Smart Energy Networks in the Northern Periphery: Development of an End-User Oriented Profiled Hybrid Micro-Grid Simulator

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Abstract: In the presented work, a hybrid micro-grid simulator has been developed from the end-user point of view. The hybrid model includes a number of selectable elements for the production and storage of energy, making a (smart) use of the available renewable energy resources based on a demand-response principle. The main role of the simulator is to model the communication with the common energy network on case of surplus or deficit of energy production.

Keywords: Smart energy network, Energy management system, Control Engineering, Environmental engineering, Northern Periphery.

1. INTRODUCTION

The global challenges that rose at the dawn of the 21st century call, among others, for a new way of conceptualizing the energy distribution platform. In particular, future trends for global energy consumption, and the associated environmental issues, are pushing for an increased use of renewable energy sources, smaller-size power plants and distributed generation. In this framework, a smart energy network can represent a solution to these needs, through which consumers are given the possibility to be directly engaged.

The expression smart energy network indicates an energy production, transmission and distribution network based on a two-ways communication between suppliers and consumers; through a real time monitoring of the network condition (i.e. energy production, consumption and distribution) it is expected to allow for a more prominent position on the market of those renewable energy resources characterized by a discontinuous and irregular generation. See IEA (2009), EIA (2010) and Mickwitz et al. (2011).

From a technical point of view, the expected benefit of a decentralized energy system can be determined in terms of redistribution of peaks loads and the overall flattening of the overall power demand curve. The negative aspects of an integrated decentralized energy production can be formulated in terms of control: the decentralized energy production can be characterized by a strong seasonal variation; each plant depends on the needs and preferences of the single users; some of the production units can be subjected to whether and climate conditions. All these components of uncertainty are making the efficient management of demand-response mechanisms an essential part of the future of smart energy networks. Notwithstanding wether based on a centralized or decentralized model, the monitoring and control of the grid not only opens the possibility for future economic development for the energy market, but it is likely to shift its entire center of mass.

In the presented study we have been addressing the potential and the adaptability of a smart system within the Northern Periphery (NP) area, aiming to develop and promote innovative and renewable energy solutions for rural small and medium-sized enterprises; see NPP (2004). A hybrid micro-grid simulator has been developed, which makes use of the available renewable energy resources on a demand-response logic principle (Caló (2011) and references therein). In this work, we report our preliminary analysis results concerning the system performance. Furthermore, we shortly describe our current effort to expand the system, assessing the performance of clusters...
of micro-grids, their interactions based on different user-based choices, their control and management.

2. SYSTEM ARCHITECTURE

The simulator, built in the Matlab® Simulink environment, has been developed maintaining a modular structure in order to guarantee the highest level of scalability and adaptability. A schematic representation of the system architecture is shown in Figure 1. The starting idea was to model the energy performance of a small- or medium-sized enterprise (SME) located in a semi-urban environment in northern Finland. This allowed us to consider electrical and district-heating network connections. Thought to eventually operate in real-time, managing on-line data, its performance has been insofar tested on the base of predetermined signal (i.e. power consumption profile) and historical data (i.e. weather and energy prices data). Simulations have been run over one year time window (00:00 1.1.2010 – 24:00 31.12.2010) based on hourly readings; the system performance has been evaluated by comparing different system configuration within the same economical and environmental conditions.

![Fig. 1. Schematic representation of the developed simulator system architecture.](image1)

The system modular structure is intended to be fully exploited for the further development of the simulator, including the possibility to monitor the repercussion, on the local energy grid, of the development over time of a sizable percentage of SME and private user making use of a smart energy system as the one modeled in our work.

2.1 The Micro-grid

The micro-grid system can be schematically described as made of five main blocks (Figure 1).

- The **SME** block contains all the necessary information and operational units necessary for a basic modeling of the built environment.
- The **Input** block includes all the necessary environmental and system information.
- The distributed renewable energy sources (DRES) block includes a number of selectable energy production systems, some of which dependent onto the environmental data inputs.
- The **Storage** block includes the electrical energy storage devices with a sub-block considering the possibility of a plug-in hybrid electric vehicle (PHEV).
- The **Output** block includes all the metering and monitoring components.

**SME block.** The considered built environment consists of a medium-sized building for commercial use (Figure 2). No architectural sophistications were included; structural energy losses have been accurately considered including U-Values from the European Insulation Manufacturer Association for sustainable buildings (EURIMA (2008)).

The power consumption profile was arbitrarily predefined and the building was assumed to include an underfloor water heating system. The structure’s power and thermal energy requirements have been considered to be independent; consistently, no electric heating or thermal effects due to the illumination or the electrical appliances were included.

