A Principled approach for smart microgrids simulation using MAS

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Abstract. Energy management is, nowadays, a subject of uttermost importance. Indeed, we are facing growing concerns such as petroleum reserve depletion, earth global warming or power quality (e.g. avoiding blackouts during peak times). Smartgrids (SG) is an attempt to solve such problems, by adding to power grids bi-directionnal communications and ICT capabilities in order to provide an intelligent autonomic management for the grid. Microgrids are a possible implementation of SG. They are defined by rather small power systems, composed of power sources (some may be renewables) and loads, that can be connected or not to the main grid. In this context, simulation is an appropriate approach for studying the introduction of SG in existing systems. Indeed, it avoids the deployment of real, costly infrastructures and reduce experimental risks. This paper presents a microgrid simulator based on Multi-Agent Systems (MAS).

Key words: multi-agent based simulation, organisational methodology, smart grids, microgrid

1 Introduction

The management of an electrical grid is a major challenge of the 21st century. The existing electrical grid has to evolve to include new distributed generators like microturbines, photovoltaic panels, fuel cells and wind turbines, and also to balance the petroleum and carbon reserve depletion. In [12], authors detail problems emphasized by the grid evolution, such as demand-side management, electrical vehicles adoption or new user types (and behavior) like energy prosumers. Smartgrids is an attempt to solve such problems, by adding to power grids bi-directionnal communications and ICT capabilities in order to provide an intelligent autonomic management for the grid.

However, deploying an intelligence over the current monolithical grid is a hard challenge. A possible solution consists in decomposing the grid into smaller interconnected power grids called microgrids. Microgrids [9] can be defined as low-voltage parts of the energy network that comprise loads, decentralized sources

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(maybe renewables) and local storage systems. Microgrids can operate either connected to the main distribution grid (and thus to others microgrids), or disconnected. In the latter case, called islanded, microgrids are in charge of controlling their power balance and voltage stability in a local way.

There are several existing approaches that try to introduce intelligence within microgrids [11, 3]. These approaches differ both with the technical characteristics of the microgrids and with the paradigm chosen for the intelligent management. It is thus difficult to compare these approaches or generalize them. The contribution of this paper consists in proposing a multi-agent based simulator for microgrids that is able to (i) reliably simulate the grid operation with a broad range of devices (ii) prototyping intelligent control mechanisms over these grids.

The use of a simulator in such a context avoids the design of new infrastructures and reduces significant investments. Nowadays, different power system simulators are developed to offer a vision of the future power systems. In the sequel of this section, the most advanced and used simulators are described.

EPRI's OpenDSS [4], a Distribution System Simulator is a very flexible and expandable research platform which wants to be a foundation for new distribution analysis applications particularly for distributed generators. It supports frequency domain analysis commonly performed on electric utility power distribution systems and provides a large collection of renewables models.

GridLAB-D[1] is a power distribution system simulation environment that provides to users tools for data analysis such as an agent-based and information-based modelling and validation for rate structures and consumer reaction. The core of GridLAB-D has an advanced algorithm that simultaneously coordinates the state of millions of independent devices, each of which is described by multiple differential equations, etc.

PowerWorld Simulator is a popular simulation software used to simulate high voltage power systems. Using this tool, it is possible to perform power flow analysis on a system with up to 100,000 buses. PowerWorld offers several add-ons such as voltage and power stability analysis, modeling and evaluation of geomagnetic disturbances, etc.

We also want to mention the MATLAB/Simulink tool `SimPowerSystems` that provides component libraries and analysis tools for modelling and simulating electrical power systems. The libraries include models of electrical power components, including three-phase machines, electric drives, and components for applications such as flexible AC transmission systems and renewable energy systems.

These simulators are very useful for data analysis but are not developed to easily and dynamically integrate intelligences and especially distributed intelligences. The integration of intelligences is the main objective of our simulator. We want to offer to users a validation for their artificial intelligences which aim to be integrated in a real power system in the everyday life.

The section 2 presents the multi-agent based simulation of microgrids. In this section, a comparison of microgrids and multi-agent system is firstly provided, then the organizational approach of our simulator is presented. A description of

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how the time is handled within our simulator is also given and also some device model implementations. The section 3 presents the first results obtained with our simulator and gives a comparison of these results obtained by `SimPowerSystems` tool for a given scenario.

