Novel Hybrid Design for Microgrid Control

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Abstract— **This paper proposes a new hybrid control system for an AC microgrid. The system uses both centralised and decentralised strategies to optimize the microgrid energy control while addressing the challenges introduced by current technologies and applied systems in real microgrid infrastructures. The well-known 3-level control (tertiary, secondary, primary) is employed with an enhanced hierarchical design using intelligent agent-based components in order to improve efficiency, diversity, modularity, and scalability. The main contribution of this paper is dual. During normal operation, the microgrid central controller (MGCC) is designed to undertake the management of the microgrid, while providing the local agents with the appropriate constraints for optimal power flow. During MGCC fault, a peer-to-peer communication is enabled between neighbouring agents in order to make their optimal decision locally. The initial design of the control structure and the detailed analysis of the different operating scenarios along with their requirements have shown the applicability of the new system in real microgrid environments.**

Index Terms-- **Microgrids, Multi-agent systems, Centralized Control, Decentralized Control, Hybrid intelligent systems.**

I. INTRODUCTION

Renewable Energy Sources (RES) have posed new challenges to the operation of the electric power system and to the integration to the Distribution Network. Particularly the uncertainty that is inherent in the generation mix and the intermittent output power makes the grid less reliable. Microgrids (MG) have been proposed [1] as a possible solution to that problem. Even though there is no universally accepted definition of MGs, it is commonly accepted that MGs contain energy sources, energy storage systems (ESS) and loads, and are able to operate in either a grid-connected or an islanded mode. The MG concept has evolved significantly during the last decade and it can be exploited as the main building block of the Smart Grid.

A number of MG applications have emerged including residential/commercial facilities, industrial sites, offshore oilrigs and spacecrafts. Depending on its particular needs, a custom-made control system must be designed. Advanced control techniques present key enabling technologies for the deployment of a MG system. This is because there are unique challenges that need to be addressed and that MGs have to operate as coordinated, stand-alone units. Many control schemes have been proposed regarding MG operation and integration, ranging from fully centralised to fully decentralised, with different degrees of success, benefits and challenges. Despite the fact that there is a variety of possible solutions to MG control systems, the majority of these follows a certain hierarchy, the so-called 0-3 level hierarchical control [2], each level of which can be implemented in either a centralised or a decentralised way.

This paper introduces a novel conceptual hybrid control system for an AC MG that combines both the centralized and decentralized designing principles. By exploiting a design that can operate with or without a MGCC, a new set of features is enabled to support optimised algorithms for secondary and tertiary controls. The primary control is further designed to operate in a decentralised manner. A set of intelligent agents are deployed to automate the functionality of the elements of the hybrid control system in the context of the 0-3 level hierarchy. The remaining sections of this paper are organized as follows: Section II includes a brief analysis of the hierarchical control principles implementations. In Section III, a literature review on existing Multi-Agent Systems (MAS) in MGs is presented. The proposed hybrid control system is presented in Section IV, followed by a specific Use Case in Section V. Finally, the paper is concluded in Section VI.

II. HIERARCHICAL CONTROL FOR MICROGRIDS

Due to high diversity in generation and loads, MGs exhibit high nonlinearities, changing dynamics, and uncertainties. The required control strategies [3] are characterised by various challenges such as bidirectional power flows, stability issues, low inertia, intermittent nature of RES and more. Thus, the control system should be designed not only to be able to tackle the challenges but also to feature a series of requirements. The most important are: output voltage and current control of the Distributed Energy Resource (DER) units, power balance between generation and load, Demand-Side Management, economic dispatch, smooth transition

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The authors acknowledge the financial support of EC FP7 ERANETMED partners of the project "3DMicroGrid" with project number: ERANETMED_ENERG–11–286 - www.3dmicrogrid.com

978-1-5386-1379-5/17/$31.00 ©2017 IEEE

between operation modes, and adaptiveness to changes in MG topologies [2]. The constraints that are imposed by the MG's operating mode (grid-connected/ islanded) need to be considered. The main challenge appears in the islanded mode, because DERs have to control actively voltage and frequency while maintaining the generation - load balance [4].

