Real-Time Modeling of Energy Transactions in Smart Grids

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***Abstract*—The recent changes on the electrical power systems make the role of distributed generation more important. Employing distributed generation in demand side allows the consumers to have active participation in the electricity markets. This paper implements the real-time simulation of a local microgrid that consists of two subsystems: home area network and neighborhood area network. In this system, the home area network is the electrical grid of a house and the neighborhood area network is the low voltage electrical distribution grid of the neighborhood. The main contribution of this paper is to assess scenarios for energy transactions between these two areas using real resources. In the case studies, several real profiles have been employed for simulating the consumption and generation of this local microgrid.**

***Index Terms*— Distributed Generation, Hardware-in-the-Loop, Microgrid, Real-Time Simulation, Renewable Energy Transactions.**

I. INTRODUCTION

Nowadays, power distribution systems have been faced with massive integration of Distributed Energy Resource (DER) and Distributed Generation (DG) units in order to reach more energy security, less energy costs and less greenhouse gas emissions [1]. DG is defined as small power generation units that can be located in the demand side [2]-[3]. The most important applications of the DG units consist of providing high level of reliability, controlling of the voltage and reactive power, and reducing the pressure from the transmission lines [2]. However, integration of DG units into the current power network brings some issues such as, power quality, network balancing and resource integration [3].

Therefore, by implementation of the microgrid concepts into the current power grid, the challenges of the DERs integration will be overcome [4]. In this context, the electricity network of a house that uses Photovoltaic (PV) arrays and/or wind turbine as power sources, can be considered as a small part of a microgrid [5]. This network, depending on the functionalities of the power resources, can be configured to operate in grid-connected or island mode [6]. Additionally, by employing an intelligent algorithm [7] on this electricity network, not only it would be possible to supply the local loads, but also it encourages the consumers to have active participation on the electricity markets [8].

This paper presents the real-time simulation of a local microgrid that uses several real resources as hardware-in-theloop (HIL). The local microgrid includes a Home Area Network (HAN), which is the electricity network of a residential house equipped with a home-scale wind turbine as a micro-generation [6] unit, and a Neighborhood Area Network (NAN), which is referred to the electricity network of a small office that is the neighbor of the HAN. This office is an electricity consumer unit. According to the several references [9]-[11], HAN and NAN are referred to the communication networks. However, in this paper, they are related to the electricity networks of a house and a small office. Concerning the real-time simulation, OPAL-RT® is employed as real-time simulator and several real hardware resources, which were built for manual and individual use, have been integrated with the OPAL-RT® as HIL. Using the real hardware resources in the simulation environments brings the advantages of the real world into the virtual world [12].

Additionally, there are several related works, which surveyed the HAN and NAN concepts of the microgrids. In [13], the authors provided a mechanism for appliance-level peak-time load balance control in a NAN based on the smart grid. Moreover, they presented a scheme to protect residents from the Non-Intrusive Load Monitoring (NILM) attacks. In [14], the authors proposed an implemented microgrid at Georgia Southern University. They employed HOMER realtime simulator in order to investigate the technical and economical aspects of the microgrids. In [15], GridLAB-D™ (a simulation and analysis platform) developed by Pacific Northwest National Laboratory (PNNL) is described. GridLAB-D™ simulates all aspects of the energy grid from the generation to the end-user. This software can be used for simulating the microgrids concepts.

The main idea of this paper is to combine the previous works and use the OPAL-RT® real-time simulator for demonstrating the renewable energy transactions between the HAN and NAN. By using several smart meters in this model, makes it as a realistic implementation. In the case study of this paper, the simulated model has been executed, in real-time, for a period of two hours. The simulated data of the HAN (consumption and generation) are the real values acquired from a residential house and a 1.2 kW wind turbine installed on GECAD laboratory. Also the consumption data of the NAN is the real-time consumption of the GECAD labs.