2 Simulation of Microgrids

To explain a simulation of microgrid, the concepts that the system has to implement is developed. A microgrid is a set of entities. An entity can be defined as an energy container. It may be a device that provides energy. This energy can be positive for a producer or negative for a consumer. An entity can also be a transmitter that transfers energy between other entities. In our simulator, the device class can be divided into 3 subclasses:

- loads that consume energy, assuming that the energy consumed is considered as negative,
- sources that produce energy, assuming that the energy produced is considered as positive, and
- storage systems that can consume or produce energy depending on its action (charging or discharging).

The transmitter class can be divided into 2 subclasses:

- the converter that links devices to other entities, and must transform the energy to match the need of devices
- the bus that is a link between converters or devices.

In order to connect an intelligent management to our simulator, two concepts are developed: the sensors that offer data acces from entity to the outside of the simulator and the actuators that receive information from the outside to influence the behaviour of entities.

We also define constraints based on physical laws that the simulator continuously verifies while running a scenario:

- each device has its own power dynamic, depending on its internal characteristics, these characteristics are fixed and could be defined by users,
- during all the simulation, the Kirchhoff first law shall always be true: the sum of currents flowing into a node is equal to the sum flowing out of that node,
- the voltage of the grid depends on the power flow between the different elements, the relation is detailed in the section 2.4.

These physical laws create a link between the current delivered by each device plugged in the grid and the voltage stability of the grid.

Considering the purpose of our simulator, the concepts defined above and the physical laws that the simulator has to take into account, the developed capabilities offered to users are:

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- a set of initial conditions, to define the characteristics of the entities and the state of the simulation at the beginning of the simulation at time $t = 0$,
- a real time simulation, thanks to the time management (see 2.3),
- an open system, with dynamic actions on microgrids (for example, adding or removing devices during a simulation) or on the devices which can be controlled by external intelligences,
- a monitoring, with extraction of information of devices and grid. Currently, the observables are the current of each device, the voltage of the transmitters and state of charge for storage systems.

2.1 Microgrid Simulation and Multi-Agent System

The simulator presented in this paper is developed with Janus [7] a multi-agent platform developed with JAVA^{TM}. This platform offers organisational model, network peer-to-peer and holonic systems. These different characteristics respectively help to simulate the dynamic variation of a grid, to distribute the simulator easily and to develop hierarchical (or holistic) microgrids.

A powergrid is composed of several devices geographically distant from each other. These devices can be connected or disconnected at any time and continuously change their consumptions or productions. The properties of an actor of a powergrid can be put in parallel with the properties of an agent [13] in a multi-agent system:

autonomy: a device cannot directly modify the consumption/production of another device,
social ability: every device presented in a powergrid have to exchange energy with other devices,
reactivity: the devices receive energy but can also observe the powergrid to dynamically change its own consumption/production,
pro-activeness: a device can change its internal state without considering the state of the powergrid.

2.2 Organizational Approach

As previously expressed, this simulator is based on Janus, an organization based multi-agent platform. Indeed, Janus is built upon the Aspecs metamodel [2] in which the concepts of role and organization are first-class entities. An agent is an autonomous entity that has specific individual goals and the intrinsic ability to realize some capacities playing different roles. A role is an expected behaviour and a set of rights and obligations in the organization context. The goal of each role is to contribute to the fulfilment of (a part of) the requirements of the organization within which it is defined. An organization is defined by a collection of roles that take part in systematic institutionalized patterns of interactions with other roles in a common context. This context consists in shared knowledge and social rules/norms, social feelings, etc. and is defined according to an ontology. The aim of an organization is to fulfil some requirements.

In Janus, the organization is implemented as a first-class entity (a class in the object-oriented sense), which includes a set of role classes. An organization can be instantiated in the form of groups. Each group contains a set of instances of different classes of roles associated with the organization which it implements. A role is local to a group, and provides agents playing the role and the means to communicate with other group members. One of the most interesting aspects of Janus covers the implementation of roles as first class entity. A role is seen as a full-fledged class, and the roles are implemented independently of the entities that play them.

