Renewable energy emulation concepts for microgrids

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Abstract

This article reviews the renewable energy systems emulators proposals for microgrid laboratory testing platforms. Four emulation conceptual levels are identified based on the literature analysis performed. Each of these levels is explained through a microgrid example, detailing its features and possibilities. Finally, an experimental microgrid, built based on emulators, is presented to exemplify the system performance.

Keywords: Emulators, Renewable energy, Platform laboratory, Power electronics.

1. Introduction

The importance of distributed generation (DG) in the power system is increasing. The energy produced in these facilities must be integrated to the grid and microgrids arise as a particularly beneficial solution. A microgrid is defined as a system compounded by different micro-sources and loads, operated by an energy manager, that is able to deliver heat and electrical power in a local area [1]. This definition has been evolving as other capabilities has been included to the concept as storage systems [2] or the islanding system operation [3]. Microgrids should be understood as small pieces of the whole power system and each of them could be designed and operated to meet different local specifications and objectives.

A microgrid is a relatively new concept, thus different studies related with the control, operation, design and protection are being developed. Among all these projects, the ones where real microgrids are built [4], are extremely interesting for testing the theoretical developments. Microgrids as the CERTS laboratory project (Consortium for Electrical Reliability Technology

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Solutions) [5] or facilities developed by other research centers are defining the specifications of the future microgrid concept [6]. In a laboratory scale, other setups are being built, as for example the IREC microgrid (Catalonia Institute for Energy Research) [7] or the platform proposed by the Energy Systems Research Laboratory, Florida International University [8]. These laboratory platforms, in contrast to the large experimental projects, include emulation devices which allow to physically represent the behavior of many different resources. Emulators in combination with real systems, increase the experimental laboratory platform capabilities enormously.

Focused on the emulation devices, this paper reviews the emulation structures proposed in the literature. As a result, emulation is divided in four different conceptual groups, defined as the emulation levels. To clarify this concept, the different emulation levels features and characteristics are explained through an example microgrid layout, also including a complete classification of the literature review. Finally, a real laboratory platform, employing two of the emulation levels defined, is presented. Three different emulators are included in this system, one acting as a photovoltaic panel, another as a battery and another one as a couple of loads, defining the basic structure of a microgrid. Experimental results are included to show the actual operation of the system including the emulators and its testing possibilities.

2. The emulation concept

An emulator is a device that attempts to mimic the behavior of a real resource. Basically, it is compounded by two interrelated parts, a software and a hardware layer. On the one hand, the software layer calculates the system variables, that the real system would show under the same conditions, based on static or dynamic operations. On the other hand, the hardware layer imposes the software calculated variables by means of mechanical, electronic or electrical devices, to follow the real system behavior. According to the previous definition, systems of all kinds could be emulated. However, this article is mainly focused on analyzing the emulation structures available for representing energy systems that could be connected to an electrical microgrid.

In order to clarify the introduced concept, an example of a photovoltaic (PV) emulator operation (Figure 1) connected to the grid is explained in detail. In this case, the emulator software layer calculates, based on the real PV installation that is being emulated and the environmental scenario conditions defined for the experiment, the voltage that would be across the real PV

power connection terminals. Once calculated, this voltage is applied by the emulator hardware layer at the emulator power terminals, by means, for instance, of a power converter. Therefore, both the real PV installation and the emulator would show the same voltage at its connection terminals, allowing the grid integration converter to perform the same control on them, without any difference.

[Figure 1 about here.]

In general, emulation devices present some features that increase the possibilities of the testing system where they are connected, regardless of the resource that is being represented:

- An emulator can represent any possible scenario employing the same software and hardware devices. The experiment conditions are imposed by the user.
- Experiments performed employing emulators avoid damaging real setups. Emulators usually include protections and securities to avoid possible problems while testing.
- Emulation allow to change the experiments time scale. For instance, long time evolution of the real system can be concentrated in a short period of time.
- Emulators are usually smaller than the emulated real setups. This feature is interesting for laboratory test benches where the testing space is usually limited.
- Its hardware and associated costs are usually lower in comparison to real systems.
- In certain configurations, an emulator is able to represent different resources or an aggregation of various systems.
- The emulator output power could be scaled to a larger one if it is needed. The hardware can be designed for a desired power level and otherwise, the software layer can scale the results of the emulation.

As it is mentioned above, the inclusion of emulators in experimental microgrid research setups could be interesting to test different aspects [9] as the system control, the islanding operation mode, the grid integration of the resources by means of power electronics, the design and operation of

microgrid energy management systems and the protection, operation and control of AC and DC electrical microgrids, among others.

3. Emulation levels definition

Based on the emulator literature review developed, it can be stated that emulators can be conceptually classified in different groups, defined in this work as the emulation levels. These levels are defined based on the degree of detail employed to represent the emulated resource, not on the software and hardware devices used for the emulation. In this section, the established emulation levels are explained using the example microgrid layout depicted in Figure 2.

[Figure 2 about here.]

The example microgrid scheme is divided in two different current nature grids, the AC side (black lines) where loads and conventional microgeneration are connected and the DC side (blue lines) where the renewable generation and storage systems are placed. The connection of the different resources to the DC microgrid part is carried out using DC/DC or AC/DC converters, depending on the system current nature. Note also that, the nature of the AC grid is not specified, thus it can be a single-phase, a three-phase or a multi-phase grid.

Once introduced the example layout, the emulation levels are explained, starting from the most generalized, to the most specific ones. Basically, the development of the different levels will be focused on the DC grid side elements of the example microgrid. It should be mentioned that converters drawn with dashed lines are related with emulation, whereas those drawn with solid lines are considered real elements.

3.1. Level 1: Global emulation

Figure 3 shows the most possible generic emulation of systems, defined as global emulation. This level considers that the generation, storage and load systems connected to a certain grid could be emulated via software (represented by a red square in Figure 3) and transformed into an equivalent aggregated active and reactive power consumed or injected to the microgrid by a single hardware layer. The emulator is not representing a single resource, it is representing the aggregation of a whole system with its different subsystems connected to it.

[Figure 3 about here.]

Therefore, the emulation system exchanges a defined amount of the power with the grid based on the total power aggregation computed by the software layer. If it is desired, an individual control could be applied on each resource, but it has to be implemented in the software stage of the emulation. Experiments related with microgrid grid integration, communications, coordination and control between different microgrids could be performed.

Note that, the green block depicted in Figure 3, corresponds to the power supply (PS) of the emulators, needed for the system operation. Then, if the emulation system consumes energy from the DC grid, this energy must be consumed by the PS system and on the contrary, if the emulation is injecting power to the grid, the PS should deliver it. Therefore, the PS must be bidirectional to accomplish the emulation system requirements. However, if the nature of the emulated system is defined, the PS could be design to be unidirectional. Hereinafter, the PS system is depicted using a green box connected to the emulators.

3.2. Level 2: Aggregated emulation of generation, storage and loads

This architecture consists on gathering the emulated systems by common flow direction. As it is shown in Figure 4, three different branches can be differentiated. These branches correspond to three emulation groups, generation, storage and loads. The emulator software layer computes the aggregation of different resources by power flow nature, calculating the equivalent power that they are injecting or absorbing from the grid. Then, the hardware layer, transforms this calculation in a real power flow. The difference between this emulation level and the previous one is purely conceptual, because the same emulation devices could perform both emulations perfectly. Again, an specific control applied to a single resource has to be computed in the software layer, because everything is calculated in it.

[Figure 4 about here.]

This architecture is useful for testing microgrid energy management systems, communications, among others.

3.3. Level 3: Resource emulation

The conceptual diagram of this emulation is shown in Figure 5. Unlike the two previous emulation levels, this architecture dedicates an emulator device to each resource. The emulators employed in this level are power emulators, thus they represent the power output that the real resource system would be exchanging with the grid, under the defined conditions. Then, not only the behavior of the resource is being emulated, but also the possible interconnection systems between the resource and the grid. For instance, a solar panel would be emulated together with the converter that is used for the grid integration of the energy produced. The software layer of the emulator calculates the variables of the system and the power output that the whole real system would be injecting under the same conditions, and the hardware layer will transform the software calculations into real power.

[Figure 5 about here.]

The difference between this emulation level and the previous ones is again conceptual, because the same emulator devices could be used for the three different levels. However, this architecture does not allow again to perform real control of the emulated resource because the system is based in power emulation, so if it is desired, it should be implemented in the software layer. This emulation concept allows to perform experiments, at a resource level, related with microgrid energy management systems, grid integration of the resources, communications between systems, coordination, protections, among others.