After this introductory section, section II presents the Microgrid Real-Time Simulator (MRTS) used in this model. Sections III and IV specify the components of the HAN and NAN. Section V describes the case study scenario. Finally, section VI has the main conclusions of the paper.

II. MICROGRID REAL-TIME SIMULATOR

The system proposed in this paper is called Microgrid Real-Time Simulator (MRTS). This model is referred to the simulation of a local grid-connected microgrid that employed real consumer and generator resources. These hardware resources have been integrated into the MRTS system by developing of the hardware and software strategies that implemented on the resources without any automation part. This system has been implemented in the laboratory of GECAD research group, located in Institute of Engineering – Polytechnic of Porto (ISEP/IPP), Portugal. The equipment applied in the MRTS system includes:

- OPAL-RT, as real-time digital simulator (called OPAL in this paper);
- Three-Phase 4 kVA variable load, as a consumer unit (called 4 kVA load in this paper);
- PCD.PLC, as a controller unit (called PLC in this paper);
- 1.2 kW wind turbine emulator, as a micro-generation unit (induction machine).

In this model, the OPAL is a central controller unit that manages the MRTS system. The 4 kVA load and wind turbine simulate the consumption and generation of the house (i.e., HAN). On the other side of the MRTS system, PLC controls the consumption of the office (i.e., NAN). All of these players have been connected to the OPAL through two communication protocols: RS-485 (Modbus/RTU) and Ethernet (Modbus/TCP). Fig. 1 demonstrates the architecture of the MRTS system.

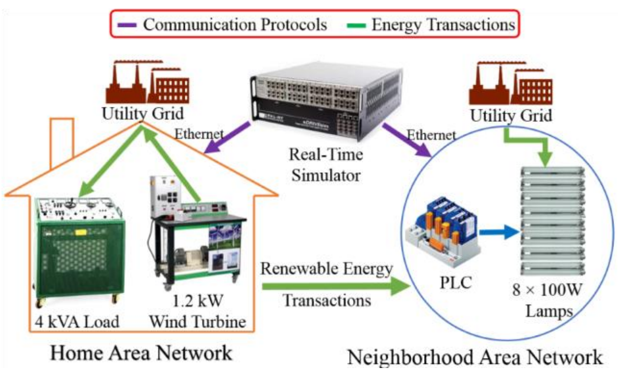

Fig. 1 – Structure of the MRTS system (HAN and NAN).

By the same token, PLC controls 8 fluorescent lamps mounted on the GECAD laboratory. Therefore, the electricity network of the GECAD laboratory has been dedicated for the NAN of the MRTS system. Additionally, two Heating, Ventilating, and Air Conditioning (HVAC) systems and several electricity sockets are available in this network. However, the consumption of them cannot be controlled by the PLC.

According to the specifications of the wind turbine emulator, which should be configured in the grid-connected mode, the generator has been connected to the utility grid in order to inject the produced power. Moreover, a 4 kVA load is supplied from this grid. In other words, the energy demand of the 4 kVA load can be met by the wind turbine, and in the lack of the wind generation, it can be supplied by the utility grid. In some cases, there is more power generated by the wind turbine than power demanded by the loads, and therefore, the excess of generated power can be injected to the utility grid or can be transacted with the NAN.

On the other side, NAN is a consumer that is supplied by the two resources: utility grid and energy purchased from the HAN. Therefore, the MRTS system simulates a house equipped with a home-scale wind turbine in which the excess of produced energy by this house, can be sold to the neighbor networks, or can be injected to the utility grid.

The following sections are described the software and hardware developed for merging the MRTS players into the central controller unit (i.e., OPAL).

III. HOME AREA NETWORK

As it was explained, a 4 kVA load simulates the consumption of a house, and a 1.2 kW wind turbine emulator operates as a micro-generation unit mounted on the house.