The organizational approach of the simulator is divided into three aspects:

the microgrid organization managing the exchange of energy between all the entities,

the hierarchical organization allowing the use of microgrids as a device,

the communication organization required to communicate with the outside.

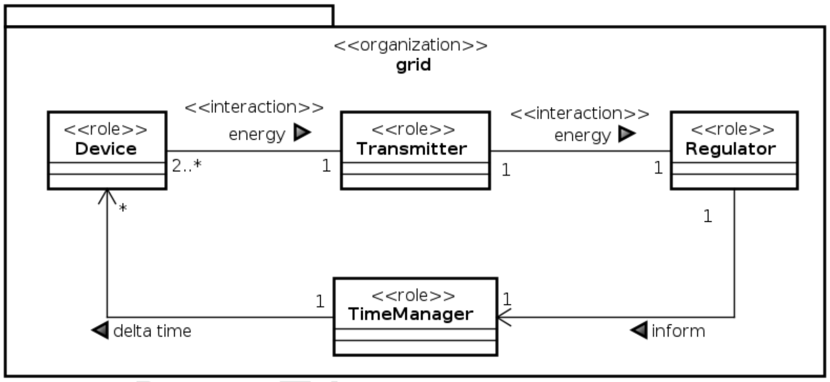

Fig. 1: the CRIO diagram of the microgrid organization

The microgrid organization (see figure 1) is composed of 4 roles: the device role, the transmitter role, the regulator role and the time manager role.

First, the device role has to be played by any entity that provides energy to the grid. The provided energy is positive for a producer, for example, a photovoltaic panel, or negative for all device that consumes energy, it could be a home, a microwave, etc.. A storage system, a battery for example, also has to play a device role. It can be a producer when delivering energy or a consumer when charging.

The second role, the transmitter role has to be played by every entity that will transfer energy between two or more roles and do not provides energy by itself. This role also offers the possibility to simulate losses during the transfer. A electrical bus is a typical example of an entity which has to play this type of role. A converter is another entity that can play the transmitter role to transfer and convert energy to entities with different characteristics.

The regulator role is connected to a transmitter to control the power flow through it. The regulation includes the stability of the network, it could be a frequency stability and/or a voltage stability depending on the entity playing this role. This role can also break the energy transmission if it considers the network as unstable.

The time manager guarantees that the time of the simulation is consistent. All the roles played in an organization are synchronized following the time given by the time manager (see section 2.3). Each cycle of a simulation is started when the time manager role decide to increment the time of the simulation.

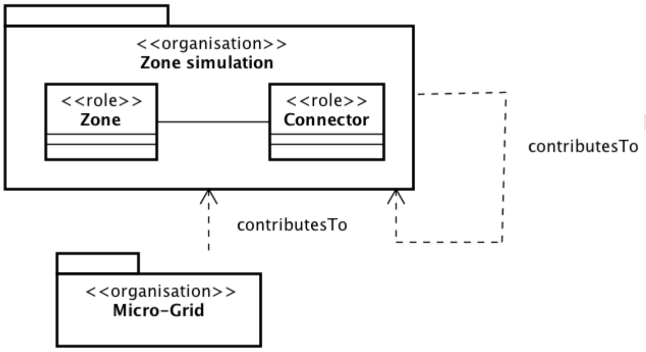

Fig. 2: the CRIO diagram of the hierarchical organization

The hierarchical or multi-levels aspect of grids is modelled by using two organizations (see figure 2).

The microgrid organization is linked to an upper-level organization. The principle is based on the connectivity of the electrical entities. Each microgrid, if not islanded, can be connected to other microgrids or more important grids by means of devices represented by a connector role.

The zone role represents a part of a network that can be independently simulated and have to be connected to another part of the network also independently simulated represented by another Zone role. These two roles work together (i.e. to exchange energy) has to be linked by a connector role.

The connector role ensures the communication of two or more zone roles. As the zone roles can simulate parts of network by different way, the connector role has to receive the energy sent by all the zone roles and transform the energy to ensure that the energy is valid for the other zone role. It roughly works as the transmitter role works in the microgrid organization.

Eventually, the communication organization (see figure 3) is composed of 4 roles: the device role, the sensor role, the actuator role and the user role.