Published research in control system designs in MGs varies from fully centralised to fully decentralised solutions, creating a spectrum of available choices. Both extremes of this spectrum are considered as practically impossible as described in Section III. The compromise between fully centralised and decentralised approaches constitutes of a hierarchical Energy Management System (EMS) [2]. It consists of three control levels, each of which provides supervisory control over the lower-level controls. The details of these control levels are described in the following subsections.

A. Level 1- Primary Control

Primary control is designed to satisfy 4 main requirements: a) voltage and frequency stability during transition to and islanded operation, b) plug-and-play capabilities for DERs, c) befitting active and reactive power sharing, and d) circulating currents mitigation to avoid over-current phenomena [5]. Typically, during islanded mode, at least one MG converter must be operated as voltage source (VSC) whereas, during grid-connected mode, commonly MG converters controls change current source (CSCs) in order to inject current to the grid. Connecting VSCs in parallel results in unwanted circulating active and reactive power. The primary control determines the frequency and amplitude of voltage reference, provided to the inner current and voltage control loops [6]. Commonly, communication is considered redundant here and thus, droop control and its improved variations are applied since they are based on local measurements only. The droop concept forces MG sources to behave like synchronous generators (i.e. reducing operating frequency/voltage level and increasing the injection of active/reactive power). The droop coefficient can be either a predetermined constant according to the size of each DER or it can be provided by the secondary control, according to specified strategies. Improved droop methods that have been developed in order to tackle the problems of conventional droop control (e.g. line impedance dependency, inaccurate power sharing) include virtual impedance and adaptive droop controls, a detailed review of which can be found in [7].

Alternative to droop techniques, the Virtual Synchronous Generator (VSG) control and the Master/ Slave (M/S) control techniques have been introduced, but they both present sever weaknesses: VSG control leads to oscillations at output power [8] and M/S control only is suitable for small-scale MGs due to its need for extensive and fast communication [9] [10].

B. Level 2 - Secondary Control

The main objective of this level is to compensate the frequency and voltage deviations that are caused by the functions of the primary control level in order to maintain system stability. Additionally, energy balance of the overall system, techniques for improved power quality through unbalance and harmonics mitigation, and a synchronization control loop in order to seamlessly connect/ disconnect the MG to or from the grid, are also functionalities of this level [2].

C. Level 3 – Tertiary Control

This level supports global MG optimization during grid-connected operational mode by managing the power flow between the MG and the grid or other MGs. By nature, when dealing with a single MG and not clusters [11], the tertiary control consists of a centralised control platform on top of the secondary control level [12], MGCC in some cases [13].

D. Secondary and Tertiary Levels Implementations:

The functionalities of both secondary and tertiary levels are referred to as EMS and can be designed in a centralised or a decentralised approach, depending on intelligence, independence and responsibility of local controllers [9]. The literature does not clearly define the characterisation of what is centralised and what is decentralized. A definition of each approach is given as follows:

1) Centralised EMS: The conventional approach is to use an MGCC in which all secondary control functions are embedded. It is responsible for the detection of power quality at the Point of Common Coupling (PCC) of the MG. It initiates transition to islanding mode in case of upstream disturbances and manages resynchronization procedure by properly matching the frequency and voltage with that on the grid side [14]. The main advantages of a MGCC include straightforward implementation and real-time and supervisory features of MG. However, collecting information from all MG components in real-time requires high-bandwidth communication and powerful processing controller. Furthermore, MGCC imposes restrictions in the desired plug-and-play functionality which affects negatively the flexibility of the MG. Examples of centralised EMS designs can be found in [9] [10] [12] [15]. MGCCs are particularly effective at detecting islanding conditions and initialisation of resynchronisation sequences, ensuring at all time the overall system stability as proven in [14]. They are able to ensure high power quality reaching the loads even during dynamic phenomena, via voltage profile enhancement [16] that prevents unnecessary or marginal under voltage tripping. Testing of MGCC in real MGs range from simple laboratory test systems [17] to complex topologies [16].

Therefore, the centralized EMS is preferred when: a) centralised information gathering and decision making can be realised with low communication and computation cost in small scale MGs, b) all the properties within the MG have a common goal so that the EMS can operate the MG as a unity, c) special applications of MGs where high privacy/ confidence are required, such as military, and d) system configuration is almost fixed which does not require high flexibility/expandability [18].