3.3.1. Level 4: Specific emulation

This emulation level (Figure 6) is focused on the emulation of a resource by representing its electrical variables. The software layer carries out the calculation of the resource variables under the defined scenario conditions and the hardware layer applies these variables to the real system. For instance, the operation of a PV panel could be emulated. Based on a supposed irradiance, the software layer calculates the voltage output that the real system would be applying. Then, the hardware layer regulates the voltage at the output terminals, to apply exactly the calculated magnitude. Therefore, if a grid integration converter is connected to the emulator, it will not detect any difference between the emulator and the real system if the first is properly designed.

This fact can be observed in Figure 6 where real DC/DC converters are performing the integration of the emulators to the real grid, in the same way as it would be connecting the real resources to the microgrid.

[Figure 6 about here.]

There is an important difference between the emulation concept employed in this level and the previous ones. While in emulation level 3, the emulators act as power sources; in this case, emulators are representing mainly the resource, applying, for instance, the same voltage that the real resource would be applying under the same conditions. Therefore, this level allows to perform real control on the emulators, as if they were real resources. Moreover, this emulation level allows to swap the emulator by the real emulated resource.

This emulation level defines a boundary on the conceptualization of the emulators. More complex structures can be defined for each resource individually, but further conceptual groups are not easy to be made. Figure 7 shows further emulation possibilities focusing on each of the elements that compound the microgrid, starting from the emulation presented above in Figure 6 (indicated with a number 1), to the real system implementation where the emulator is substituted by a real installation. Next, these structures are described:

- Wind energy emulation

1. Turbine-generator emulator. The emulator is designed to represent the electrical system gathering the wind turbine and the generator.
2. Turbine emulation. The wind resource and the turbine are emulated by a motor controlled by a frequency converter. The motor axis is coupled to the real (or scaled) generator. Then, supposing a wind resource and defining the turbine blades, the torque or the speed of the motor could be calculated and regulated by the frequency converter. Then, the real generator could be controlled by a real converter.
3. Wind emulation. The generator and the turbine are the real ones (or a scaled version). The wind is emulated using a fan, allowing to perform real tests with the whole setup.
4. Real wind generation system. The wind emulation system is replaced by the real resource.

- Solar energy emulation
 1. PV cell emulator. The emulator represents the behavior of a PV cell or a combination of them.
 2. Light emulation. The PV emulator is replaced by the real panel (or a scaled version) and it is excited by artificial light.
 3. Real PV installation. The solar emulation system is replaced by the real resource.
- Battery emulation
 1. Battery emulator. The emulator represents the behavior of a battery. It could be designed and configured to represent any type of battery.
 2. Real batteries. The emulator is replaced by a real battery system.
- Electric vehicle emulation
 1. Electric vehicle emulator. The electric vehicle behavior is represented by an emulator. It can be configured as a fast or conventional charging system. It also could include not only the electrical part, but also the communications including different protocols.
 2. Real EV with fast charging capability. The EV emulator is substituted by a car with fast charging capability.
 3. Real EV with conventional battery charger. The EV emulator is substituted by a car with a conventional charging capability.
- Flywheel emulation
 1. Flywheel-generator emulator. The flywheel together with the generator behavior is represented by an emulation system.
 2. Flywheel emulator. The flywheel is emulated by a motor and a frequency converter. The real flywheel generator (or a scaled version) is connected to the emulation motor-frequency converter setup that will behave as the rotating mass.
 3. Real flywheel. The emulator is substituted by a real flywheel.
- Fuel cell emulation

1. Fuel cell emulation. The behavior of a fuel cell is represented by an emulation setup.
2. Real fuel cell. The fuel cell emulator is replaced by a real fuel cell.

[Figure 7 about here.]

As it is mentioned before, it is not possible to define another emulation level including the different emulated resources. Therefore, these emulation proposals are considered inside the frame of the specific emulation.

To conclude, it is interesting to state that researchers always can choose between the different emulation levels proposed. Then, depending on the objectives of the experiment to be performed and the detail of the system variables needed, an emulation level could be selected to accomplish the specifications.

3.4. Other considerations

It should be mentioned that the emulation level does not depend on the nature of the grid where the emulator is connected. However, the hardware of the emulator should be adapted depending on the grid nature to perform a proper emulation. As an example, the connection of the elements to the DC Grid, as it is shown in Figure 2, could be substituted by a connection to an AC grid without modifying the emulation level.

The emulators power supply has been shown in all cases represented with a green box for all the emulators. Note that, each of the emulators could include its own individual power supply. Besides, the power supply could also be provided in DC current instead of AC as it is supposed in the different emulation systems.

This document does not include all the systems susceptible of being emulated. For example, a diesel generator could also be emulated properly. The analysis is focused on renewable resources, because they are the most common emulated systems found in the literature. However, if it is desired, the emulation level concept can be easily applied to other technologies.

4. Emulation literature review

Based on the review presented in this section, the previous emulation level definition has been made. First, this literature analysis is focused on the platform laboratories where emulators are

part of the platform structure. Table 1 shows the results of the literature review, classifying the platforms emulators by its corresponding emulation level.

[Table 1 about here.]

In addition to this classification, other emulation test benches have been proposed focused on a single resource. Table 2 shows the classification of these emulators by its corresponding emulation level. Note that, as these devices are emulators that are representing a single resource, they can be classified between emulation levels three and four.

[Table 2 about here.]

The information provided in Tables 1 and 2 is expanded in the appendix section, where a detailed explanation of the laboratories and the emulators found is developed. Next, based on this literature review, several conclusions are drawn:

- In the major part of the laboratories, emulators are combined with real elements, fact that increases the laboratory experimental possibilities, allowing to represent scenarios that could not be possible without an emulator.
- Laboratories are implemented using an AC grid, a DC grid or a combination of both, with emulators connected at both sides.
- The power levels of the elements included in laboratories, either real resources or emulators, range from 100 W to a few kilowatts.
- One of the main objectives of this type of laboratories is the validation of energy management system strategies.
- The interconnection of several renewable energy sources within the same system is another of the topics analyzed using microgrid laboratory platforms.
- The AC side voltage range depends on the country where the laboratory is installed, according to the local typical voltages.

- It can be seen that the most common emulation systems are levels three and four, because usually a single emulator is employed to represent a single resource. However, there are examples of emulators representing more than one system, showing that levels one and two are also interesting structures to experiment with.
- Some of the emulators articles are focused only on the development of the emulation device. Whereas in the rest of the reviewed articles, the emulator is used to validate new developments, acting as the real resource. This type of articles, where the emulator is used as a validation tool, are classified in the appendix with the acronym NFE, which stands for Not Focused on the Emulator.
- Emulators representing the same resource, employing the same emulation level, have in common the concept of how the resource is being represented. However, the software and hardware layers of these emulators, could be sufficiently different. For instance, many different PV cell emulators classified into the level 4 of emulation, are built employing various electronic configurations. Of course, depending on the software and hardware employed, the accuracy of the emulation results can vary.
- The hardware layer of the solar emulators reviewed is mainly built based on a DC/DC converter or programmable DC power supply. Different proposals for the structure of the DC/DC converter are shown to improve the transient dynamic response and the efficiency.
- Wind emulators are typically based on a 4-2 emulation level structure, in which the wind resource and the turbine are emulated by a motor controlled by a converter. The current nature and the power rating of the motor included in the emulation structure, depends on the experiment.
- Fuel cell and battery emulators hardware layers are based on DC/DC converters or programmable DC power supplies. The different emulators reviewed show a level 4 emulation structure.
- Load emulators are developed based on a DC/DC converter or a three-phase Voltage Source Converter (VSC).

- The electric vehicle emulator found in the literature is based on an Induction Machine (IM) applying a defined torque to the EV motor. The emulation levels included are defined for devices connected to microgrids. In this case, the emulator is developed to analyze the operation of the EV, while it is not connected to the grid. Even so, it has been included in the literature review due to the interesting test bench proposal.
- Regarding the software layer of the emulators, different elements are proposed to control the hardware structures: Digital Signal Processors (DSP), dSPACE® systems, Field Programmable Gate Arrays (FPGA), Peripheral Interface Controllers (PIC®), among other controllers.
- Typically, emulators are custom systems built in the laboratory. However, commercial emulators, to represent the behavior of PV panels and fuel cells, are available.

The previous points summarize the findings of a selection of the emulation structures present in the literature. Of course, other emulator topologies can be developed, based on the testing requirements.

5. Microgrid platform based on emulators

In this section, as an example of the possibilities that the emulation systems offer, a complete microgrid including generation, storage and load systems is built only employing emulation devices. It is compounded by three different emulators connected to the same AC grid, a PV generation system emulator, a battery emulator and a load emulator, as it is shown in Figure 8. Figure 9 shows a picture of the setup, where the actual emulators are installed.

