Design and Implementation of Smart Micro-Grid and Its Digital Replica: First Steps

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Abstract: It is evident the digital transformation that is spreading in more and more areas of science and technology in recent times, as demonstrated by scenarios such as Smart Grids, the Internet of Things, Cyber-Physical Systems or the Industry 4.0. This article outlines the first steps followed to develop a research project which aim is to bring this digitalization to the field of renewable energies and intelligent energy generation and distribution grids, the so-called Smart Grids (SG). The objective of this project is twofold. On the one hand, all the steps necessary to develop digital replicas of the devices that make up a Smart Micro-Grid will be covered. On the other hand, an automation and energy management system will be implemented over the micro-grid to optimize the operation of each of the systems that compose it, while guaranteeing the energy demand and maximizing the use of solar energy. Additionally, hydrogen is used as mid/long-term energy storage system (backup).

1 INTRODUCTION

A digital transformation is revolutionizing every area of science and technology, attested by scenarios such as the Internet of Things (IoT) and the Cyber-Physical Systems (CPS) (González et al., 2017). This last emergent concept is orchestrated around the communication through the network of devices with embedded connection capacity, in order to sensorize, monitor and act on physical elements in the real world (Monostori et al., 2016).

In summary, CPS derives from the convergence of the physical and virtual or digital worlds. These systems bring capabilities that turn them into a promising solution which provide new frameworks to produce advances, being able to talk about a whole digital transformation. The impact of CPS is evident in many fields. For example, in the industrial scope it gives rise to the so-called fourth industrial revolution, also referred to as Industry 4.0 (Industrie 4.0 homepage).

In the energy context, intelligent grids for generating and distributing energy, called Smart Grids (SG), are a clear example of the establishment of CPS. In fact, they are considered as the result of the convergence of energy systems and Information and Communication Technologies (ICTs) (Camarinha-Matos, 2016). These networks are, therefore, an ideal environment to apply these technological currents (González et al., 2017; Bedi et al., 2018).

As a consequence, in recent times, there has been a transition from systems based on the interconnection of physical systems where transmitted information was used for control purposes, to systems in which information constitutes the core of the system (Bradley et al., 2015). That is, it has gone from granting a preponderant role to the physical components/hardware to transfer this role to the digital media/software. The role of information and software tools has gained greater prominence in the new technological paradigms. Currently, considering independently the physical and digital parts in an advanced scenario (CPS, SG, Industry 4.0, IoT, etc.) lacks sense.

Within the Industry 4.0 concept, one trend that is receiving great attention from Industry and Academia is the digital replica, also called digital twin. Originated in 2002, this paradigm receives multiple definitions; there is no exact and generally accepted

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definition. Autiosalo (Autiosalo, 2018) proposes a concise definition for the aim of this work: A digital replica is the cyber part of a CPS. It is also referred to as a simulation environment that accurately represents the dynamics of the real-world system (O`Dwyer et al., 2019).

Therefore, nowadays, one of the most challenging tasks in this philosophy of digital transformation is the development of digital replicas of physical processes. Figure 1 illustrates the interplay of the physical and digital parts, where information flows are established between both entities. On the one hand, data about the status of the physical system are fed to the digital replica. On the other hand, data generated by the digital counterpart are sent to the physical facility.

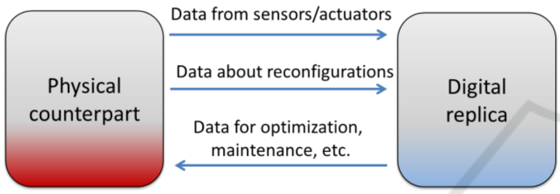

Figure 1: Schematic representation of interplay between physical system and digital replica.

There is a large and increasing amount of papers dealing with digital replicas in industrial context (Kritzinger et al., 2018; Borangiu et al., 2019). Even, the digital replication of employees is being explored in order to improve the integration of human operators in Industry 4.0 and CPS scenarios (Graessler and Poehler, 2018). On the other hand, some efforts are oriented towards energy optimization in industrial processes that are digitally recreated. For instance, in (Lu et al., 2019) it is noted that to achieve an energy-efficient manufacturing in Industry 4.0 environment, energy models must be considered while developing a digital twin of an intelligent factory.