2) Decentralised EMS: Distributed control techniques are employed in order to deal with the shortcomings of centralised controllers. The key design objective is to allow the overall intelligence of the control system to be distributed on local controllers that have their own autonomy and are able to take their own decisions. MAS technologies enable the implementation of decentralised control systems due to their inherent distributed nature. Additionally, recent progress in alternative communication technologies and information exchange algorithms [19] [20] [21] (Peer-To-Peer, Gossip, Consensus etc.) enable the possibility of decentralized management in practical applications. A MAS-based EMS can have the same hierarchy and functions as a centralized one. The decision making authority is transferred to the local side by increasing the intelligence level of local controllers and thus, reducing the computational burden on individual controllers. The local decisions are made based on necessary information from the environment. Even if some MAS are complemented by a supervisory centralised controller to coordinate the MG units in black start process or energy management [12] [22], the basic functions of the MG are not affected in case of MGCC failures, and thus, avoiding single point failures. Additionally, the decentralised control facilitates the implementation of the plug-and-play functionality, but is heavily dependent upon robust, efficient, and secure communication systems. In this case, system safety, stability, and information security are considered as critical issues. Weighing pros and cons, decentralized schemas are most likely applied in cases where large or highly dispersed MGs must be managed. They are also applied in cases where goals are restricted by co-ownership or multi-property of assets, and ultimately cases where periodical fast reconfigurations of the systems are required [23] [24] [25].

III. MULTI-AGENT SYSTEMS FOR MICROGRID CONTROL

MAS have become a distinguished research trend as it provides the possibility to actualize decentralized management functions. Regardless of its complexity, MAS technology contributes to the evolution of classical power systems by making them more flexible and intelligent. The key characteristics of intelligent agents, such as reactivity, pro-activeness, and social ability, add improved functionalities of multiple aspects to MGs. The first MAS approach in MG control [26] employed three different types of agents for optimal energy exchange between production units and local loads, as well as the utility grid. In [27], a 7-type MAS was simulated in order to manage distributed resources of a specialized MG. The main objectives of the agents were voltage and frequency regulation, calculation of active and reactive power and maximization of profit. In more recent work, an improved 4-type MAS has been introduced to disconnect and stabilize the MG that is interconnected with the local utility [28]. It is evident from the examples that there is no consensus on the optimal amount of different agents in a MG, but all of them have in common a supervisory control agent. In [24], however, there is no centralised supervisory component. The control objectives are concerned with frequency stability during islanded operation that is achieved by using consensus for cooperative frequency control and multi-stage load shedding.

Concerning the algorithms that are employed by MAS, two are the most popular: auction algorithm [26] [29] and consensus algorithm in [24]. More precisely, usage of ratio-consensus algorithm was proven very effective in system frequency regulation and operational cost minimization for a laboratory testbed islanded MG [30]. Other algorithms that were successfully used in MG control are: distributed cooperative algorithm for regulation of charging/ discharging behaviour of multiple batteries in order to mitigate the power fluctuation at the PCC [31]. Overall, MAS control can take advantage of Artificial Intelligence technologies, which has been proven successful in simulations. A fault-tolerant ontology-driven MAS, for instance, was proposed in [32], with 5 types of agents, for optimal demand response and dispersed generation management in a MG.

Yet, MAS control has been rarely applied to real MG environments. Most systems have been either just simulated in appropriate computational environments or tested in laboratory facilities. The most popular agent simulation platform is the open-source and FIPA-compliant [33], JADE [32] because of the detailed representative capabilities it provides. Detailed examples of JADE usage for MAS-based MG can be found in [29] [33] [34]. In the near future, MAS-based controllers should be more actively tested in real environment MGs in order to assess their efficiency and effectiveness.

IV. PROPOSED HYBRID CONTROL

In literature, several MG hierarchical control systems have been proposed combining centralised and decentralised features, and thus, characterised as "hybrid" controllers. The majority of these suggest primary control level implemented in a decentralised way and the upper levels in a centralised way. Each one differentiates from the other based on the control techniques that the levels invoke. Indicative examples of such control systems can be found in [35]. However, as far as the authors are aware, all these hybrid hierarchical controllers are vulnerable to single-faults on the upper levels and very few attempts have been made to explore re-configurability and fault tolerance in MGs. Recently, authors of [36] demonstrated the effectiveness of a reconfigurable MG controller both in simulation and in a scaled laboratory prototype. The overall controller is based on dual communication through CAN and RS-485, which puts practical constraints in case of extended MGs.

