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Renewable sources integration through the optimization of the load for residential applications.

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Abstract

This work presents the implementation of two different control strategies for the control of Microgrids a Model Predictive Control (MPC) technique coupled with a Mixed-Integer Linear Program (MILP) structure and a Rule Based Control (RBC) strategy both applied to a residential MicroGrid. The validation of the models has been performed with an experimental setup laid out in the laboratory of University of Rome - Tor Vergata. Results obtained show that MicroGrids connected to the main network have enough potential to support grid balancing actions, thus allowing for a greater penetration of renewable sources into the mix, and giving economic benefits for both end users and providers. In particular, using a MPC strategy major benefits can be obtained in terms of reduction of the unbalanced energy exchange with the main grid and a more efficient use of the micro-grid components.

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Keywords: DC MicroGrids, Model predictive control, Fuel cells, Distributed generation, Renewable energy source, Demand Response

1. Introduction

The production of electricity from renewable energy sources and their integration into the electricity system has grown at a remarkable rate in recent years [1]. Despite the great growth and great benefits of renewable systems, there are uncertainties regarding the stability of the grid connected to intermittent, floating, unpredictable and non-scheduling sources of energy, especially when referred to small and micro-scale systems. From this point of view, control and scheduling strategies have become key for improving the system stability. The need thus arises for

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advanced technological solutions to control, manage and estimate the available resources over time, with the main objective of optimizing the use of the energy locally produced from renewables.

In this scenario, this work aims at establishing the actual benefits of the adoption of residential microgrids as balancing unit focusing on the design in terms of optimal configuration and control strategy for the accomplishment of such tasks. In fact, proper microgrid management may increase the renewable energy penetration or even increase the durability of critical components such as battery and FC [2]. In this paper, two control strategies have been considered: a Rule Based Control strategy (RBC) and an optimization procedure based on the Model Predictive Control technique (MPC). As a matter of fact, MPC based control strategies allow for a the implementation of effective demand side management and appliance load scheduling [3-5].

2. Microgrid description

The HPS is composed of a load randomly and independently controlled due to the main appliances of a typical Italian household, with a power consumption of 3.5 KW on average, and energy consumption over the year of 4 MWh. The PV has a power size of 3 KWp, connected to the DC bus via MPPT and DC/DC converter. The battery has a capacity of 160 Wh. The FC has a power size of 1200 W at full load, connected to the bus DC bus via a DC/DC converter. The GRID has a peak power of 6 KW and is connected to the DC Bus via AC/DC converter. The DC/DC and AC/DC converters were considered ideal for this test, i.e. neglecting losses. Special attention has been given to the definition of the residential load, through stochastic random functions, based on the most common household appliances, the probability of use and most probable use timings in the region studied (Rome- Italy). Due to the lack of real historical data, the daily simulations of the load profile of a model house have been simulated for a period of 4 years. Appliances such as: Lighting, Electric Boiler (Shower), Electric Oven, Fridge, Microwave, PC, TV, Dishwasher, Wash Machine and Dryer have been considered to compose the load in this work. A period of one week has been considered, and namely between 06/01/2015 and 12/01/2015 (7 days). The period was characterized by relatively low solar irradiation and rather high energy consumption, and thus the use of high load household appliances, such as Dryer and Boiler, may be critical for the stability of the HPS.

3. Control Strategies

3.1. Rule-based management system (RBC)

The RBC strategies have been extensively investigated when dealing with microgrid power management for their simplicity and robustness [6], consisting in rules based on threshold values (for example in terms of voltage) and pre-established operating constraints [7]. Although providing a simple, reliable, high-potential control strategy, when used to manage complex systems, it must be properly adapted and tested. This method has been tested in previous work [8].

3.2. Model predictive control (MPC)

The MPC strategies with MILP formulation have been intensively tested, obtaining outstanding performances, on experimental microgrids such as Athens [9] or the Savona campus microgrid [10]. Despite intensive literature has been published on microgrid optimization and management, no considerations on the potential of improving grid stability are given. In general, the results proposed in different works [9-12] have shown a good performance and computational processing capacity of the proposed algorithm, although there is still room for improvements.

As already stated, the residential microgrid has a randomly load profile, attending the probability of daily use of each individual household appliances. For the management system based on the MPC/MILP algorithm, the appliances that represent the largest consumption in an Italian residence (Wash-Machine, Dryer and Dishwasher) are controlled directly through the MPC algorithm.