However, for energy-related frameworks, this topic has been scarcely treated. Interesting and recent publications are found in (González-González et al., 2018) and (Tao et al., 2018) dealing with digital replicas of wind turbines; in (Kaewunruen et al., 2019; O’Dwyer et al., 2019) and (Wang et al., 2019) where a building is digitally mirrored; and in (Senthilnathan and Annapoorani, 2019) where a cyber model is proposed for power electronics in the context of micro-grids.

Out of the academic arena, important enterprises are also devoting efforts to digital replication of power grids, like General Electric (GE) or Siemens (Siemens).

Given the aforementioned lack of publications, it is evident the need to develop technologies and methods to be applied to real systems, namely, SGs, in order to overcome unsolved challenges.

The present work is framed in a research project which objective is to bring this digitalization to the field of renewable energies and SG.

Specifically, this project consists of the design and implementation of a CPS that incorporates a representation or digital replica of a Smart Micro-Grid (SMG) based on renewable energies and hydrogen. In fact, SMGs can be defined as small-scale SGs which can be autonomous or grid-tied (Koohi-Kamali and Rahim, 2017). SMGs integrate physical elements in the power grid and cyber elements (sensor networks, communication networks, and computation core) to make the power grid operation effective (Yang et al., 2016). SMGs are excellent candidates for the implementation of these digital replicas. Thus, the processes involved in the generation, storage and distribution of energy can be reproduced virtually.

The aim of this project is twofold. On the one hand, all the steps necessary to develop digital replicas of the devices that make up the SMG will be covered. All this with the purpose of obtaining models that allow real micro-grids to be simulated, so that the generation of a digital micro-grid model can be addressed, enhancing the application of ICTs in the energy field.

On the other hand, an automation and energy management system will be implemented to optimize the operation of each of the systems that make up the SMG, while guaranteeing the energy demand and maximizing the use of solar energy. With this SMG will be achieved the generation of electricity from renewable energy sources (especially photovoltaic), using hydrogen as an energy storage system (backup).

The remainder of the rest of the paper is as follows. The next section covers the challenges that arise when the development of a digital replica is addressed. Section 3 provides an overview of the research project where this work is contextualized and portrays the steps followed. The elements that compose the platform are reported in the fourth section. Finally, the main conclusions of the work are addressed.

2 CHALLENGES TO FACE

In this section, the main challenges to be solved for the implementation of digital replicas are addressed. In this regard, the degree of maturity of the technologies involved has not yet reached an adequate state, which makes it difficult for the ambitious expectations of digital replicas to bear fruit in an authentic reality.

2.1 Non-generally Accepted Concept

One of the first difficulties found to design a digital replica is derived from the aforementioned lack of generalized concept. To overcome this issue, in this work, the authors consider a digital replica as a representation of a physical process/system which runs in a digital environment.

In addition, a linkage between both the physical and digital counterparts is required, enabling the updating and adjustment of the digital side. Under this perspective, a digital replica can adopt multiple formats, from an equation-based mathematical model, to dynamic representations in 3D.

2.2 Massive Data Gathering

To create the digital replica, a great variety of sensors monitor all sorts of data during the operation of a process (Stock et al., 2018), and are processed and stored to design a precise representation of the physical process. As pointed by Haag and Anderl (Haag and Anderl, 2018), traditional data collection and processing methods do not meet the needs of the digital replica paradigm and need to be rethought.

Consequently, another challenge to face is the need of massive amount of data about the physical system in order to be properly and accurately characterized.

In a common scheme of automating a system, a number of magnitudes must be sensed and processed, but the focus is mainly put on those that are considered as critical for control tasks. In the case of implementing a digital replica, not only critical magnitudes must be measured, but many other variables are required to reach the highest fidelity of the replica.

Even, the acquired data on generation, operation and consumption of power plants are called Big Data of electrical energy, and have an enormous potential to support the decisions of optimization and management (Wen et al., 2018).

This fact implies two questions to solve. On the one hand, the deployment of an infrastructure for sensing, data acquisition and data communication has to be tackled. This infrastructure must be able to handle a large amount of sensors and data acquisition devices fulfilling features about scalability, accuracy, reliability and modularity.

On the other hand, the magnitudes to sense need to be determined in order to be illustrative enough for the system behaviour and, at the same time, not to increase the expenses to prohibitive levels.

To overcome this difficulty, in the project low-cost and open-source devices are being integrated in order to sense and monitor the physical assets (further commented in Section 4).