Note that, the emulators are connected to a single-phase AC grid, unlike in previous sections, where the description of the different emulation levels is developed considering that emulators are connected to the DC grid. However, as it is mentioned in Section 3, the emulation level is preserved regardless of the nature of the grid to which the emulator is connected. It can also be seen that the PS of the emulators is a single 6 kVA bidirectional converter, for the three emulators.

[Figure 8 about here.]

[Figure 9 about here.]

Next, a brief description of each emulator behavior is detailed:

- The PV generation [Emulation level 3]. It is emulating the photovoltaic module together with the control converter. The emulator software is considering that the PV module is operated at the Maximum Power Point (MPP). Then, defining the PV characteristics, introducing the system geographical location and loading the scenario irradiance and temperature temporal data, the software emulation part is able to calculate the power generated P_{MPP} by each panel and the total power injected to the grid [10]:

$$\begin{aligned} P_{MPP} &= V_{MPP} \cdot I_{MPP} \\ V_{MPP} &= V_{MPP0} \cdot \frac{\ln(G)}{\ln(G_0)} \cdot (1 + k_v \cdot (T_p - T_{p,0})) \\ I_{MPP} &= I_{MPP0} \cdot \frac{G}{G_0} \cdot (1 + k_i \cdot (T_p - T_{p,0})) \end{aligned} \quad (1)$$

where, G and T_p are the irradiance and the panel temperature (temporal data input) and V_{MPP0} , I_{MPP0} , G_0 and $T_{p,0}$ are the solar panel parameters at the Standard Test Conditions (STC). Also, it should be mentioned that the whole system is assumed to have zero losses. Anyhow, the efficiency of the inverter could be straightforwardly included in the model.

- Load emulator [Emulation level 2]. It is programed to consume from the grid a programmed active power with a certain power factor (PF) emulating a couple of real loads.
- Battery emulator [Emulation level 3]. The emulator represents the battery together with its corresponding charging/discharging converter. The system is controlled to absorb or inject power when it is required. This implementation does not consider losses within the system. However, the battery and converter efficiencies can be straightforwardly included in the model.

The emulators power rating is 1.5 kVA, but the emulation results can be scaled to represent larger power scenarios. Next section shows two different experimental case studies performed on the microgrid, to validate the emulator performance inside the system. The first one is focused on the

time range of milliseconds, whereas the second one shows the operation of the platform during longer emulations.

5.1. Microgrid scenario 1 description

This experiment is focused on the range of hundreds of milliseconds, to demonstrate the operation of the emulators within this time frame. The electrical scheme configuration is shown in Figure 10 and the experimental scenario conditions are:

- Load emulator. It starts consuming 500 W from the grid with a 0.9 power factor and changes to 1200 W with the same power factor.
- PV emulator. It is injecting constantly 900 W due to an irradiance of 600 W/m².
- Battery emulator. It is operated to achieve the goal of zero active and reactive power exchange between the main AC grid and the microgrid during the test.

Figure 11 shows an oscilloscope capture of the system currents. The currents measured are the PV current (magenta), the load current (blue), the battery current (green) and the main grid current (yellow) (see Figure 10 for the color code). It can be observed that during the first part of the test, the microgrid is exchanging zero energy with the grid (the current flowing to the grid is almost zero). This fact is achieved because the PV generation is enough to feed the load, so the excess of power is being stored in the battery. When the load changes its value to a higher one, transiently, it can be seen that the grid feeds it because the PV installation does not produce enough power to do it. However, a few milliseconds later, the battery starts to inject the extra amount of active and reactive power to compensate the extra load consumption, in order to maintain the objective of exchanging zero active and reactive power with the grid.

[Figure 10 about here.]

[Figure 11 about here.]

In this case, the power references for the battery operation are calculated off-line and changed manually during the test, acting as the energy manager would need to do, to maintain the power

exchange with the grid set to zero. A real energy management system could be included to control the state of charge of the battery, in order to achieve the same goal or others, autonomously.

It can be stated that the employed emulators show a proper behavior during the experiments, both in steady state and during transients, representing the emulated resources accurately.

5.2. Microgrid scenario 2 description

This second experiment is designed to show the behavior of the emulators during a longer run test. The electrical scheme configuration is shown in Figure 12 and the experimental scenario conditions are:

- Load emulator. It is consuming active power from the AC grid, following the predefined profile shown in Fig. 13a.
- PV emulator. Based on experimental irradiance measured in field tests, the PV emulator injects to the grid the equivalent amount of power that a real installation would be injecting under the same conditions. The power profile generated by the PV system software emulator layer is shown in Fig. 13b.
- Battery emulator. It is operated to achieve the goal of zero active power exchange between the grid and the microgrid during the test.
- Test duration: 8 hours compressed in 8 minutes, applying the accelerated emulation with a factor of 60.
- Power level: The power profiles shown in Fig. 13 are properly adapted to the range of the emulators power hardware layer. The output results are rescaled back to their real magnitudes.

Once the power profiles for the PV array emulator and the load are calculated in the software layer of both emulators, the corresponding hardware layers inject/absorb to/from the AC grid the calculated power. Regarding the battery emulator, its software layer measures the injected power by the PV and the consumed power by the load, and it calculates in real time the power to exchange with the microgrid in order to maintain the zero power flow to the grid.

Thanks to the emulators, the platform also offers the possibility of accelerating the emulation. Then, a 500 minutes experiment can be carried out in 500 seconds applying an acceleration factor of 60. This experiment could be extended to include results for several days or months, if large temporal data for the PV emulator were available.

[Figure 12 about here.]

[Figure 13 about here.]

Fig. 14 and Fig. 15 show the obtained results of the proposed emulation scenario. Specifically, Fig. 14 shows an oscilloscope capture of the emulators phase currents flowing through the system. The color code for the currents is consistent with the previous scenario (see Figure 12). Note that, as the duration of the experiment has been accelerated, 500 min are represented in 500 s (Scope scale: 50 s/div, 10 divisions). The system currents reflect the power variations imposed by the hardware layers of the emulators, which are tracking the corresponding power profiles. However, this scope capture is not illustrative enough to understand the system behavior, as it does not show the real power flowing through the system.

In order to better understand its operation, the average real power calculation of the power flowing through each of the emulators is shown in Fig. 15. For the sake of clarity, as single phase converters exchange an oscillating power with the AC grid, only the average component of the power is shown. It can be observed that the hardware layer of the PV and Load emulators is able to inject/absorb power, tracking the power profiles calculated by the software layers. In this experiment, the power reference for the emulators is refreshed every 5 seconds. This value could be reduced to smaller values to improve the power reference tracking. Regarding the battery emulator, during the experiment it is able to compensate the energetic balance with the main grid, absorbing power when there is PV power excess (interval between 250-300 s) and injecting power when the load consumes more power than the PV generated power (interval between 25-60 s), in order to maintain the zero exchange power with the grid.

[Figure 14 about here.]

[Figure 15 about here.]

5.3. *Experimental microgrid discussion*

The microgrid structure presented is based on three different elements, a PV array, a battery and a load emulator of 1.5 kVA rated power each, connected to a single phase AC grid. Other microgrid laboratory proposals, shown in the literature review, include the same resources, either represented only by means of emulators [11] or in a combination of real elements and emulators [8, 12, 13, 14, 15, 16]. The connection to a single-phase system is considered in the proposed platform, due to the reduced power and voltage levels defined for the emulators. Moreover, the connection of generation, storage and loads to a single-phase system could represent a possible microgrid installed in a conventional house or flat, which is interesting to be analyzed, as the power distribution grid could evolve to include this type of systems. According to the literature, laboratories are mainly focused on analyzing hybrid systems combining three-phase AC and DC grids within the same microgrid [8, 13, 17, 18, 19, 15, 20], even considering a single-phase AC side connection [14, 16]. Other authors, focus their studies either on systems connected to a three-phase AC grid [7, 11, 21], or to a DC grid [12]. Of course, the laboratory microgrid structure can vary depending on the objectives of the study to be performed.

Regarding the experimental possibilities, the proposed emulation platform includes emulators based on levels 2 and 3 (power level representation of the resources). This type of emulators are not representing the resource variables in detail, but they are behaving equivalently in terms of power flow, being able to carry out experiments related to the highest control levels of the microgrid, as the implementation and testing of energy managers, communications between the different elements, interaction between devices, among others. Based on the literature review, it can be stated that the majority of the laboratories are also developed to implement and study issues related to the energy management system, instead of focusing on a single resource.