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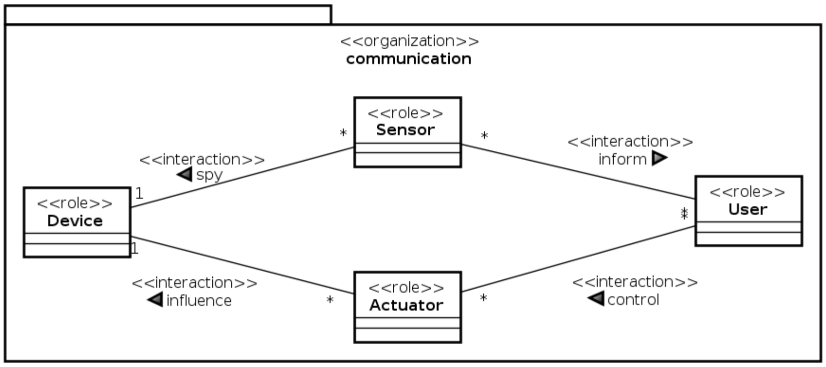

Fig. 3: the CRIO diagram of the communication organization

Firstly, the device role offers a two-way communication. The agent that played this role can change its behaviour following information received from the outside and can also be monitored by extracting local information.

Secondly, the sensor role is played by an agent that want to monitor a device role. The communication between a sensor role and a device role is a one-way communication, the agent cannot influence the device role by sending data.

Thirdly, the actuator role is played by an agent that has to send data to a device role. This one-way communication offer to the device role a aperture to the outside. The sent data shall not change the behaviour of the device role directly but must inform the device role of any change in its environment.

Eventually, the user role is a boundary role that can be played by any external intelligence and must be linked to some sensor roles and actuator roles to be aware of information of the simulation and influence the device of the latter.

For example, an intelligence wants to change the production of a fuel cell following the consumption of an engine. To do so, it has to play two user roles: one to monitor the consumption of the engine, and one to influence the production of the fuel cell.

2.3 Time Management

When simulating MASs, time management is a critical point because the timing delays introduced by the underlying execution platform may affect the simulation results [8]. Following the classification in [5], the time management used by our simulator can be classified as conservative with a Lower Bound on the Time Stamp. These approaches do not allow an agent to process an event until it has been guaranteed to be safe. In this algorithm, all messages sent during the same time stamp are safe. No future or past messages will be processed during all the simulation. Also, if the time is incremented following the real time, the simulator implements as real as possible the time flow and the exchange of messages.

In our simulator, an event becomes safe at the end of the time frame in which it was launched. Thus the amount of energy provided by the devices during a

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time frame will be managed by the regulator at the end of a time frame. It ensures that the time frame is the time unit of our simulator. As the duration of the time frame of the simulator can be set by the user the simulation speed can be controlled by user. The simulator can also be executed as fast as allowed by the underlying hardware.

The implementation is realized by the time manager role of the microgrid organization. After each step of the simulation, the time manager informs the device roles that they have to send power to the transmitter. The transmitter ensures the power flow between each device connected to itself. If connected device roles do not provide the energy during the time frame the transmitter assumes that no energy transfer is made. Then it sends the amount of power to the regulator to check the stability of the system. The time manager finally increments the time of the simulation.

2.4 Physical Model of Devices

Currently, the simulator contains several types of devices which can be producer, consumer or storage systems :

- photovoltaic panels and wind turbines whose energy production is directed by weather conditions. They are stochastic producers,
- fuel cells whose power can vary between 0 and a maximal power following their own dynamics.
- storage systems which have their own dynamic and their own capacity. Both of these properties are limited depending on the type of storage system. Batteries have a low dynamic but a great capacity compare to supercapacitors which have a high dynamic but a small capacity),
- electric network is an equivalent to the existing network in a microgrid: no limitations are made in its properties.
- a set of loads (consumers). Currently these loads are not controllable.
- a DC bus allows other devices to exchange energy. Its voltage shall be maintained in a defined voltage range otherwise the system will crash.

The developed models detailed below are simple and will be completed when a validation with real model will be realized. For exemple the electrical impedance is negligible and the converters are concidered as gains.

Renewables As the renewable energy ressources are currently stochastic, they are simply represented as current profiles. These data can be read from a file or a stream.