Based on the 3-level hierarchical control requirements, a conceptual high-level control architecture is proposed in Fig.1. The main objective is to create an open-source, autonomous, reconfigurable MAS framework by combining the merits of centralised and decentralised approaches in the creation of a hierarchical control system for optimising MG performance. The system consists of agents with varying intelligence degrees, placed on all control levels and on physical assets of the MG (called "3DMG Agents"). It provides centralised functionalities (such as optimised planning), decentralised power sharing techniques, as well as auxiliary subsystems like forecasting units. The proposed control system is also reconfigurable in such way that, in case of a MGCC malfunction, the MG is able to continue its operation and thus, single fault tolerance is bypassed without the addition of redundant components.

A. Tertiary Control Platform

The *TCP* module essentially represents the tertiary control level, which mainly involves operational planning of the energy strategy that will be followed by the MG during grid-connected mode. This strategy is then disseminated to the secondary control in a time interval in the scale of minutes to a day-ahead scheduling. The platform consists of two components:

On-Grid Manager: This component is responsible for handling communication between *TCP* and the Grid & Market Services. When a signal or service request is received from the grid, it will be properly formulated in order to be either sent directly to the *Dispatch Optimization* module or stored in a repository for further accessibility by the other components. Furthermore, the *On-Grid Manager* communicates with the *Transition Controller* in case of a downstream disturbance is detected, in order to define all variables necessary for transition from grid-connected to islanded mode.

Dispatch Optimisation: Short-term to mid-term operation of the MG will be handled by a set of dispatch optimization tools. These tools will evaluate real-time conditions and simulation results generated by applying different optimal control actions. The sub-components are:

Optimal Power Flow (OPF) to compute corrective actions of the MG devices to respond to the requirements of a particular action e.g. active & reactive power exchange at PCC. The *OPF* also computes corrective actions to solve any internal technical problem that is detected (voltage sags, line overload, etc.).

Day-Ahead Planning (DAP) to receive as inputs electricity prices or an hourly generation program computed by an external entity (e.g. ESCO), along with demand and generation forecasts in order to determine the optimal scheduling of the MG resources in a 24-hour horizon. Successive updates closer to real-time are subsequently made when more precise information is available.

B. Demand and Generation Forecasting

This auxiliary module delivers the potential energy demand and supply ahead of time. Stochastic forecasting techniques of generation and demand scenarios will be used based on historical data in order to provide the *TCP* and the MGCC with a set of scenarios with their probability of occurrence.

C. Secondary Control Platform

The *SCP* module includes all actions that constitute the MGCC, namely:

Off-Grid Manager: This component gets data from the auxiliary modules of *DER Forecasting* and *Demand Forecasting* in order to define the rules that must be followed when operating in an islanded mode. Furthermore, in case islanded operation is extended over several hours or days, *TCP* intervention may be required in order to optimise the MG economical function.

Agent Balance: This component is responsible for the coordination of all *3DMG agents* that are connected to MG assets. Based on the inputs from *TCP* (during grid-connected mode) or *Off-Grid Manager* (during islanded mode), the *Agent Balance* calculates a series of variable constraints in regards to the overall system stability and reliability. These calculations are subsequently delivered to the *3DMG agents* in order to alter their attitude. In cases where sufficient and efficient balances cannot be applied, the MGCC will request from *TCP* (or *Off-Grid Manager*) updates on the strategy by providing necessary data that best describe the issues in hand.

