a conglomerate of the best ideas, as none of the approaches significantly stands out of the rest. Given the already mentioned distributed character of Smart Grids, it is surprising to find no MAS approaches which consequently introduce a decentralized control concept.

MASGrid aims to address this deficiency by adapting the Automation Agent concept from a preceding project and demonstrate its proven advantages, e.g. self-diagnostics and self-reconfiguration, in the electric distribution domain. The agents provide monitoring and diagnostics abilities required for the robust functioning of components in the distributed environment. By gathering data from a variety of sensors and combining them with information from different interpretation algorithms and multi-agent interactions to generate an overall diagnostic conclusion and inform other responsible agents. Furthermore, the MAS will automatically reconfigure the power system topology in case of changed conditions of the system to keep nodal voltages within predefined bounds and avoid overstressing of equipment. Moreover, it is of a vital importance to offer the human user a complete overview of the agent's activities as well as a possibility to supervise its actions through an adequate human-machine interface (i.e. SCADA).

Among others, one especially notable difference to other MAS approaches on electric distribution grid control is the deployment of the so-called Bus Agent (BAG), which does not directly relate to a physical device but instead acts as a facilitator. Each BAG observes and controls the other Automation Agents of the devices connected to the corresponding bus. This concept offers a number of advantages:

- It eradicates the problem of single-points-of-failure. Although the control concept provides the singleton System Agent which carries out global supervision and optimization tasks, the Automation Agents are not dependent on it for maintaining basic grid functionality.
- It significantly simplifies agent negotiations and hence the number of communicative acts. Only the BAGs are carrying out negotiations among each other, whereas the other Automation Agents are simply responding to BAG requests and enquiries.
- It allows representation of both the logical and physical network topology in an undirected graph structure, in which busses are considered as nodes and lines as edges. Each BAG has its own graph representation of the grid with itself as the root node. The nodes carry information about the available power production capacity and bus voltage, and the edges about available line capacity. This allows the BAGs to reach quick decisions while again effectively reducing the number of communicative acts.

One major target of MASGrid is to provide grid optimization functionalities in terms of power loss minimization under given constraints like voltage levels. Since the BAGs possess only local information and therefore (generally) cannot find global optima, a superior agent, the System Agent, is necessary to take over this task. As opposed to other MAS approaches, this superior agent directs the Automation Agents into the desired working point but is not required during normal grid operation.

In order to demonstrate the abilities of the developed control approach in a real environment, the original project plan envisaged to merge ACIN's competencies with the Energy Department of the AIT Austrian Institute of Technology, which has outstanding expertise and state-of-the-art infrastructure in the field of the Smart Grids development. As the project also aims to provide a flexible and universal solution, the opportunity for a TA in the frame of DERri will help to expand the control approach accordingly by making use of different hardware in addition to the equipment provided by AIT. Furthermore, the cooperation will increase the visibility of the project outside of Austria and substantially help to gain further input acquired by potential new information sources.

Proposed Host TA Infrastructure/Installation – Justification (about one page)

Several institutions in the frame of DERri offer the appropriate infrastructure to conduct experiments for the MASGrid project. Given the focus on the islanding case in early MASGrid developments stages and the therein considered test network, the Institute of Communication and Computer Systems (ICCS) of the National Technical University of Athens (NTUA) offers the most suitable laboratory setup to verify the developed designs and is therefore the preferred choice for the transnational access programme.

The Electric Energy Systems Laboratory (EESL) of ICCS-NTUA offers a low-voltage (LV) microgrid that consists of a representative set of DERs, namely two PV generators, a wind turbine, battery energy storage, controllable loads as well as a controlled (switched) interconnection to the local LV grid. The battery inverter is capable of regulating the voltage and frequency when the system operates in islanding operation mode by taking over the control of the active and reactive power. In addition to the physical grid equipment, a rack of a commercially available real time digital simulator (RTDS) running dedicated electric power network simulation software is installed. A switch-mode amplifier interconnects the RTDS with the physical equipment and enables the users to perform power-hardware-in-the-loop (PHIL) experiments. This allows expanding the physical network, which only consists of a limited number of components, into a greater scale by coupling it with virtual equipment and hence performing more complex experiments.

Apart from its physical aspects, the laboratory also provides apt communication and control infrastructure suitable to support the development concepts of MASGrid. It is explicitly designed to support distributed control using Multi-Agent Systems (MAS) in order to address specific operational problems of future energy distribution grids like the increasing number of DER owners and lack of dedicated communication facilities, as well as new tasks like local voltage regulation and autonomous fault recovery capabilities. According to the information provided by one of the ICCS staff members, the MAS is actually based on the Java Agent Development Framework (JADE).

Given all the above stated laboratory features, **ICCS-NTUA** covers all the necessary facilities both on the hardware and software side, making it perfectly suitable for performing a variety of significant experiments to test and verify the proposed control concept. First-hand information about the local infrastructure suggests that the implementation of the developed MAS control can be conducted with reasonable time and effort.