Fuel Cells - simplified model The power of the fuell cell is calculated according to the current i_{fc}^{dc} (the current coming from the fuel cell on the DC bus) following this relation:

$$P_{fc} = \frac{i_{fc}^{dc} \cdot v_{dc}}{\eta_{fc}}$$

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with η_{fc} the converter efficiency (between 0 and 1) linked to the fuel cell.

The instant consumption of hydrogen in terms of electrical power of the fuel cell is given by:

$$q_{H_2} = \frac{P_{fc}}{\eta_{fc}(P_{fc}) \cdot HHV_{H_2}}$$

with q_{H_2} is the hydrogen output. $\eta_{fc}(P_{fc})$ is the efficiency (between 0 and 1) of the fuel cell depending on the functional point. HHV_{H_2} is the Higher Heating Value of the hydrogen and is a constant at $140MJ/kg$ [6].

The quantity of hydrogen consumed during a interval Δt is:

$$m_{H_2} = \int_{t}^{t+\Delta t} q_{H_2} dt$$

The power of the fuel cell must be between 0 and the maximal power P_{fc}^{max} authorized by the system. The dynamic of the power also must be between the minimal dynamic power dP_{fc}^{min} (a negative value) and the maximal dynamic power dP_{fc}^{max} (a positive value). Finally, when the fuel cell cannot have hydrogen the production of energy will be null.

Storage Systems - simplified model The storage systems are modelled by an energy balance. The power P_{ss} of the system can be calculate by :

$$P_{ss} = \begin{cases} \frac{i_{ss}^{dc} \cdot v_{dc}}{\eta_{ss}} & \text{if } i_{ss}^{dc} \geq 0 \text{ (discharging)} \\ i_{ss}^{dc} \cdot v_{dc} \cdot \eta_{ss} & \text{if } i_{ss}^{dc} < 0 \text{ (charging)} \end{cases}$$

with η_{ss} is the efficiency (between 0 and 1) of the storage system linked to its converter.

The state of charge $SOC_{ss}(t)$ of the storage system is calculate following this relation:

$$SOC_{ss}(t) = SOC_{ss}^{init} - \frac{\int_0^t P_{ss} dt}{E_{ss}^{tot}}$$

with SOC_{ss}^{init} the initial state of charge of the storage system. E_{ss}^{tot} is the energy capacity of the system. The state of charge of a storage system also should be between minimal value SOC_{ss}^{min} and maximal value SOC_{ss}^{max} in order to preserve the system.

The power of storage system must be between the minimal power P_{ss}^{min} and the maximal power P_{ss}^{max} authorized by the system. Both of these value must be positive. The dynamic of the power also must be between the minimal dynamic power dP_{ss}^{min} (a negative value) and the maximal dynamic power dP_{ss}^{max} (a positive value). Obviously, if the storage system is empty, it cannot deliver energy, also if the storage system is full, it cannot receive energy.

Electric Grid The electric network is the usual network already existing plugged with a microgrid. It can deliver or receive any energy of the microgrid.

Loads As the loads are currently stochastic, they are simply represented as profiles of current from experiments. These data can be read from a file or a stream.

DC Bus - simplified model The DC Bus is composed by a capacitor which required the voltage of the DC Bus. The voltage of the DC Bus is given by:

$$i_c = -C\frac{dv_{dc}}{dt}$$

with i_c is the current in the capacitor, C its capacity and v_{dc} the voltage across the capacitor. The current i_c is inferred from the current balance on the DC Bus from the Kirchhoff law:

$$\sum_k i_k + i_c = 0$$

with k the number of devices plugged on the DC Bus and i_k the current deliver by the device k. Thereby the DC Bus voltage can be inferred from the following relation:

$$v_d c = v_{dc}^{init} - \frac{1}{C}\int i_c dt$$

with v_{dc}^{init} the initial voltage of the capacitor.

3 Experiments and First Results

3.1 Scenario

The reliability of our simulator was empirically validated using a simple scenario and compared with a simulator developed thanks to `SimPowerSystems`.