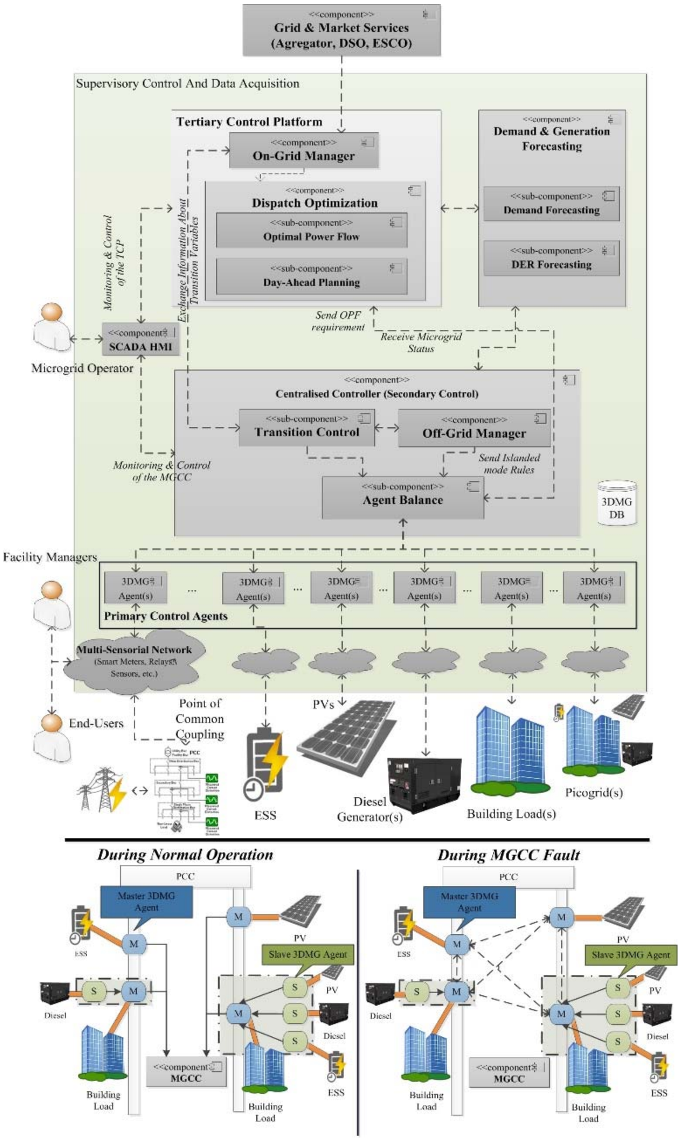

Fig. 1. (a) Conceptual high-level control architecture and (b) 3DMG agent operational logic during normal operation and MGCC failure.

Transition Controller: This component communicates with the *On-Grid, Off-Grid Managers* and the agent on PCC in order to set the conditions (e.g. sequence of relays) under which a transition from grid-connected to islanded operation and vice versa can be achieved optimally in terms of system stability. By evaluating real-time conditions of relays and assets, *Transition Control* will inform the other relevant subsystems whether the switch is possible or not.

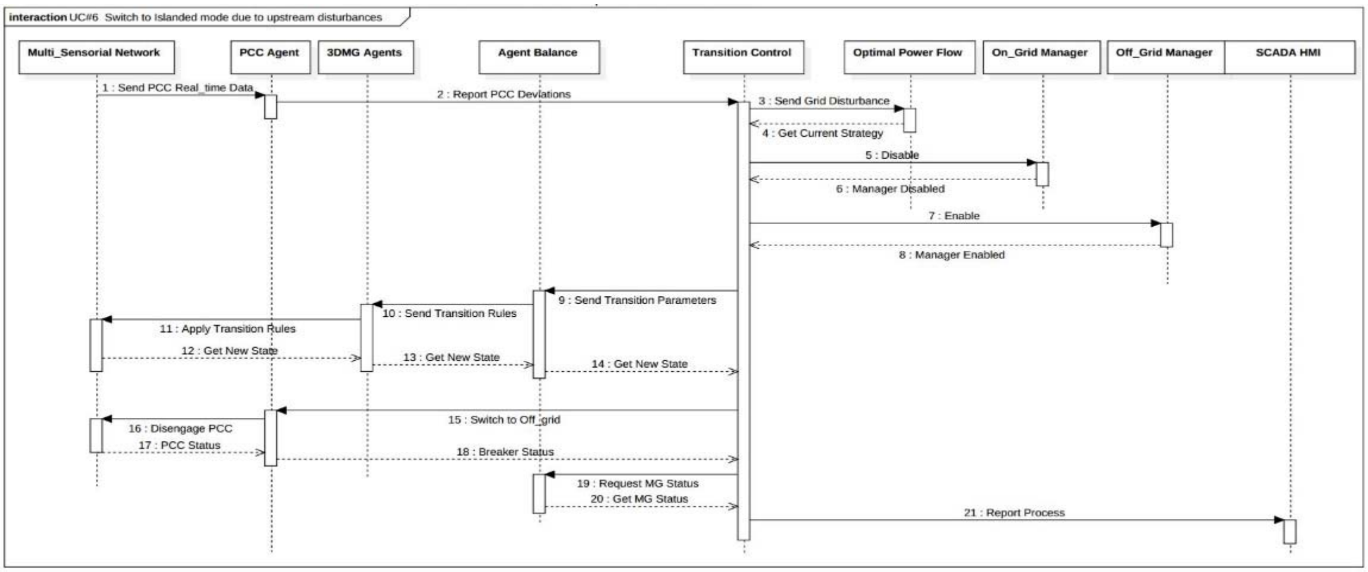

Fig. 2. UML Diagram during switching to islanded mode due to downstream disturbances