Also, as the three emulators of the proposed test bench are based on the same topology, the software layer could be modified to emulate other type of resources. This possibility is also described in [7, 11, 12, 18, 15, 20], whereas the other laboratories include more specific emulators, designed for representing a single resource.

Focusing on the PV emulation results, among the laboratories that include a PV emulator, only [11, 12, 15] include a level 3 PV emulator structure, corresponding to an emulator operated

in power mode. Comparing the obtained results in the second experiment, to the results shown in [11] and [12], it can be seen that the PV emulated power output profile, obtained in all cases, is quite similar, as it is calculated based on real measurements.

Regarding the battery emulator, the majority of the laboratories include real lead acid battery banks, instead of an emulator. Only [7] and [11] include a level 3 battery emulator, as in the presented microgrid. However, [7] and [11] include the calculation of the battery state of charge, whereas in the proposed microgrid this calculation is not included in the experiments.

The load representation within the microgrid laboratories is carried out using either real systems or emulators. Laboratories [14, 17, 15, 20] use real loads, [7, 11, 12, 13, 18, 19] and the presented microgrid, include load emulators, and others incorporate a combination of both [8, 16].

Focusing on the acceleration capability of the proposed platform, in [12] the experiment time is accelerated to reduce the experimental test duration, as in the second experiment proposed.

In summary, the proposed platform based on emulators include valuable features for the development experiments related with single-phase microgrids, showing similarities and differences compared to other laboratories found in the literature.

6. Appendix

In this section, an analysis of the different laboratories and emulators presented in Section 4 and classified in Tables 1 and 2 is performed. Tables 3, 4 and 5 describe the different laboratories found in the literature and Tables from 6 to 15, detail the different emulators proposed for the analyzed resources.

[Table 3 about here.]

[Table 4 about here.]

[Table 5 about here.]

[Table 6 about here.]

[Table 7 about here.]

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[Table 9 about here.]

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[Table 12 about here.]

[Table 13 about here.]

[Table 14 about here.]

[Table 15 about here.]

Besides, Fig. 16 shows a world map including the location of the different emulators reviewed, classified by resource. Also, the location of the laboratories is included. Some of the articles do not exactly clarify where the system is installed. In this case, the location is defined based on the affiliation of the corresponding author.

[Figure 16 about here.]

7. Conclusion

In this work, a review of the emulation systems available for different resources is developed. First, based on the literature analysis performed the emulation concept is defined, differentiating four emulation levels based on the emulation characteristics. Next, features and possibilities of each of these levels are explained through an example microgrid. Then, the literature review results, of the laboratory platforms and emulation test benches classified by resource and emulation level, are shown. Finally, a small scale microgrid research laboratory platform based on emulators is presented in order to show the proper performance and the possibilities of the emulators. This literature review, along with its classification by emulation levels, could be a useful guide during the design stage of an experiment including emulation systems.

Acknowledgements

This work was supported by the *Ministerio de Economía y Competitividad* under projects IPT-2011-1892-920000, ENE2012-33043 and ENE2013-47296. This research was co-financed by the European Regional Development Fund (ERDF).

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Figure 1: Photovoltaic emulator concept

Figure 2: Microgrid base electrical layout

Figure 3: Level 1 - Global emulation scheme

Figure 4: Level 2 - Aggregated emulation scheme

Figure 5: Level 3 - Resource emulation scheme

Figure 6: Level 4 - Specific emulation scheme

Figure 7: Level 4 - Specific emulation scheme for each resource

Figure 8: Scheme and physical implementation of the platform

Figure 9: Setup of the emulation platform

Figure 10: Scenario 1 - Scheme and physical implementation of the platform

Figure 11: Currents flowing through the emulators - PV (magenta) - Load (blue) - Battery (green) - Grid (yellow)

Figure 12: Scenario 2 - Scheme and physical implementation of the platform

(a) Load emulator power profile

(b) PV emulator power profile

Figure 13: Power profiles for the PV and load emulator

Figure 14: Currents flowing through the emulators - PV (magenta) - Load (blue) - Battery (green)

Figure 15: Power flowing through the emulators - PV (magenta) - Load (blue) - Battery (green)

Figure 16: Laboratories and emulators world map

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Table 1: Classification by emulation levels of the laboratory platform emulators found in the literature

Reference	Wind	PV	Fuel Cell	Battery	EV	Flywheel	Load demand
[7]	3	-	-	3	-	-	3
[8]	-	4	4	Real	-	-	Real, 3
[11]	3	3	-	3	-	-	3
[12]	3	3	Real	Real	-	-	3
[13]	-	Real	-	Real	-	-	2
[14]	-	4	Real	Real	-	-	Real
[21]	-	-	Real	Real	-	-	3
[17]	3	3	-	-	-	-	Real
[18]	1	1	1	1	-	-	3
[19]	4	-	-	Real	-	-	3
[15]	4	3	3	Real	-	4	Real
[16]	4	4	-	Real	-	-	Real, 3
[20]	2	2	2	-	-	-	Real

Table 2: Classification by emulation levels of the emulation test benches found in the literature

Emulated resource	Level 3	Level 4
Solar power	-	[22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33]
Wind power	-	[34], [35], [36], [37], [38], [39], [40], [41], [42], [43], [44], [45], [46], [47], [48], [49], [50], [51], [52], [53], [54], [55], [56], [57], [58]
Fuel cell	-	[59], [60], [61], [62], [63], [64], [65]
Battery	-	[66], [67], [68], [69], [70]
Load	[71], [72]	[73]
Electric vehicle	-	[74]

Table 3: Laboratories review - Part I

Ref.	Location	Year	Owner	Objectives	System description	Generation emulators	Voltage ranges
[7], [11]	Barcelona, Spain	2013	Catalonia Institute for Energy Research (IREC)	Study of the management system for a utility connected low-voltage microgrid. A hierarchical control in three different layers is implemented in the microgrid. The system is used to test and validate management modes, power control algorithms and market participation of microgrids.	<ul style="list-style-type: none"> ·AC microgrid ·Centralized and distributed operation mode ·Control of active and reactive power ·Communications among layers based on IEC 61850 standard ·Emulators are three-phase VSC in back-to-back configuration Emulated loads: <ul style="list-style-type: none"> ·One 5 kVA emulator acting as an active load 	<ul style="list-style-type: none"> ·Two 5 kVA emulators representing a wind generator and a battery 	AC side: 400 V (3 ph)
[12]	Seville, Spain	2013	University of Seville	Building and management of a microgrid including a fuel cell combined with other sources. Different aspects of the microgrid operation are analyzed as demand profiles, operation modes, failure mitigation and power management strategies.	<ul style="list-style-type: none"> ·DC microgrid ·Combination of emulators and real elements. Real elements: <ul style="list-style-type: none"> ·PEM Fuel Cell (1.5 kW) ·Lead-acid battery (24 mono-blocks of 2 V, 367 Ah) Emulated load: <ul style="list-style-type: none"> ·Programmable load to emulate different conditions (2.5 kW) 	<ul style="list-style-type: none"> ·Electronic power supply to emulate renewable sources (6 kW) 	DC side: 48 V
[13]	Compiègne, France	2013	Université de Technologie de Compiègne	Development and implementation of a building-integrated microgrid laboratory with storage. The implementation of an energy management system considering peak-reduction, time-of-use tariffs, storage capacity, grid capacity, loads and renewable generation is exposed.	<ul style="list-style-type: none"> ·DC microgrid ·Combination of emulators and real elements ·Composed by two load emulators and real PV panels Real elements: <ul style="list-style-type: none"> ·PV panels (1 kW) ·Lead-acid battery (24 V/550 Ah) ·Grid emulator with a bidirectional linear amplifier (3 kVA) Emulated load: <ul style="list-style-type: none"> ·Building emulator with a programmable DC load (2.6 kW) 	-	AC side: 115 V DC side: 200 V
[8]	Miami, USA	2012	Energy Systems Research Laboratory, Florida International University	Analysis of the interconnection of several renewable energy sources considering its corresponding control, monitoring and protection issues within the smart grid concept. A comparison between different architectures is derived. The microgrid laboratory is used for educational purposes.	<ul style="list-style-type: none"> ·AC/DC hybrid microgrid ·Combination of emulators and real elements ·Custom hardware and software design Real elements: <ul style="list-style-type: none"> ·Twelve lead-acid batteries connected in series ·Four AC resistive loads (3 kW) ·Single phase AC load (4 kW) ·Four induction machines (250 W), connected to DC machines, acting as AC loads Emulated loads: <ul style="list-style-type: none"> ·DC dynamic load (3 kW, DC side) 	<ul style="list-style-type: none"> DC side: <ul style="list-style-type: none"> ·PV emulator (3 kW) connected to a boost converter ·FC emulator (3 kW) connected to a boost converter 	AC side: 208 V (3 ph) DC side: 300 V
[14]	Bologna, Italy	2012	Faculty of Engineering, University of Bologna	Development and implementation of a micro-controller-based power management system to monitor and control real fuel cells for microgrids. The fuel cell allows to operate the grid in connected or in islanded mode, and it also allows to produce heat and power.	<ul style="list-style-type: none"> ·AC microgrid ·Combination of emulators and real elements. ·Fuel Cell controlled by a FPGA. Its main objective is to manage the battery state-of-charge Real elements: <ul style="list-style-type: none"> ·PEM Fuel Cell (4.5 kW electric and 4.7 kW thermal) ·Lead-acid battery (40-65 V/100 Ah/4.2 kW) ·Two transformers with on-load tap changers connected to a resistor or an inductor 	<ul style="list-style-type: none"> ·PV-array emulator (0.6 kW) to simulate the V/I curve characteristics connected to an inverter 	AC side: 230 V (1 ph) DC side: 40-70 V