The control system compares the set indoor temperature with the actual indoor temperature at one hour interval. Each time the control system aims to maintain the predetermined indoor temperature within the selected level of tolerance using a relay controlled switch to activate the connected cogeneration units. The collected heat (either produced or imported) is then transformed in heat transfer and, once heat losses have been considered, the new temperature is calculated (Figure 3).

![Fig. 2. Built environment structure, shape and size utilized in the simulation](image2)

**Fig. 2.** SME Block architecture.

Heat losses ($Q_{\text{loss}}$) have been calculated as follow:

$$Q_{\text{loss}} = U \cdot A \cdot \Delta T \quad (1)$$

where $A$ is the exposed surface area and $\Delta T$ is the indoor/outdoor temperature difference. Using the reported
data it has been possible to calculate, for each case, the final heat transfer ($Q_{\text{tot}}$) and the corresponding temperature:

$$T = \frac{Q_{\text{tot}}}{m \cdot c_p}$$  \hspace{1cm} (2)

where $m$ is the total mass (of air) and $c_p$ is the specific heat. The used values for air density and specific heat are:

$$\rho = 1.205 kg \cdot m^{-3} \hspace{1cm} c_p = 1.005 kJ \cdot kg^{-1} K^{-1}. \hspace{1cm} (3)$$

**Input block.** The system and environmental information include selectable indoors temperatures and power consumption profiles, environmental and weather information, electricity prices and car usage data.

The power consumption was described using a double peak model following a $\cos^2$ trend in order to mimic the seasonal variation (Figure 4). The thermal energy requirements were determined by the outdoor temperature, which on the basis of the modeled built environment previously described, could be assumed to be directly proportional to the total thermal energy needs; simulation results verified the validity of this assumption. Other environmental and previously described cloud cover coefficient, $I_n$ is the average month insulation (measured in kWh m$^{-2}$ day$^{-1}$) and $R$ is the ratio of beam radiation for the selected location calculated by comparing the data for PV potential in Finland for optimally orientated and horizontally mounted PV modules (PVGIS (2008)).

$$R = \frac{\text{Output at optimum angle}}{\text{Output at } 0^\circ \text{ angle}}. \hspace{1cm} (5)$$

The final results were collected in the PV System performance input signal.

Electricity prices for the corresponding time and location were included. Prices indicated the electricity cost at retailer and at the (nationally averaged) consumer level, providing a basic comparative evaluation on the economic performance of the system. Input data collected the electricity cost for Finland in the year 2010 as reported on the NordPool Spot energy market website. See Nord Pool (2012). Input related to the use of the plug-in hybrid electric vehicle (PHEV) included car and battery usage, the battery consumption and recharging time. The first input signal has been randomly generated considering different statistical weight for the usage of the car in different hours of the day (Figure 5). The second input indicates for how long the vehicle (specifically its battery) is used. The third signal communicates the battery status once the vehicle is again plugged into the domestic system. These last two signals, randomly generated, allow to consider different possibilities of vehicles usage (in time and intensity). The last input signal is simply communicating to the system whether the vehicle (and therefore its battery) is plugged or not.

![Fig. 4. Electricity consumption profiles used in the simulations. The winter (upper left) and summer (bottom left) electricity consumption differ for a 2/3 scale factor.](image1)

![Fig. 5. PHEV usage modeled distribution (top) and cumulative distribution (bottom). The probability for car usage has been arbitrarily considered to be 85%, corresponding approximately to 6 days a week.](image2)
DRES block. The energy source block contains five selectable elements reproducing the energy contribution of different technologies. Three combined heat and power (CHP) generators (Figure 6) set to reproduce the contribution of different type of biofuel combustions: a small-scale pellets based combustion system, a gasification unit and an anaerobic digestion unit. The energy outputs have been arbitrarily chosen to be 10 kW (power + thermal) based on OPET (2002) and Kirjavainen (2004).

Fig. 6. Cogeneration unit system architecture.

A 10 kW wind turbine, a three blades model operating in wind condition below 25 m/s whose output is described by the power curve shown in figure and is determined considering the weather records, and a 10 kW PV system whose performance is calculated taking in consideration the monthly average sun radiation values and the hourly cloud cover data. The system architectural structure for these units (Figures 7 and 8) is fundamentally the same as for the CHP units (Figure 6) with no thermal energy output. Both units have their actual output calculated considering the installed power and the environmental conditions.

Storage block. The energy storage system is divided in two components: a fixed electric energy storage and the electric energy storage of a plug-in hybrid electric vehicle (PHEV) (Figure 9). On the considered scenario, any time

Fig. 7. Wind turbine system architecture.

the system power production exceeds the system needs, the battery is loaded. In case of power need, energy is drawn from the battery. The considered battery size is 600 kWh.