The 4 kVA load consists of three independent parts: resistive, inductive, and capacitive. The resistive part is automatically varied through a control process that is illustrated in Fig. 2, using a 12 V DC motor to control the motion of the resistive gauge. Therefore, by controlling the direction of the rotation in this small motor (clockwise or counterclockwise) the resistive gauge can be moved upward or downward in order to increase or decrease the load consumption. Moreover, a power meter was used for measuring the real-time consumption of the 4 kVA load. An Arduino® (www.arduino.cc) equipped with an Ethernet shield and a Relay module has been employed for controlling the 4 kVA load.

Fig. 2 – Controlling process of the 4 kVA load.

For integrating the 4 kVA load into the MRTS system, Arduino® follows an algorithm to control the consumption of the 4 kVA load. In this algorithm, Arduino® receives the desire power rate from the OPAL via Ethernet interface, and real-time consumption of the 4 kVA load from the power meter through RS-485 interface. Afterward, it compares these two values. If the desired power rate is more than the real-time consumption, the 12 V DC motor moves the resistive gauge to upward and the consumption will be increased until the amount of the desire power rate. In the reverse mode, if the desired power rate is less than the real-time consumption, the 12 V DC motor moves the gauge to downward and the consumption will be decreased until the amount of the desire power rate. In the last stage, if the desired power rate is located on the range of ± 20 W of the real-time consumption, Arduino® stops the 12 V DC motor.

Furthermore, IEEE 754 standard of communication was employed for transmitting the desired data between the units. IEEE 754 converts any decimal value to a 4-bytes hexadecimal message. In this model, the communication paths that follow this standard include:

- OPAL to Arduino®: transmitting the desired power rates;
- Power meter to Arduino®: sending the real-time consumption of the 4 kVA load;
- Arduino® to OPAL: transmitting the value received from the power meter.

By this method, the OPAL can transmit the desired power rates to the 4 kVA load and receive the real-time consumption.

Therefore, the MRTS system uses the 4 kVA load as hardware-in-the-loop (HIL).

In the case of the micro-generation unit, a 1.2 kW wind turbine emulator has been employed. According to the generation capacity of this emulator, it can be applied as a home-scale wind turbine. This emulator consists of an inductive three-phase generator that has been coupled with a

three-phase asynchronous motor. This motor simulates the blades of the wind turbine. There is a speed controller unit installed on the emulator. Therefore, by controlling the speed of rotation in this motor, the produced energy by the generator can be managed.

For controlling this emulator by the MRTS system, the analog input terminal of the speed controller unit has been integrated to the analog output board of the OPAL. Then, the wind speed data have been converted from km/h to a value in the range of 0 to 10 V, provided to the analog output board of the OPAL. The computations of this conversion have been done in the Simulink environment. In the last stage, the related power meter of the wind turbine emulator has been connected to the OPAL via Ethernet interface, with Modbus/TCP protocol. These configurations have been demonstrated on the Fig. 3.

Fig. 3 – Management scenario of the micro-generation unit.

Therefore, the use of this emulator enables the MRTS system to receive the real-time wind speed data in km/h and provide the produced energy related to these data.

IV. Neighborhood Area Network

As it was described, NAN is the electricity grid of an office that is the neighbor of the HAN. NAN players contain:

- PCD.PLC: main controller unit of the network;
- 8 fluorescent lamps, 2 HVAC systems and several sockets: electricity consumers;
- Power meter: consumption measurement.

In this network, the PLC manages the NAN by controlling the 8 fluorescent lamps and requesting the rate of the consumption from the power meter. This scenario has been illustrated in the Fig. 4. In this model, 8 fluorescent lamps simulate a part of consumption of the office that can be controlled.

Fig. 4 – Controlling decision of the fluorescent lamps.

The power meter has been attached to the PLC via RS-485 interface, with Modbus/RTU protocol. In the MRTS system, the PLC has been connected to the real-time simulator (i.e., OPAL) through Ethernet interface, with Modbus/TCP protocol. By this method, the OPAL can control the state of the lamps (turn on or turn off) and simultaneously request the real-time consumption of the NAN from the power meter.