Table 4: Laboratories review - Part II

Ref.	Location	Year	Owner	Objectives	System description	Generation emulators	Voltage ranges
[21]	Ontario, Canada	2012	Department of Electrical and Computer Engineering, University of Western Ontario	Implementation and validation of a load-sharing control scheme in a laboratory microgrid.	<ul style="list-style-type: none"> ·AC microgrid ·Combination of emulators and real elements ·Composed by a fuel cell, a battery bank, a programmable load, and two synchronous generators ·The load-sharing control is based in a load-voltage scheme ·Strategies implemented are: Minimal Unit Participation and Base Load Priority <p>Real elements:</p> <ul style="list-style-type: none"> ·PEM Fuel Cell (1.2 kW) ·Lead-acid battery bank for the startup and shutdown functions, and also to maintain the voltage <p>Emulated load:</p> <ul style="list-style-type: none"> ·One variable AC programmable load 	<ul style="list-style-type: none"> ·Two synchronous generators to emulate distributed sources (0.25 kW) 	AC side: 208 V (3 ph)
[17]	Xi'an, China	2011	School of Electrical Engineering, Xi'an Jiaotong University	Design and implementation of a fast simulation platform for microgrid applications with a seamless droop-control strategy	<ul style="list-style-type: none"> ·AC microgrid ·Combination of emulators and real elements ·The test-bench is composed by 2 inverters to emulate distributed sources <p>Real elements:</p> <ul style="list-style-type: none"> ·Two real resistive loads 	<ul style="list-style-type: none"> ·Two droop-control inverters to emulate renewable sources 	AC side: Not specified DC side: 750 V
[18]	Eindhoven, The Netherlands	2011	Department of Electrical Engineering, Eindhoven University of Technology	Building and controlling a series-parallel converter for grid-interfacing purposes to improve the connection of distributed generation to the grid. The control of this converter, based on a multilevel technique, is able to handle voltage disturbances and to compensate harmonic currents. The emulators allow to validate the correct capacities of the series-parallel converter described.	<ul style="list-style-type: none"> ·AC microgrid ·A series-parallel converter composed by two three-phase converters with four-leg IGBT modules. One converter is the series inverter and the other one is the shunt inverter. ·Combination of emulators (grid, load and renewable emulators) with the real series-parallel converter <p>Emulated loads:</p> <ul style="list-style-type: none"> ·One nonlinear programmable load emulator ·One programmable grid emulator 	<ul style="list-style-type: none"> ·One DC source as a renewable source emulator 	AC side: 400 V (3 ph) DC side: 750 V
[19]	Braşov, Romania	2011	Department of Electrical Engineering, Transilvania University of Braşov	Development and implementation of an aggregate load-frequency controller for autonomous microgrids to test it in a laboratory microgrid with a wind and micro-hydro emulators.	<ul style="list-style-type: none"> ·AC microgrid ·Combination of emulators and real elements ·Micro-hydro and wind emulators inject the power directly to the microgrid without power converters ·The electronic load controller regulates the microgrid frequency. It is based on controllable loads and a battery ·Emulators based in hardware-in-the-loop techniques <p>Real element:</p> <ul style="list-style-type: none"> ·Lead-acid battery (60 V/26 Ah) <p>Emulated load:</p> <ul style="list-style-type: none"> ·The load (6 kW) consists in a power converter connected to a resistors bench 	<ul style="list-style-type: none"> ·Wind emulator is an induction machine with a vector controlled inverter that emulates the wind and it is mechanically connected to an induction generator (2.2 kW) ·Micro-hydro emulator has also a induction machine to mimic the mechanical requirements of the micro-hydro turbine. It is connected to a synchronous generator (5 kVA) 	AC side: 400 V (3 ph) DC side: 60 V

Table 5: Laboratories review - Part III

Ref.	Location	Year	Owner	Objectives	System description	Generation emulators	Voltage ranges
[15]	Miami, USA	2010	Energy Systems Research Laboratory, Florida International University	Development and implementation of a microgrid laboratory with emulated distributed sources and conventional power plants in a smart grid framework. The laboratory allows to experiment with: the interaction between various sources and loads, system protections, multi-agent based controllers, communications, sensor coordination and microgrid operation considering economic dispatch and unit commitment. Also, the microgrid is used for educational purposes.	<ul style="list-style-type: none"> AC/DC hybrid microgrid Combination of emulators and real elements Emulators are real time hardware-in-the-loop models based on dSPACE® The system employs a multi agent platform The microgrid management system is implemented in LabView® <p>Real elements:</p> <ul style="list-style-type: none"> Battery bank (8 kW) in the DC side Two loads of 10 kVA with induction machines, synchronous motors and load boxes One auxiliary load and generation system of 10 kVA with two induction machines, a synchronous motor and a DC machine 	<ul style="list-style-type: none"> Wind emulator (0.25 kW) PV emulator (6 kW) in the DC side Flywheels model (2.2 kW) in the DC side Microturbine emulator in the AC side 5 power plant emulators (4 AC machines and 1 DC machine) with a total power of 21 kVA in the AC side 	AC side: 208 V (3 ph) DC side: 120 V
[16]	Tunis, Tunisia	2010	Laboratory of Electrical Systems (LSE), ENIT	Implementation and testing of a laboratory microgrid with a central inverter and its energy management system to demonstrate the capability of the inverter to operate in islanding and connected mode.	<ul style="list-style-type: none"> DC microgrid Combination of emulators and real elements Wind and photovoltaic emulator connected in the DC side through power converters The energy management system controls the generation and the storage The DC side is connected to the AC side through an inverter capable to operate in connected and islanding mode <p>Real element:</p> <ul style="list-style-type: none"> The battery bank is a real 4 serial lead-acid battery of 12 V and 38 Ah per battery AC load as a microgrid local load <p>Emulated load:</p> <ul style="list-style-type: none"> Grid emulator acting as generator and as a load 	<ul style="list-style-type: none"> Wind emulator is mechanically coupled with a direct driven permanent-magnet synchronous generator of 600 W with a diode rectifier and a DC/DC buck converter PV emulator is a programmable voltage source (400 W) 	AC side: 230 V (1 ph) DC side: 48 V
[20]	Hsinchu, Taiwan	2009	Department of Electrical Engineering, National Tsing Hua University	Implementation and validation of a droop control for imbalance compensation, in a laboratory microgrid. It includes a comparison between islanding and grid-connected modes.	<ul style="list-style-type: none"> AC microgrid Combination of emulators and real elements Two power converters to emulate renewable sources connected to the grid with an imbalanced load <p>Real elements:</p> <ul style="list-style-type: none"> One R-L load connected between phases A and B (7.8 kW) One R-L load connected between phases B and C (8.2 kW) to emulate imbalances 	<ul style="list-style-type: none"> Two emulators based on three-pole inverters 	AC side: 220 V (3 ph) DC side: 380 V