Apart from ICCS-NTUA, several other research infrastructures have appropriate laboratories, notably RISOE in Denmark and TECNALIA in Spain. RISOE's SYSLAB facility offers an extensive 400V network consisting of three substations, whose decentralized setup promotes the development of distributed control concepts. TECNALIA focuses more towards component tests, yet allows the development of grid control using a proprietary SCADA interface.

Synergy with ongoing research (about ½ page)

MASGrid is a co-operation between the Technical University of Vienna, which takes over the development of the control system, and the AIT Austrian Institute of Technology, which provides its expertise as well as simulation models and laboratory infrastructure. Furthermore, AIT is Austria's largest non-university research institute and among European research institutes a specialist in the key infrastructure issues of the future, it is involved and directly responsible in numerous projects in the Smart Grid domain, hence offering important expertise as well as opportunities for related future research. As AIT's Energy Department has already conducted several tests using IEC 61499 for power system control, distributed control techniques are shifting more and more into focus.

The Electric Energy Systems Laboratory (EESL) as part of the Institute of Communication and Computer Systems at the National Technical University of Athens has already participated in more than 40 mostly collaborative research projects, many of which are directly or indirectly related to the subject of electric distribution grid control. Among those activities, the EESL has already successfully implemented a Multi-Agent System for power system control in a pilot microgrid on Kythnos island, Greece [16]. As their control approach has several apparent likewise features inherently given by the MAS as well as the layered structure compared to the one used in MASGrid [20,21], the TA would offer the great chance to exchange knowledge in both directions and to raise, in continuation of the planned activity, potential future co-operations.

Dissemination – Exploitation of results (about ½ page)

The MASGrid project emphasizes scientific and industrial visibility both inside and outside of Austria by means of disseminating results in industrial journals and on scientific conferences. To set MASGrid apart from other comparable research projects, the experimental data resulting from the DERri exchange will enhance the impact of the proposed approach as opposed to mere simulation data. For this reason, the results lend themselves to be published cooperatively within the frame of DERri. The verification for the applicability of MASgrid by successfully implementing it on real hardware will also allow to approach electric network operators and related companies. By raising their interest in new technologies with the aid of working examples, ideas for constitutive projects and even potential future research co-operations may emerge.

Last but not least, the results are going to be included in the Ph.D. thesis of the proposing team's leader, Alexander Prostejovsky, with references to all external persons and institutes involved.

Time schedule (about ½ page)

The estimated period for executing the necessary tasks is 4 weeks. In order to have sufficient time to perform first implementations at the AIT, the earliest time for the exchange would be April 2013.

Task	Week 1	Week 2	Week 3	Week 4	Comment
Evaluation of laboratory setup					Parts of this task are performed before the TA
Implementation of the control system					
Performing islanding test case					
Performing reconfiguration tests					
Test refinements					Adjustment of parameters and design changes if necessary
Evaluation of results and consideration of dissemination possibilities					
Documentation					

Description of the proposing team

DI Alexander Prostejovsky is the main developer on the MASGrid project and willing to seize the transnational access opportunity. He graduated as Diplomingenieur (equivalent to MSc) on Control Engineering in fall 2011 at the Automation and Control Institute (ACIN) of the Vienna University of Technology, where he is currently working as a research assistant in order to achieve the PhD degree. His research activities include modelling and development of the high-level part of the agent system, power system modelling as well as mathematical optimization. In the frame of MASGrid he contributed to three publications (see [21-23] in the state-of-the-art section of this document).

Dr. Munir Merdan is the project leader of MASGrid and directly responsible for its successful accomplishment. He is also involved in the design and development of ontologies and the Automation Agent architecture. He studied Mechanical Engineering at the University of Sarajevo, Faculty of Mechanical Engineering, and finished his studies in 2001 with a Master degree. He received the PhD degree in electrical engineering from the Vienna University of Technology, Vienna, Austria, in 2009. His research focuses on the application of artificial intelligence techniques for achieving agile control in the manufacturing environment. He is author and/or co-author of 57 publications (http://users.acin.tuwien.ac.at/mmerdan/?site=2). Munir Merdan conducted and led several projects and was awarded two times for his work with the Wirtschaftskammerpreis in 2006 and 2007 by the Viennese Economic Chamber. He is the editor-in-chief of the International Journal of Advanced Robotic Systems and member of the IEEE-IES Technical Committee on Industrial Agents as well as IEEE-IES Technical Committee on Distributed Intelligent Systems. Currently, he holds the position of Head of Research for Cognitive Automation at the Automation and Control Institute.

One additional person, either from the Vienna University of Technology or the Austrian Institute of Technology, might be required for several days in the implementation phase in order assist the lead user of the proposing team (Alexander Prostejovsky) setting up the experiments.