V. Case Study

In the case study of this paper, the MRTS system is employed for real-time simulating of a local microgrid. The HAN and NAN are the two subsystems of this microgrid. HAN is the electricity network of a house equipped with a home-scale wind turbine and NAN is the electricity network of an office, which is a consumer unit. In this microgrid, the energy demand of the HAN can be met by the renewable resource (i.e., wind turbine) and while the renewable energy produced by the HAN is more than the demand of the house, it can be transacted to the NAN. The real-time simulation of this local microgrid was executed for a period of two hours and the acquired results have been shown on the Fig. 5 and Fig. 6.

The methodology used in this case study for the renewable energy transactions, follows direct redistribution of the generated power. By the same token, the excess of produced power of the HAN has been sold directly to the NAN and while the demand of the NAN has been completely met by this resource, the additional amount of power will be injected to the utility grid.

The consumption data of the HAN have been selected from IEEE PES Intelligent Data Mining and Analysis [16], private house 1, in the date of 25/07/2012 from 19:45 PM to 21:45 PM. The consumption profile of the NAN has been obtained experimentally from the GECAD laboratory. Additionally, the wind speed data for the generation profile of the HAN were selected from ISEP Meteo website [17].

As it can be seen in the Fig. 5, in some sections of this simulation, the orange areas have been reached to the blue line. It means that the energy demand of the HAN is completely met by the wind turbine generation. In these sections, the HAN is able to sell the excess of the produced energy to the NAN. These energy transactions have been demonstrated in the Fig. 6 by the orange areas. As it can be seen in the Fig. 6, there are some sections that orange areas are reached to the blue line. This means that the energy demand of the NAN also has been met by the renewable energy purchased from the HAN. Moreover, while the consumption of the both HAN and NAN is less than the wind turbine generation, not only the wind turbine can supply the both networks, but also the excess of the generated power can be sold to the utility grid.

Additionally, in some parts that the renewable energy was not sufficient for the HAN and NAN, they purchased energy from the utility grid. The gray areas in the Fig. 5 and Fig. 6 show the purchased energy from the utility grid. The energy consumed by these two networks during the two hours of this real-time simulation is illustrated on the Fig. 7 and Fig. 8.

Fig. 7 – Energy consumption (watt-hour) of the HAN.

As the Fig. 7 demonstrates, the energy consumed (watthour) by the HAN has been met by the two main resources: utility grid and renewable resource (home-scale wind turbine). Although this wind turbine is a small-scale renewable resource but it plays an important role for decreasing the electricity costs. This would be achieved by consuming less energy from the utility grid and effort to shift the high consumption loads to the periods that there is a sufficient amount of wind generation.

Moreover, while the consumption of the HAN is less and the wind turbine is generating a significant amount of the power, the excess of produced energy can be sold to the NAN with a price lower than the price of purchased energy from the utility grid.

Fig. 8 – Energy consumption (watt-hour) of the NAN.

In the Fig. 8, the orange areas show the renewable energy purchased from the HAN. It is clear that half of the consumed energy has been supplied by the renewable resource. In this model, it is considered that the price of the renewable energy is less than the purchased energy from the utility grid. Therefore, this scenario encourages the NAN to balance its consumption regarding to the renewable energy transacted from the HAN, because it will reduce the electricity costs of the NAN.

VI. Conclusions

This paper presented a simulated microgrid that includes two local power networks: home area network and neighborhood area network. The system analysis and modelling is carried out based on the real-time simulation and real generation and consumption profiles using real resources.

The proposed system demonstrates the benefits of mounting home-scale renewable resources, such as photovoltaic systems or home-scale wind turbines, both regarding the demand side and the energy transactions between the two units that are equipped with these kinds of resources. This scenario can reduce the electricity costs of the consumers. Additionally, if the price of the transacted energy between the two units is less than the price of the energy purchased from the main grid, it will encourage the consumers to shift their high consumption loads regarding to the renewable energy transacted from the other units. Therefore, this method can prevent some damages that can be caused to the main power grid during the peak load times.

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