Table 6: Solar emulator review - Part I

Ref.	Location	Year	Type	Objectives	System description	Main findings
[22]	Blacksburg, USA	2014	PV Level 4	Development of a high efficiency PV emulator with a reduced output ripple. Static and dynamic emulation is considered under different loads and environmental conditions, including partial shading and bypass diodes effects.	The emulator is based on an AC/DC rectifier combined with an interleaved DC/DC buck converter, controlled by a Digital Signal Processor (DSP) board.	Experimental tests validate the system design, showing a high efficiency besides a fast transient response.
[23]	Sao Paulo, Brazil	2013	PV Level 4, NFE	Analyze the operation of different Maximum power point tracking (MPPT) algorithms to be applied to PV panels.	The PV array is emulated by a commercial Agilent Solar Array E4350B simulator, which can be programmed with a set of irradiation and temperature curves, creating power profiles. The DC/DC converter applying the MPPTs is connected to the emulator.	A comparison between the most typical MPPT algorithms: Fixed Duty Cycle, Constant Voltage Method, MPP Locus Characterization, Perturb & Observe (P&O) and P&O based on PI, IC and IC Based on PI, beta method, System Oscillation and Ripple Correlation and Temperature Method is shown.
[24]	Taipei, Taiwan	2013	PV Level 4	Study and build a programmable emulator for PV panels to operate based on a uniform solar illumination model. Besides, a partially shaded model, considering two PV modules connected either in series or in parallel, is also studied.	A DC/DC buck converter controlled by a DSP is used to represent the physical models of the photovoltaic panels. Solar illumination and ambient temperature can be set to represent the behavior of a PV panel considering dust pollution effects, clouds shading or solar oblique incidence, allowing to represent different scenarios.	The emulator behavior is compared to an actual PV panel showing similar V/P characteristics, under uniform solar illumination conditions. Besides, series/parallel association of PV modules can be represented along with different solar illumination scenarios.
[25]	Kaohsiung, Taiwan	2013	PV Level 4	Development of a PV array emulator based on a LLC resonant DC/DC converter, to achieve high system efficiencies.	The emulator topology is a DC/DC converter, compounded of a LLC resonant inverter, connected to a current-driven transformer with a center-tapped rectifier.	Experimental tests shows that the emulator efficiency operating at the MPP is around a 92.5%.
[26]	Palermo, Italy	2013	PV Level 4, NFE	Development of an intelligent manager of a grid-connected PV system. An emulator is employed to represent the PV source, including all possible conditions, even partial shading.	The PV emulator reproduces the V/I set of characteristics of a real PV power plant. It is implemented by a DC/DC buck controlled by a DSP low cost board.	The PV system, including the developed MPPT, has been experimentally tested, showing better response than other proposals.
[27]	Sydney, Australia	2012	PV Level 4	Development of a PV emulator for testing PV power systems. A piecewise linear approach is applied to represent the V/I curve, which is implemented in a reduced cost micro-controller.	The PV emulator consists of a DC input source and a DC/DC buck-boost converter, which is able to represent the V/I curve. The control stage is implemented in an 8 bit micro-controller.	The PV emulator has been tested connected to resistive loads and also to experiment with MPPT algorithms.
[28]	Seoul, South Korea	2012	PV Level 4	Development of a dual-mode power regulator for PV panel emulation, based on the combination of a voltage and a current regulator.	The PV emulator power stage is compounded by two different regulators, a low dropout linear voltage regulator, and an adjustable current regulator, based on the same hardware. The overall system is controlled by an ARM Cortex-M3, which selects the preferred operational stage.	A PV emulator is built using a hybrid combination of a voltage and a current source, to improve the conventional proposals. The accuracy of the developed emulator is compared to conventional emulation methods.

Table 7: Solar emulator review - Part II

Ref.	Location	Year	Type	Objectives	System description	Main findings
[29]	Coimbatore, India	2012	PV Level 4	Development of a PV array/module emulator for different operating conditions. Analysis of the system in steady state and during transients.	The emulator consists of a DC/DC buck converter fed from a DC voltage source, controlled by a PIC® micro-controller. The mathematical parameters of the model are implemented in the micro-controller program. The user can program the irradiance and temperature. The PV array/module parameters are extracted from the manufacturer data-sheet, using a curve fitting technique.	The time response achieved, for a step change in the irradiance, is between 50-150 us, which is considered fast enough to represent the PV cell dynamics. The mathematical model can be applied to represent any commercial panel behavior.
[30]	Poitiers, France	2012	PV Level 4	Analysis of parallel and series connection of solar cells exposed to the same light/temperature behavior. Development a PV array emulator to evaluate the system components.	The emulator is based on a programmable power supply, controlled using a dSPACE® control board, programmed in Matlab-Simulink®.	A matrix representation of the equations of a PV cell is obtained. The emulator is used to analyze the behavior of PV arrays and to validate MPPT techniques, considering partial shading and transients.
[31]	Poitiers, France	2011	PV Level 4, NFE	Design and experimental validation of a high performance MPPT based on voltage-oriented control.	The PV panel emulator consists of a programmable DC voltage source controlled by a dSPACE® system. The programmable voltage source is connected to a DC/DC converter that is applying the MPPT algorithm.	Good response of the proposed MPPT both in simulation and in experimental results, showing a robust and fast response. The overall efficiency is increased due to the implemented MPPT.
[32]	Blacksburg, USA	2010	PV Level 4	Build a PV emulator with an improved dynamic response.	The emulator consists on three different parts: a PV equivalent circuit to provide the reference signals, a control system, and a buck converter with an output LC filter. The filter allows to increase the system bandwidth, while attenuating the switching ripple.	The power stage output represents the behavior of the PV system with reasonable speed and accuracy.
[33]	Palermo, Italy	2010	PV Level 4	Development of a PV field emulator, based on a DC/DC step-down converter, which allows to obtain the array V/I curves, considering irradiance and temperature changes, partial shading and fluctuating conditions.	The emulator consists of a 3 kW DC/DC buck converter controlled using a dSPACE® card with a floating-point DSP. The control strategy included is based on the PV mathematical model deduced from the maximum power point data. The method for obtaining the V/I curves is based on experimental measurements performed on the whole plant.	The proposed emulator is able to represent static conditions, partial shading and dynamic transitions of a PV module, as a part of a PV plant.

Table 8: Wind emulator review - Part I

Ref.	Location	Year	Type	Objectives	System description	Main findings
[34]	Valladolid, Spain	2014	Wind Level 4	Design of a wind turbine emulator able to simulate the turbine power curves, without using a closed loop control system.	The wind turbine open loop emulator consists of a DC voltage source, a power resistor and a DC motor with separate excitation. The system is mechanically coupled to the generator. Wind speed variations are applied by changing the DC voltage source output value.	The presented emulator, operating in open loop, is able to represent the power curves of a wind turbine. Experimental tests validate the emulation system operation.
[35]	Barcelona, Spain	2013	Wind Level 4 NFE	Experimental validation of the droop control for multi-terminal VSC-HVDC grids. Simulations and an experimental platform are developed to validate the theoretical droop control design.	Two different wind turbines are emulated by two Squirrel Cage Induction Machines (SCIM), driven by frequency converters. The emulators are mechanically coupled to the Squirrel Cage Induction Generators (SCIG), that are connected to their respectively wind farm AC grids.	The results show that the design of the droop controller accomplish the system specifications, both in simulations and in experimental results.
[36]	Miaoli, Taiwan	2013	Wind Level 4 NFE	Design of a recurrent modified Elman Neural Network (NN) to control a Permanent Magnet Synchronous Generator (PMSG) wind turbine generation system.	The wind turbine emulator is a field oriented controlled Permanent Magnet Synchronous Machine (PMSM) that is able to represent the power speed characteristic curve of a wind turbine. The emulator is mechanically coupled to the PMSG, controlled by the recurrent modified Elman NN designed. The algorithm is implemented in two different DSP control boards.	The implementation of the recurrent modified Elman NN control system, to regulate both the DC bus voltage of the rectifier and the AC line voltage of the inverter, is shown for a standalone power application.
[37]	Akron, USA	2013	Wind Level 4 NFE	Analysis of a MPPT method based on the characteristic power curve, both in steady-state and in dynamic operation. Validation of the wind turbine proposed control system through simulation and experimental tests.	The wind emulator employed is a 2.2 kW induction machine controlled by a frequency converter. The wind turbine model and power curve-based MPPT algorithm are implemented in a DSP control board.	The MPPT algorithm based on the power curve of the turbine provides a robust and cost-effective control method.
[38]	Gyeongbuk, South Korea	2013	Wind Level 4 NFE	Description of a hybrid control scheme for PMSG wind turbines, combining energy storage and braking systems, to provide Fault Ride Through (FRT) capability and power fluctuation suppression.	The wind emulator consists of a 3 kW SCIG driven by a back-to-back converter, which applies torque to the generator shaft, based on the wind turbine characteristics.	With the proposed scheme, the output power of the system can be smoothed. It also provides FRT capability, even loosing completely the grid voltage.
[39]	Sfax, Tunisia	2013	Wind Level 4 NFE	System and control design of an autonomous wind energy conversion system, to feed isolated loads.	A DC motor is employed to reproduce the mechanical behavior of the wind turbine, controlled by a dSPACE® system. The emulator is mechanically coupled to the PMSG under test.	The proposed design is validated through simulation and experimental results, showing a good performance of the controller, while supplying isolated loads.
[40]	Pamplona, Spain	2013	Wind Level 4 NFE	Development of an accurate model of a wind energy generation system based on a PMSG, connected to a diode bridge.	The wind turbine emulator employed is a PMSG connected to an inertia of $5 \text{ kg}\cdot\text{m}^2$. The emulator is coupled to the mechanical shaft of the PMSG generator under test. The real wind turbine and the wind turbine emulator, have similar parameters.	Based on the wind energy conversion system model equations, an MPPT control is designed and tested using a wind turbine emulator, employing a real wind speed profile. The experiments show good results, in terms of accuracy and robustness.