Every 24 hours the controller performed the optimization based on the weather forecast and the load prevision updated by the last 24 hours load and weather profiles. Then using the actual weather and load conditions the optimization is performed every 20 mins in order to follow the actual needed of the users. The Sun radiation forecast data have been provided by CNMCA (Italian Air Force Meteorological Service) [13], while the real weather data have been measured at the weather station of the University of Rome "Tor Vergata".

The optimized cost function accounts for all the costs foreseen such as costs due to energy from the grid, FC operation and wear costs, unbalance costs, etc. The optimization operation undergoes specific constrains for each controlled variable. The state of charge of the batter has been kept between 45% and 100% of the maximum battery charge. The power produced by the FC has been limited within 1200 and 300 W respectively the maximum and the standby power values. Moreover constrain to avoid simultaneous operation of standby mode and operative mode have been imposed as well as a special equation to quantify the number of FC start-ups in order to take it into account in the optimization process. To limit the maximum power exchanged with the main grid up to 3000 W in both directions and to avoid simultaneous positive and negative power flow three different constrains have been imposed to the system. The equivalence between the actual grid exchange power profile and the reference profile, in case it cannot be maintained, is ensured by means of two soft-variables (Punb+|t, Punb-|t). Each appliance has been modeled by means of a binary variable for each discretized sample, plus a binary variable to represent the appliances status (switched on or turned off). The appliances controlled by the MPC, are subject to specific restrictions: The Appliance is activated only once a day (if used that day). Following a logical condition, the Dryer can only be activated after the Wash Machine cycle has ended. The number of weekly uses of an appliance is strictly imposed equal to the value reported in the common habits used for the generation of the load. Finally, after an appliance is activated by the algorithm, the cycle cannot be interrupted.

4. Details of strategies and costs

Three different test cases have been studied:

- A Standard Prosumer case where only LOAD, PV and GRID are considered;
- A Microgrid controlled by means of a RBC strategy;
- A Microgrid controlled with a MPC strategy.

Grid costs have been evaluated according to the Italian market prices for users in tariff D3 [14]. Electricity cost is 0.30 €/kWh when withdrawals occur on weekdays from 8:00 am to 7:00 pm (F1 period), otherwise it is 0.25 €/kWh (F2 /F3 period), tax included. The unbalance value depends on several factors such as the regional area, time of withdrawal, transport operators' compensation cost, errors in the production forecast and even the percentage of renewable sources penetration in the grid. This demonstrates clearly the huge variation in the net unbalance cost, and thus for this study, the unbalance values have been restricted to energy amounts expressed in kWh, assuming the value of 0.195 €/kWh as suggested in [15]. Standard commercial battery costs has been evaluated for the battery pack at 1000 €/KWh. Batteries usually have a duration of 10000 cycles, meaning 2.20 €/day for a 8 kWh battery pack. Fuel costs have been assumed at 0.8 €/smc, with a heating value of 9.6 kWh/Smc, resulting in a price of 0.0833 €/kWhe produced by the fuel cell. Laboratory test run for PEM fuel cells for static and combined heat and power use have demonstrated a durability of 40000 h in according with targets and a costs of 1200 $/kW [16]. For our purpose, we considered a PEM FC of 1.2 kW with a durability of 40000 h and a capital costs of about 1400€. This would turn into a hourly operational cost of 0.10 €/(kWh). Moreover, the number of fuel cell starts and stops strongly affects the fuel cell durability. Every FC shutdown has been assumed affecting the lifetime by 3 steady hours operation time [17].

5. Analysis of Results

Figure 1 shows the amount of energy exchanged with the grid for the three different strategies for each period of observation. It is worth noting that the MPC helps reducing the energy exchanged with the grid, both acquired and sold, as well as making more effective its use. In particular the energy consumed in the F1 period has been strongly reduced with respect to the other periods, as it is cheaper , thanks to the synergic effect of storage and scheduling.

The Standard Prosumer strategy presents a greater amount of energy exchanged with the grid. The amount of energy sold is similar to energy purchased, proving that the energy produced by the PV is hardly self-consumed by the Prosumer. Improvements may already be observed by using RBC control strategy, giving a more efficient utilization of RES available thanks to the storage capability of the microgrid system. Even better benefits can be obtained with the MPC strategy thanks to load scheduling based on weather and energy forecasts.