In this scenario (see Figure 6), the microgrid is composed of a DC Bus connected to some renewables (a mix of photovoltaic and wind turbines), loads (a consumption equivalent to 50 homes), a fast storage system – a set of supercapacitors – with strong dynamic but low energy, a slow storage system – a set of batteries – with low dynamic but a lot of energy and the electrical grid assumed to have infinite dynamic and energy. The virtual duration of the simulation has been set to two days. The table 1 sums up the values of the data presented in the section 2.4. In this example, the time step between each stability verification is one second.

3.2 Artificial Intelligence

The intelligence developed to verify the usability of the simulator is a simple intelligence. The main objective of the intelligence is to keep the DC Bus voltage stable.

The intelligence first manages the behavior of the battery by regulating the energy. If the battery has not enough dynamic to regulate the DC Bus voltage or has a state of charge not correlated to the decision, then the supercapacitor comes into play and delivers some current according to a behavior similar to the battery's one. In any case, the electrical network stabilizes the DC Bus voltage.

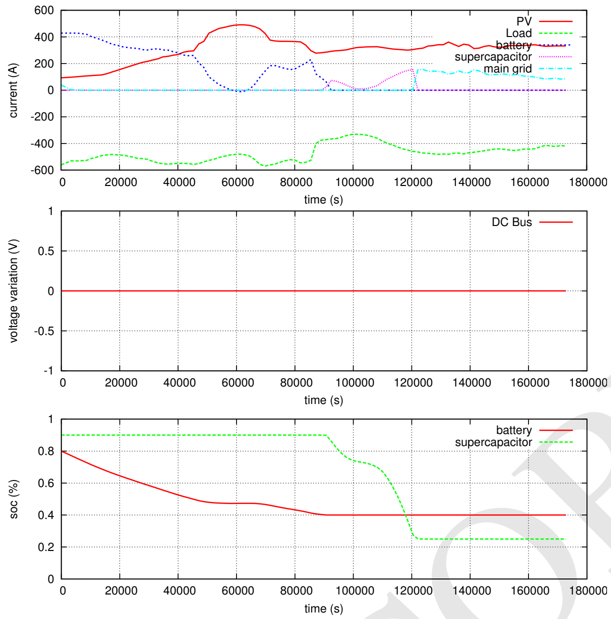

Fig. 4: Simulator: Top chart, current - Middle chart, voltage variation - Bottom chart, state of charge

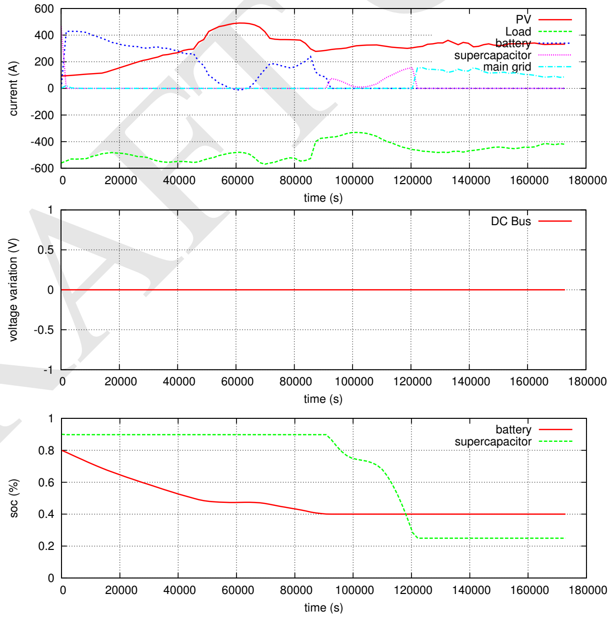

Fig. 5: `SimPowerSystems`: Top chart, current - Middle chart, voltage variation - Bottom chart, state of charge

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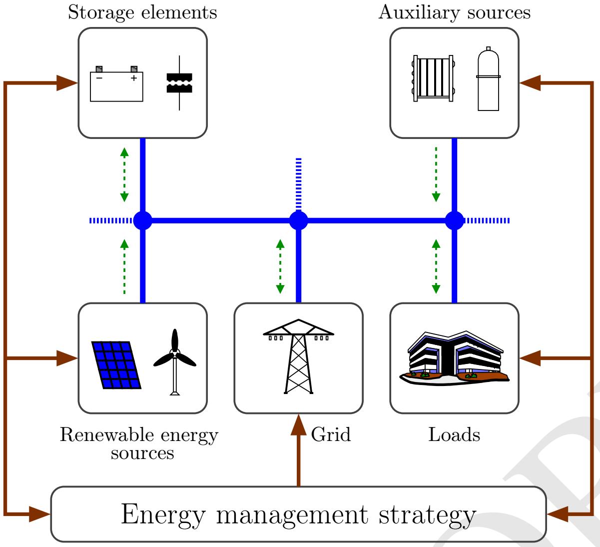