D. *Primary Control Agents*

Finally, primary control agents are assigned to each energy junction node of the MG, named as *3DMG agents*. Each agent has the capability to communicate with the MGCC. These agents will be responsible for the regulation of the active and reactive power generation or consumption and of the voltage and frequency of the node to which they are connected. Their operational logic follows a rule-based variant of improved droop control with specific MGCC dynamic constraints. In order to lighten the MGCC from excessive computations, a master-slave approach is adopted: the *3DMG agents* that are directly connected on nodes of the MG behave as Master Agents whereas the agents of the assets beneath Master Agents behave as Slave Agents. This tree-like control scheme is designed in order to enhance the modularity, expandability and flexibility of the MG. In case of an MGCC malfunction, the Master Agents are capable of fulfilling all primary control and basic secondary control (i.e. stable power and load sharing) functions by collaborating (Fig.1b). Consequently, the overall MG control system becomes fully decentralised. In order to achieve this Master Agent collaboration, algorithms such as consensus, auction, generic, and particle swarm optimizer will be investigated. In this scenario, the MG will have to be islanded and thus, the agents will only have to perform the basic secondary control level functions.

V. PRELIMINARY RESULTS

One of the most significant capabilities that a MG should accomplish is the transition and operation in islanded mode. A Use Case (UC) is given in Fig. 2 to illustrate the switching to the islanded mode, which occurs due to downward disturbances from the grid. The *Transition Control* module is the key module in this particular UC, as it should acquire PCC information that denotes an imminent MG disconnection from the main grid. Consequently, it requests information from *Agent Balance* module in order to assess the overall MG stability in terms of power production, energy reserves and consumptions. If the MGCC does not take into consideration all necessary factors for evaluating the *Demand Forecasting* in the next minutes while the transition occurs, it is possible to create an imbalance between supply and demand for a few seconds that leads to potential instability due to significant changes in voltage and frequency. After all information is processed and if islanding is possible, then *Transition Control* transmits the necessary signals to the Agent of PCC in order to proceed to islanding.

VI. CONCLUSION & FUTURE WORK

A conceptual hierarchical three level hybrid agent-based conceptual control design has been presented for an AC MG. It combines both centralised and decentralised principles. The envisioned framework offers various benefits that can adhere to MG performance optimisation while introducing an automated intelligent system that can operate as an autonomous supervisor, even in case of failure. The new design overcomes limitations presented from current MG control systems while also taking into consideration physical constraints of actual MG premises. Its main features are:

Intelligent Automation: The control system is designed with components that can automatically (with no or minimal user interference) achieve profit maximisation, load scheduling, increased power quality, and efficient DER/RES integration.

Increased Reliability: By enhancing the 3DMG Agents with capabilities to accomplish secondary control level functionalities in a fully decentralised way, the single fault tolerance of a conventional centralised EMS is lifted and thus, the MG becomes more reliable and thus, suitable for special applications (e.g. military, offshore, space-based MGs).

Modularity and Scalability: A highly modular primary control along with a user-friendly and easy-to-use EMS enable the plug-and-play and also, facilitate the expandability of the MG by allowing the easy connection of loads, DGs, or ESS or even other MGs/picogrids.

It is intended that the new design will not only be tested under various simulation scenarios but also will be deployed to three different (in terms of size, use, assets, etc.) pilot MGs in order to validate and evaluate these benefits in real MG environments. The pilot MGs are: a picogrid, in Greece (ITI/CERTH) and two large-scale university campuses in Malta (MCAST) and Jordan (GJU). The envisioned architecture will be extensively modelled, executed in real-time simulation scenarios and finally deployed to actual MG sites revealing the feasibility degree of the novel hybrid design.

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