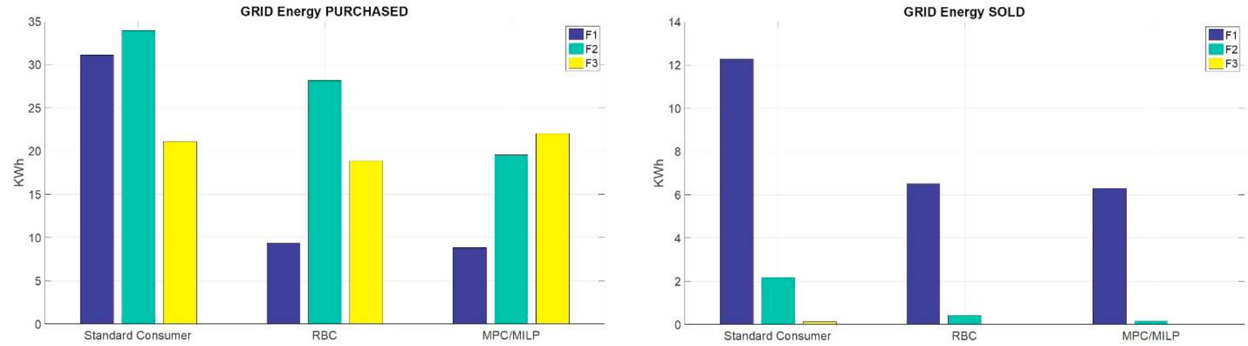

Figure 1 - Amount of energy purchased from GRID per strategy (left), amount of energy sold to GRID per strategy (right).

Figures 2 to 4, show the details of power profiles over time for the three different cases tested for all the energy sources.

The Standard Prosumer (Figure 2) consumes energy whenever a requirement arises. Since the demand side management is not considered in this case, and no energy storage systems are present, even the smallest energy over-produced from the PV panels cannot be self-consumed and the excess is given to the grid (negative grid power flow).

The RBC (Figure 3) case does not include a forecast strategy, so it is not able to consider the system project trajectory over time. The grid reference and load profiles do not match, resulting in a not very efficient use of the battery pack.

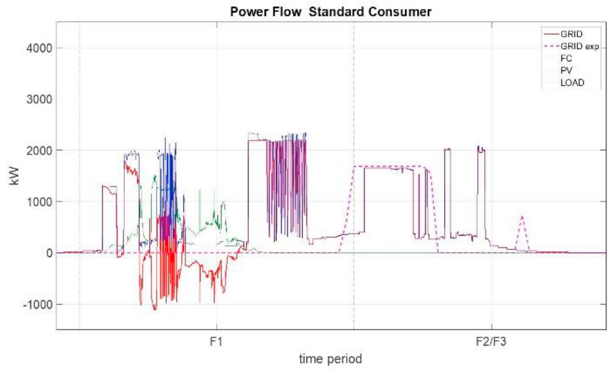

Figure 2 - Standard Prosumer vs energy sources profiles

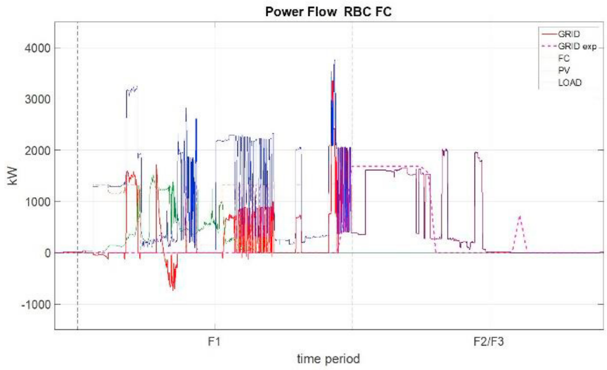

Figure 3 - RBC vs energy sources profiles

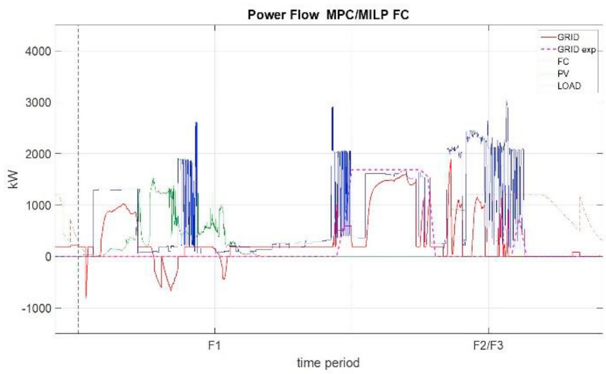

Figure 4 - MPC vs energy sources profiles

In the case of the MPC strategy (Figure 4), although the grid reference and load profiles do not completely match, the energy purchased from the network off the reference profile is reduced and spread over time, thus not transmitting peaks to the grid. This is in fact one of the most favorable results obtained thanks to the employment of this strategy.

In Figures 5 to 7 the energy consumed from the grid is compared with the reference profile.