2.3 Software Requirements

Developing a digital replica implies the complex task of designing various models in order to properly reproduce the geometries, physical properties and behaviours of the physical system (Tao et al., 2018). For instance, the geometries can be represented by CAD models that reflect the 3D aspect of the real counterpart (Um et al., 2017; Tao et al., 2018). Therefore, to implement a digital replica of a SMG, several software packages/environments are required.

Concerning previous works, commercial software directly focused in energy-related systems, as EnergyPlus, are used to implement the digital replica (O'Dwyer et al., 2019). A different perspective consists on using a mathematical model through Matlab (González-González et al., 2018). Other approaches are based on black-box models or artificial intelligence tools like Neural Networks (Rahman et al., 2018). Indeed, a software package commonly used for industrial instrumentation and monitoring/supervision can be also applied for digital replication as reported in (Senthilnathan and Annapoorani, 2019).

The integration of those models is another problem to solve. Digital replicas are nowadays considered as more than just collections of digital artefacts, but rather, as collections of linked digital artefacts (Vrabic et al., 2018). To achieve a consistent digital replica, an effective information exchange among the models must be performed (Talkhestani et al., 2018). In fact, there is a scientific deficit about approaches addressing data exchange for systematically updating the multi-domain models in case a physical change occurs (Talkhestani et al., 2018).

Moreover, an additional issue deals with the synchronization between the physical system and the digital replica (Talkhestani et al., 2018). The digital replica must be kept updated with the current status of the physical system (Talkhestani et al., 2018). Obviously, any change in the physical asset like deletion or addition of a component must be updated in the digital replica (Talkhestani et al., 2018).

In this sense, at the current stage of the project, the software Matlab/Simulink is being applied for the modelling of the subsystems of the SMG whereas LabVIEW is used to collect data from the physical facility.

2.4 Scheduling

A decision to take concerns the appropriate stage to elaborate the digital replica. In this sense, some literature reports the convenience of developing the digital replica before the real-world deployment in order to test different control algorithms or to avoid prohibitive costs (O'Dwyer et al., 2019).

However, other publications point out the need of acquiring massive amount of data of the physical system operation to develop data-based models (Stock et al., 2018; Madni et al., 2019). Indeed, some authors propose creating the digital replica in parallel to the physical facility (Talkhestani et al., 2018). Moreover, in any case the digital replica is iteratively updated and verified along the life cycle of the physical system (Schneider et al., 2019).

In the present case, the last option has been chosen, so data gathered from the characterization and initial operation of the components (photovoltaic modules, hydrogen equipment, etc.) is being used to generate digital replicas in parallel.

3 PROJECT MAIN STEPS

This section is devoted to describe in a brief manner the steps to implement the SMG and the associated digital replica.

On the view of the surveyed literature, the following pillars are considered for the implementation of a digital replica. Namely, massive data acquisition through smart sensor networks, cloud-based storage and processing of the data, and utilization of such data in expert supervisory applications.

Consequently, the stages to be covered include the design of sensorization for the collection and massive accumulation of data, the organization of transmission and communication in the information network, the integration of multiple and heterogeneous components (hardware/software), the real-time connection of physical and digital systems, the validation and implementation of prototype installations in which to develop and evaluate the technologies involved. Additionally, concerning SGs, a necessary premise is the development of a management strategy taking into account both technological and energy constraints.

Firstly, the identification and analysis of the necessary sensorization for the registration of the magnitudes of interest has been carried out.

Subsequently, the design and development of the appropriate auxiliary elements is being addressed to develop a network of intelligent sensors through an interoperable and scalable architecture.

Next, the energy management strategy will be defined and implemented for the operation of the SMG, as well as a system for the monitoring and supervision, which will allow online remote access.

The development of the digital replica will be performed from the models of each one of the elements that compose the SMG. Namely, this equipment includes photovoltaic generators, electrochemical accumulators, fuel cells, hydrogen generators, and hydrogen storage vessels. Likewise, the necessary elements to compose the control, monitoring and management system of the SMG will be deployed. These ones comprise Programmable Logic Controllers (PLCs), sensors, human-machine interfaces, and programming software.

The validation of the designed replica will be carried out with the data obtained from the parallel operation of the experimental micro-grid at laboratory scale and its digital replica.

Once these steps are fulfilled, the virtual illustration of the SMG will be applied for diverse purposes. It can be applied to simulate the system behaviour while making reconfigurations and, also, to improve the system performance and detect any failure (Talkhestani et al., 2018).