Table 9: Wind emulator review - Part II

Ref.	Location	Year	Type	Objectives	System description	Main findings
[41]	Newcastle, UK	2012	Wind Level 4	Development of a test facility to evaluate the behavior of a Doubly Fed Induction Generator (DFIG) under a range of grid fault conditions.	The wind emulator is based on a 10 kW motor, driven by a four quadrant converter, which emulates the mechanical dynamics. The software layer has the mechanical model of the wind turbine programmed in a controller, which is able to replicate the torque input of the wind turbine shaft. The parameters for the emulation calculations are obtained from industrial data and real measurements.	The test facility have been used to investigate the FRT performance of a DFIG, with different configurations. The test bench can be used to test other types of wind generators.
[42]	Madrid, Spain	2012	Wind Level 4 NFE	Design of a solution for wind farms, based on fixed-speed generators, to guarantee the grid code compliance, including an STATCOM.	The wind turbine emulator consists of a 3 kW DC motor connected to an AC/DC power converter, controlled by means of a PC.	This work demonstrates that the proposed solution is able to accomplish the most exigent grid code requirements. An analysis of all possible grid faults is presented.
[43]	Sfax, Tunisia	2012	Wind Level 4 NFE	Experimental validation of an autonomous PMSG-based wind energy system, in a test bench. Analysis of the behavior of the test bench and the system controllers.	The wind turbine emulator is based on a 3 kW DC motor, controlled to reproduce the mechanical behavior of a variable speed wind turbine. The system is controlled by a DSP embedded in a dSPACE® system. The equivalent aerodynamic torque is applied to the shaft, which is coupled to the PMSG under test.	The obtained results show that the proposed controller is able to regulate the voltage at the connection point, even under disturbances. Experimental results employing the emulator also confirm that the strategy proposed can properly control the system.
[44]	Auckland, New Zealand	2012	PV Level 4 NFE	Analysis of a smart wind turbine concept, with variable length blades and an innovative hybrid mechanical-electrical power conversion system.	The wind turbine emulator is a variable speed induction motor, which mimics the aerodynamics of the system under varying wind conditions.	The study concludes that the wind turbine structure could be interesting for small scale renewable energy applications. Experimental results are shown to demonstrate the concept.
[45]	Madrid, Spain	2012	PV Level 4 NFE	Analysis of the introduction of an electronic on load tap changer to increase the generator contribution to the short circuit current, during grid voltage sags. Design of the converter control, based on a non linear current source, to ensure the required fast response.	The wind emulator is based on a DC motor and an AC/DC power converter, controlled by a PC. The emulator includes the turbine aerodynamic characteristics to emulate the corresponding shaft torque. The emulator is mechanically coupled to the PMSG to perform the experiments.	The obtained results show that the proposed ideas could improve the response of the wind generation systems during short circuits.
[46]	Brasov, Romania	2012	PV Level 4 NFE	Development of a sensorless control method for small variable-speed, fixed-pitch wind turbines including direct-driven PMSG.	The wind turbine emulator consists of an induction motor controlled by a frequency converter, which simulates the static and dynamic behavior of a real system. The emulator is mechanically coupled to the PMSG shaft.	The sensorless control strategy proposed is validated through simulations and experimental results.
[47]	Madrid, Spain	2010	Wind Level 4	Design of a system for training engineers on the DFIG control. The system is based on two main parts, the simulation part, and the experimental part, which includes a wind turbine emulator coupled to an electric generator.	The wind turbine emulator consists of a DC machine driven by a commercial converter, controlled by a microprocessor. The DC machine is mechanically coupled to the DFIG shaft, in order to apply torque based on the turbine emulation.	Design of both the simulation tool and the experimental test bench. The possibilities that the system offers for training students and professionals are detailed.

Table 10: Wind emulator review - Part III

Ref.	Location	Year	Type	Objectives	System description	Main findings
[48]	Pilani, India	2010	Wind Level 4 NFE	Analysis of the operation of low mechanical inertia isolated grids compounded by the combination of wind and diesel generation units.	The wind turbine emulator is developed by a DC motor with a separately excited field. The motor armature is controlled by a DC/DC buck converter. The wind turbine model is implemented in a computer which controls the DC motor to apply the corresponding torque to the system. The emulator is mechanically coupled to the SCIG connected to the AC grid.	The proposed dynamic control of the alternator excitation is able to mitigate the voltage variations at the electrical output terminals of the unit, which is specially interesting for isolated wind-diesel generation systems.
[49]	Nantes, France	2009	Wind Level 4 NFE	Description of a control scheme for a DFIG wind generation system. Three different controllers are proposed for the machine inverter and a different strategy is studied for the grid converter.	The wind is modeled based on the spectral decomposition and it is applied to a small 10 kW wind turbine. The output torque is applied to a DFIG wind generator.	The proposed schemes are validated through simulation and experimental results. A comparison of the three different machine controllers, in terms of power tracking, rotational speed variations and control robustness, is shown.
[50]	Lille, France	2009	Wind Level 4 NFE	The possibility to participate in the primary frequency control, with a variable speed wind generator, is investigated.	The wind turbine emulator is implemented using a DC machine with separated excitation, controlled by a dSPACE® card. A real wind speed profile, measured in real tests, is used for the system experiments.	The experimental tests confirm that the wind turbine generation system is able to participate in the primary frequency control, with certain limitations related with the forecast required.
[51]	Punta Arenas, Chile	2009	Wind Level 4 NFE	Analysis of a new control system to regulate the reactive power supplied by a variable wind speed generation system, including an induction generator driven by a matrix converter.	The wind power emulator is based on a speed regulated SCIG. A wind speed profile is sent from the PC to a second-order model of the wind turbine system implemented in a DSP.	The reactive power control concept is validated through experimental results, considering different wind profiles, capacitive/inductive operation, step changes in the reactive power demand and emulating different values of inertia.
[52]	Punta Arenas, Chile	2008	Wind Level 4 NFE	Analysis of the performance of several Model Reference Adaptive System (MRAS) observers for a sensorless vector control of a DFIG, for stand-alone and grid-connected applications.	A SCIM driven by a frequency converter is used to emulate the wind turbine. The turbine equations are programmed in a DSP control board. The SCIM is mechanically coupled by the shaft to the DFIG, where the sensorless scheme is applied.	Several MRAS observers are compared and conclusions regarding the system performance are shown. The best and the worst observers for stand-alone and grid connected systems are highlighted.
[53]	Bidart, France	2006	Wind Level 4 NFE	Implementation of a wind turbine controller, with fast dynamics, in a real test bench. This controller should lead the system to a better efficiency.	A 25 kW DC machine is connected to a DSP controlled converter, used to emulate the wind turbine.	The comparison analysis concludes that the proposed controller allows to increase the efficiency of the system, compared to other turbine controllers.
[54]	Hualien, Taiwan	2006	Wind Level 4	Design of a Radial Basis-Function Network (RBFN) to control a wind turbine emulator and a SCIG system, by means of an AC/DC power converter.	The wind turbine emulator is built using a PMSM servo drive, controlled by a field-oriented control implemented in a DSP. The emulation system includes the turbine power/speed curve. The emulator is mechanically coupled to the SCIG, to validate the proposed strategy.	The proposed controllers are validated within the study, both for the wind emulator and the SCIG, showing good performance, even during transients.