The standard configuration without ESS is not able to move any load. Performances are improved whenever battery, fuel cell and demand side management are considered.

The MPC strategy tries to match the grid reference profile by moving consumptions mainly during night time and whenever the grid requires greater power consumption to balance the excess production from RES.

Thanks to this control strategy, that is able to perform a proper demand side management, energy fluxes off the reference profile are strongly discouraged occurring mainly during the F2 and F3 periods.

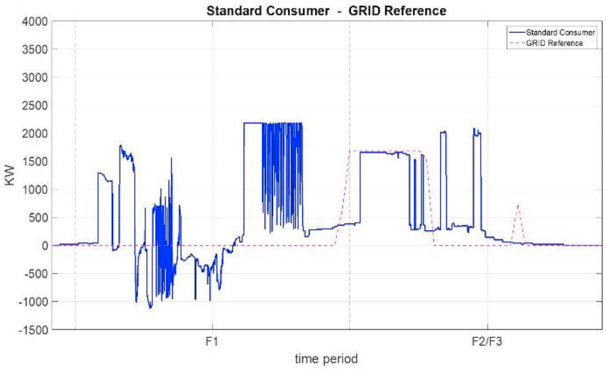

Figure 5 - Standard Prosumer vs energy sources profiles

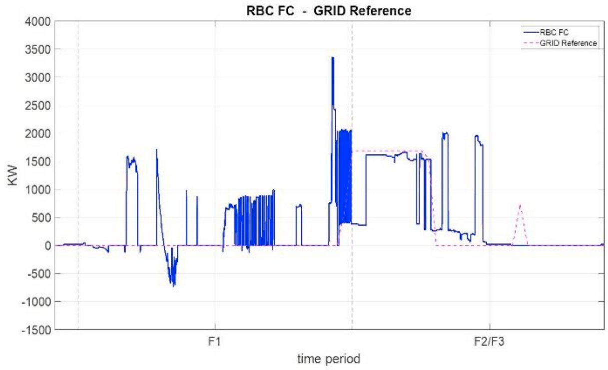

Figure 6 - RBC vs energy sources profiles

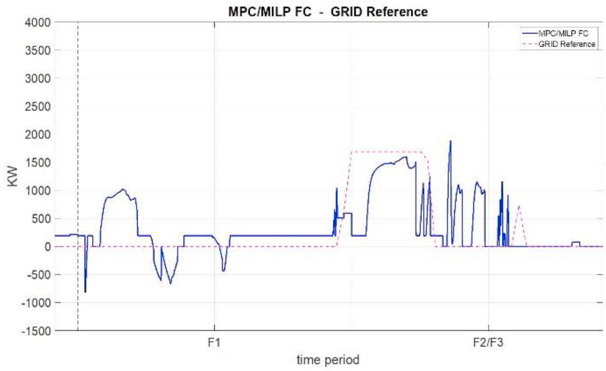

Figure 7 - MPC vs energy sources profiles

6. Conclusions

This work presented the study of a comprehensive microgrid system, composed by programmable and non-programmable renewable energy sources, with short- and long-term energy storage and the use of efficient control strategies for the management of production and consumption, to the final aim of contributing to the sustainable implementation of the Smart Grid and Distributed Generation concepts

Through the use of the control strategies proposed, a consumer may be able to perform a "proactive" demand response strategy by modifying the energy consumption profile according to Grid requirements. This would thus allow for combining the definition of the utilization profile with the profile of energy consumed from the grid, through the use and integration of programmable energy sources, energy storage systems and predictive strategies of production and consumption.

Different microgrid configurations have been simulated to look for the optimal technical solution.

The management strategies based on RBC and MPC have been compared with the Standard Prosumer in terms of energy exchanged with the main network.

The results obtained support the following conclusions:

- Despite high capital costs, including photovoltaic panels, batteries, fuel cells, sophisticated forecasting, demand management strategy and attractive pricing policies, the control concept is robust enough to offer economic benefits to the end user and to the network provider at once;
- The simple inclusion of batteries in a standard system does not guarantee efficiency in the residential case;
- Performance improve whenever a DSM, using predictive control logic has been considered ;
- The use of a battery-coupled with a DMS helps reducing fluctuations in the power exchanged with the grid, improving the stability at the end-user and at the network sides;
- The inclusion of the FC in the microgrid helps improving the stability of the whole system, thus mitigating the grid unbalance issues;
- The lack of a predictive system or poor configuration of parameters in a RBC strategy may significantly penalize the indirect costs due to the misuse of equipment, for the limited durability of the FC system.

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