In this sense, this digital representation acts as a powerful platform on which to test, probe, evaluate, analyse, etc., as if it were the real physical system, avoiding the limitations and technical-economic disadvantages of taking the physical system to certain states operatives.

Namely, there are many possible applications in the energetic context. Among these, the following ones can be highlighted: preventive and predictive maintenance to increase the life time (Prognostics and Health Management, PHM); reduction of downtimes and associated costs; improvement of availability, reliability, trustworthiness and robustness of assets; study of behaviour, detection of deviations and reaction to extreme situations (resilience); optimization of efficiency and operation from an economic and energy point of view; as well as making decisions based on data management (expert supervision). It must be remarked that the applications regarding extreme situations cannot be covered with the thoroughness desirable in the current state of maturity of the R&D project

All these potential uses derive from the fact that the digital replica can be executed offline or in real time simultaneously to the physical system, so that both respond to the same stimuli. Therefore, the obtained conclusions can be extrapolated directly to the physical system.

4 COMPONENTS OF THE SMG

The SMG integrates solar energy and hydrogen to achieve an autonomous system. A set of monocrystalline photovoltaic modules up to 2.4 kW, as a primary renewable energy generator, compose the Photovoltaic subsystem (PV). An electrochemical 500 Ah battery system, as a short-term backup element, hosts the electrical flows, playing the role of DC Bus.

An energy balance is continuously performed to determine if there is surplus of solar energy. In such case, a modular Polymer Electrolyte Membrane (PEM) Hydrogen Electrolyzer (HE) up to 0.75 kW is used to generate hydrogen. In the opposite case, a PEM Fuel Cell (FC) up to 1 kW acts as a renewable secondary (or reserve) generator of electrical energy.

This way, the hydrogen will be used as a long-term backup element to feed the FC when the energy demand in the micro-grid cannot be satisfied by the PV generator and the battery. The hydrogen is stored in metal hydride vessels. DC and AC loads close the system.

In addition, there is a series of automation, instrumentation and monitoring devices that will make up the control and supervision system, which in turn, will serve as a system for the massive acquisition of data. The automation and management system will be solved using a PLC and a Supervisory Control and Data Acquisition (SCADA) system. Namely, the model of PLC is S7-1500 of Siemens and LabVIEW is used to implement the supervisory system.

Telemetry is achieved by means of remote units, namely to connect the PLC with remote signals, a decentralized periphery station ET200 (Siemens) is applied. For massive data collection, an additional data acquisition device (DAQ) is materialised by the open-source platform Arduino. This technology brings benefits like low-cost and easy-to-use due to the wide support provided by the open-source community.

For the integration of software/hardware entities, the industrial protocol Open Platform Communications (OPC) will be used, which allows to establish an exchange of data between the components, abstracting from their specific nature (González et al., 2019).

The real-time connection of both physical and digital systems will be based on the same communication network used to interconnect the sensorization, automation, management and supervision systems of the SMG. Thus, both the physical system and its digital replica share the same signals. It must be noted that the digital replica is still being developed, so the achieved results will be reported in further publications.

A preliminary block diagram of the described SMG is depicted in Figure 2. Also, the interconnection of the described elements for automation and management is schematically portrayed in the figure.

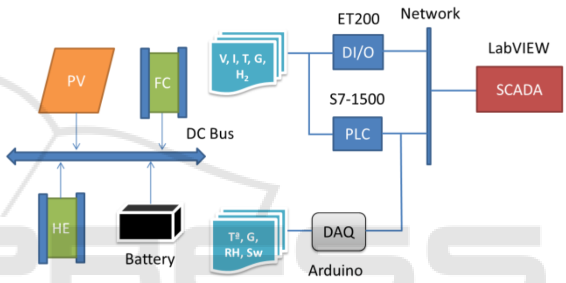

Figure 2: Block diagram of the SMG.

5 CONCLUSIONS

Digital replication of physical systems is a challenging task that is receiving increasing attention in modern trends like SGs or Industry 4.0 frameworks.

The paper has presented the activities that are being developed in a research project that deals with the design and implementation of a SMG based on renewable energies and hydrogen as well as its digital replica.

The main challenges to address have been expounded, as well as the steps required to develop the project. In addition, the components of the physical counterpart, e.g. the SMG have been described.

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