The algorithm regulating the behavior of the battery for the PHEV – in our case set for 50 kWh – was the same as the one for the fixed battery. Additional elements take in consideration when the car is needed, if the car is plugged and the recharging time. The battery of the PHEV is considered to be always plugged if the vehicle is not used. Energy is always drawn from the battery unless the vehicle is needed, in which case at time t recharging time the battery begins to recharge and it is delivered at 100% of its capacity at the due time. The choice of modeling a PHEV and not an electric vehicle allows more freedom from the car usage point of view: the negative values in the car battery levels indicate that the car would have compensate for the lack of battery load using conventional fuel.

Fig. 8. Photovoltaic unit system architecture.

2.2 Local Network

The system has been designed to model the role of a micro-grid within a larger smart-energy network. As such system is expected to guarantee the possibility for the
Fig. 10. Schematic representation of the considered network structure.
end-users (now also small-scale distributed producers) to share surpluses of energy, the overall performance of different scenarios include the combined performance of a cluster of micro-grids. As the true innovative potential of a micro-grid system relies on the communication and the collective performance of clusters of micro-grid systems operating in a constructive and collaborative manner, a smart-energy network can be schematically described as a semi-hierarchical structure (Figure 10). The structure of the system does not represent a strict relation of subordination or prioritization (smart energy networks rely on a networked-meshed structures rather than radial or pyramidal structures) but it represents the system management and control logical structure.

3. RESULTS AND FUTURE DEVELOPMENT

In our simulations we considered a number of different scenarios corresponding to different system configuration. While maintaining weather and environmental conditions unchanged, the control system was set to operate with different energy production and storing unit combinations.

Our preliminary results showed how the developed system is capable to perform the required tasks and to respond to the changes in the system and environmental conditions. Thermal and electrical energy requirements were properly monitored and system requirements fulfilled. We were able to follow the performance of different system configurations, to describe in detail the performance of difference renewable energy resources and their combination reflecting real local environmental conditions. Furthermore, we were able to compare their convenience and feasibility under a number of parameters: financial, environmental, economical, etc.

Concerning the system thermal energy operations, the control system was shown being capable to maintain the indoor temperature within the desired range from the user-selected values. In the example shown in Figure 11 the outdoor temperature (top) shows the actual recorded temperature in the considered area in 2010, the actual indoor temperature (middle) is kept within the selected parameters and monitoring the total thermal energy consumption on a hourly base (bottom).

Concerning the power requirements, we were able to determine the overall performance of different energy production system combinations and their effectiveness in facing different consumption profiles. In the example shown in Figure 12, the overall power consumption profile is as previously described; the second figure shows the overall power production, with an increase of power output in the summer months due to the PV unit contribution and an irregular power output due to the contribution of the battery and the PHEV; the difference between the power consumption and production is shown in the power balance graph, with negative values indicating a power deficit. The corresponding cumulative power balance shows how the system run in a power deficit regime in the colder (and darker) months while recovering in the warmer (and brighter) time of the year.

Beside the expected results in terms of energy savings and, consequently, financial benefits for the end users, an important aspect of the modeled system can be pointed out. From the uppermost graph in Figure 12, we can see that the power demand of a system modeled as entirely depended on the common network is varying quite significantly between winter and summer seasons,
oscillating between 15 kW and 25 kW in the colder months and between 19 kW and 17 kW in the warmer months. If the actual values of the electricity demand depend on the arbitrary choices of the modeled simulator, the represented trends reflect a realistic situation. This potentially translates in capital costs for energy providers and high greenhouse gases (GHGs) emissions usually due to the necessity to cover energy demands in the peak hours. A comparison with all the other cases on the other hand shows important contributions in these aspects. In every case, an important portion of the stress on the energy network is, if not eliminated, at least reduced. This is one common effect recorded in all the considered scenarios is the partial stabilization of the energy dependence on the common grid. This is a very important outcome for the future possible development of a smart energy grid system.

Based on the obtained results, our current efforts focus on the development of a system able to efficiently build, monitor and manage clusters of hybrid micro-grids (or mini-grids as indicated in Figure 10). Our ultimate goal is to build a tool capable of rapidly build a complex structured local or regional network, monitoring and effectively improving its performance. In particular, we are planning to develop our simulator both vertically and horizontally.

The vertical development of the smart energy network model aims to include a more detailed description of the interaction between the energy network and the built environment (i.e. energy management system) and a more sophisticated interplay between different energy sources. The horizontal development of the smart energy network model aims to assess the scalability and the multiplicity of the model with the expected effects on the energy network. In particular the expected reduction of green house gases emissions achievable while preserving or improving the current level of energy quality (i.e. security, affordability, diffusion, etc.).

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