Fig. 6: A simple schema of the microgrid used for validation

3.3 Results

The figure 4 shows the results obtained by our simulator and the figure 5 shows the results provided by the `SimPowerSystems` tool. In both figures, the top chart shows the variation of current of the devices. The second (middle) chart shows the success to keep the DC Bus voltage stable. The bottom chart shows the dynamic of both storage systems with their states of charge.

The comparison of the two figures highlights that the devices of our simulator globally have the same behaviors than those of the other simulator. To details the difference between the two results which is not visible on the charts, A numerical comparison is given the detail the variation of values between the two simulators:

- For the batteries, the mean of the differences between the intensities is 0.24A and the deviation is 5.74A.
- For the supercapacitors, the mean of the differences between the intensities is 0.29A and the deviation is 5.88A.
- For the electrical grid, the mean of the differences between the intensities is 0.30A and the deviation is 7.57A.

4 Conclusions and future works

In this paper a subject of importance for the Smart Grids community is presented. The proposition consists of a simulator capable of reproducing the behaviours of electrical devices in order to test MAS for Smart Grids management. This simulator is compared to MATLAB/Simulink `SimPowerSystems` which

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Renewable	
see Figure 4, top chart, curve in red	
Loads	
see Figure 4, top chart, curve in green	
Battery	
$SOC_{bat}^{min} = 0.25$	$SOC_{bat}^{max} = 0.9$
$P_{bat}^{min} = -300kW$	$P_{bat}^{min} = 300kW$
$\frac{dP_{bat}^{min}}{dt} = -2kW/s$	$P_{bat}^{min} = 2kW/s$
$E_{bat}^{tot} = 2MWh = 5kAh$	$\eta_{bat} = 1$
Supercapacitor	
$SOC_{sc}^{min} = 0.8$	$SOC_{sc}^{max} = 0.4$
$P_{sc}^{min} = -600\ kW$	$P_{sc}^{min} = 600\ kW$
$\frac{dP_{sc}^{min}}{dt} = -10kW/s$	$P_{sc}^{min} = 10\ kW/s$
$E_{sc}^{tot} = 100\ kWh = 250Ah$	$\eta_{sc} = 1$
DC Bus	
$v_{dc}^{init} = 700V$	$C = 20mF$
$v_{dc}^{min} = 680V$	$v_{dc}^{max} = 720V$

Table 1: Data of the testing scenario

is, in the energy community, a well-known and widely used simulator. The results of this experiment shows that the outputs of the MAS are very close to `SimPowerSystems`. However, the architecture of the two simulators are radically different. `SimPowerSystems` is based on a centralized architecture and closeness is among it basic hypothesis. The MAS based simulator presented, on the contrary, is based on a pure agent architecture that allows distribution and openness.

Moreover, the presented principles allow to replace the simulator with real devices without changing the Smart Grids management part. Indeed, one of the aim of this simulator is to enable a prototyping approach for MAS dedicated to Smart Grids management. The simulator has been designed according to a specific MAS methodology, namely ASPECS [2]. This methodology is based on organizational concepts and is supported by a development platform that eases the implementation of the methodology concepts, namely Janus [7].

This new simulator is a first step toward the development of a library of devices to create a huge variety of scenarii. The idea is to enable the test of smart management strategies for power systems. One can thus test several techniques over a set of benchmarks for learning, or only to experience new dynamic controls. Currently the simulator contains some device implementations and is base on an DC bus architecture.

In the future, we plan to evaluate different MAS for Smart Grids in order to identify efficient approaches. These MAS will be tested within the proposed simulator and on real grids. More specifically, a reinforcement learning approach is under study [10] and an implementation of an AC bus architecture is planed.

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