Table 11: Wind emulator review - Part IV

Ref.	Location	Year	Type	Objectives	System description	Main findings
[55]	Tallahassee, USA	2006	Wind Level 4	Analysis of how, an established real-time hardware-in-the-loop (HIL) test facility created for electric ship propulsion, can be used for wind energy research.	The wind turbine emulator could be built employing two 2.5 MW AC motors in tandem, which are able to reproduce the turbine dynamics on the shaft of a wind turbine. The shaft of both machines is mechanically coupled to the generator under test. A low power test bench is also proposed as the large bench was not finished when the article was written.	The steady-state and dynamic performances show that the proposed system can be an interesting tool for the development of new technologies related with wind energy conversion systems.
[56]	Punta Arenas, Chile	2004	Wind Level 4 NFE	Design of a sensorless vector-control strategy, for a wind turbine induction generator, employing a model reference adaptive system (MRAS) observer to estimate the rotational speed.	The induction generator is coupled to a speed-controlled DC motor, which emulates a wind turbine. The speed of the DC motor is controlled following the characteristics of the emulated turbine. High order wind turbine models are included to accurately emulate the system dynamics.	The sensorless strategy proposed shows a good performance, both in simulation and in experimental results.
[57]	Dortmund, Germany	2001	Wind Level 4 NFE	Design of a management system acting on the rotor power output, designed to reduce problems related to the smooth start, tower effect and aerodynamic forces of the wind turbine.	The wind emulator is built using a DC machine and a rotating mass. The emulator is mechanically connected to an induction machine. The wind rotor characteristic is obtained from the curve derived from a simulation program.	Three methods for the power control are designed and described. One of the methods is tested showing a smooth start, besides a compensation of the tower effect.
[58]	La Plata, Argentina	1996	Wind Level 4	Description of the structure and operation principle of a wind turbine emulator. The emulator allows to modify the wind conditions and the wind turbine parameters. It also includes a supervision of the system variables.	The wind emulator is built employing a DC motor to provide the necessary torque in the shaft. The motor is controlled by armature, using a phase-controlled AC/DC converter. The system is controlled by means of a dual-DSP system, which reproduces the torque/speed characteristics of the emulated turbine.	The control system interconnected with the PC, converts the wind emulator into a powerful and flexible device for developing and testing new controllers for wind energy conversion systems.

Table 12: Fuel cell emulator review

Ref.	Location	Year	Type	Objectives	System description	Main findings
[59]	Cape Town, South Africa	2013	FC Level 4	Development of a High Temperature (HT) Proton Exchange Membrane Fuel Cell (PEMFC) emulator to represent the system steady-state and transient conditions.	The HT PEMFC emulator is based on a FC model which is able to run in real time. The emulator is implemented in two stages, a control stage based on a multiphase interleaved converter to represent the FC fast transients, and a power stage, which regulates the DC voltage of the interleaved converter.	The proposed approach shows good performance, compared to other emulators based on classical DC/DC converters.
[60]	Belfort, France	2012	FC Level 4	Development of a PEMFC stack model. Implementation of a real time emulator based on the derived model.	The FC stack model is implemented in three real-time computation cores, which are able to predict the stack performance in the electrical, fluid and thermal domains. This software layer is communicated through CAN bus to a DC/DC buck converter which represents the fuel cell stack power output.	The model of the PEMFC and the emulator are compared, through experimental results, to a real FC, showing satisfactory results.
[61]	Tarragona, Spain	2012	FC Level 4	Development of a real-time FC emulator based on a Matlab Real-Time Windows Target controlling a power source. The emulator is able to accurately reproduce both static and dynamic fuel cell behaviors.	The FC is emulated through a Real-Time Windows Target that allows to control a power supply which physically interacts with the load or the devices under test. The power supply applies the corresponding voltage at the output of the emulated FC.	The static and dynamic behavior of the developed emulator are compared to a real FC, showing good results, including calculations as the oxygen ratio.
[62]	Zagreb, Croatia	2012	FC Level 4 NFE	Development of a linear model with changeable parameters of a controlled DC/DC boost converter supplied by a PEMFC stack.	A commercial Magna Power Electronics fuel cell emulator is employed to be connected to the DC/DC boost converter.	The derived model is valid for the whole range of the converter and fuel cell typical conditions.
[63]	Belfort, France	2011	FC Level 4	Development of a multiphysical PEMFC stack model suitable for real-time emulation. Implementation of a FC emulator, based on the derived model, employing a buck converter.	The emulator is based on a real-time model running in an OPAL-RT® real time structure. The model establishes communications with the DC/DC buck converter through CAN bus. The converter is able to regulate the DC voltage output using a DSP.	The modelling approach is validated in comparison with a real FC. The developed emulator can be used for HIL applications. Fast transients cannot be tracked with the buck converter topology.
[64]	Belfort, France	2009	FC Level 4	Development of a PEMFC emulation system using a DC/DC buck converter, able to represent different types of FCs.	The emulator is based on a dynamic model block of the entire FC including its auxiliary systems, together with a DC/DC converter which is able to impose the specified voltage at the emulator output terminals. The system is controlled by a dSPACE® system.	The DC/DC converter, controlled by the state-space regulator, has a high bandwidth, fact that allows a good dynamic performance of the emulator.
[65]	Lille, France	2009	FC Level 4 (Electrolyzer)	Development of an emulator to represent a hydrogen electrolyzer, installed in a wind power plant.	The emulator is based on two different parts, a power stage using a boost converter and control stage programmed on a DSP board.	A hardware in the loop system, to represent the hydrogen production process, is presented. The power electronics stage is able to offer similar characteristics as the real electrolyzer.

Table 13: Battery emulator review

Ref.	Location	Year	Type	Objectives	System description	Main findings
[66]	Bristol, UK	2013	Battery Level 4	Development of a HIL simulation system to emulate energy storage components, allowing to test cell balancing circuits.	A flyback converter is used to emulate the behavior of the battery cells.	The proposed emulator allows to test cell balancing circuits, usually tested with real batteries. HIL tests, based on emulators, show similar results compared to the real system ones.
[67]	Graz, Austria	2013	Battery Level 4 NFE	Development of a battery emulator used to supply an electric motor inverter for hybrid and electrical vehicle power trains.	The battery emulator is based on a programmable DC power supply which replicates the voltage output of the battery, supplying the required power. The measured current of the load is introduced into the simulation model to recalculate the state of charge in real time.	A model predictive control approach is applied to control the DC/DC converter connected to the battery emulator.
[68]	Graz, Austria	2013	Battery Level 4 NFE	Development of a battery emulator, based on a power supply, to implement HIL testing of power trains for hybrid and electric vehicles.	The battery emulator power stage is based on a DC/DC step-down converter, with three different interleaved switching channels.	With the methodology proposed, a highly accurate traction battery emulation is developed for test beds of electric vehicles.
[69]	Shanghai, China	2013	Battery Level 4 NFE	Development of a configurable battery cell emulator to implement the HIL validation of the cell Battery Management System (BMS).	Based on the internal cell models and the compensation algorithm developed, a DSP calculates the voltage output of each emulated channel. Then, the voltage is applied to the circuit by means of a power amplifier.	The cell emulator developed is able to generate the cell voltage signals to emulate the dynamics of the battery cells. The emulated cell can be connected also in series. Based on the emulation proposed, cell BMS proposals can be evaluated.
[70]	Versailles, France	2012	Battery Level 4 NFE	Experimental validation of a lead-acid battery charger. The converter topology is a DC/AC/DC step down converter, including a high frequency isolation stage.	The battery emulator is implemented by a power supply with a series resistance.	The emulation system has been used to perform thermal endurance tests of the IGBT power modules of the proposed converter.

Table 14: Load emulator review

Ref.	Location	Year	Type	Objectives	System description	Main findings
[71]	Huelva, Spain	2011	Load Level 3	Development of a flexible DC load emulator to test and evaluate V/I characteristics of FC stacks and PV modules employing DC/DC converters.	The converter to represent the flexible load is a SEPIC converter controlled by a PIC [®] microcontroller, connected to a resistor.	The analysis concludes that the SEPIC converter is the optimal converter for the application. The proposed load can represent a variable resistance/current/voltage/power load, also following a defined load profile.
[73]	Mumbai, India	2010	Load Level 4	Development of load emulator based on a three-phase inverter. The emulation performed is the connection of a SCIM to a three-phase AC grid.	The emulation software layer is based on a DSP. It controls the hardware layer implemented on a three-phase voltage source inverter.	The proposed testing approach allows to use the emulator during the design process, which reduces the overall cost.
[72]	Dearborn, USA	2008	Load Level 3	Analyze the power management of hybrid electric vehicles with several energy storage systems: a battery, a fuel cell, and an ultra-capacitor.	The load emulation is carried out by an electronic load, based on three DC/DC converters controlled by a real time control board.	The analysis shows that the power management algorithm is able to distribute the load profile among the different storages included, according to their characteristics.

Table 15: EV emulator review

Ref.	Location	Year	Type	Objectives	System description	Main findings
[74]	Novi Sad, Serbia	2012	EV NFE	Development of a high reliability EV based on an induction machine propulsion system	The induction motor is mechanically coupled to another motor acting as a load, representing an EV conditions.	The proposed control strategy is validated using the HIL system and in real tests.