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Grid-Connected Microgrids to Support Renewable Energy Sources Penetration

S. Bifaretti[a], S. Cordiner[a], V. Mulone[a], V. Rocco[a], J.L. Rossi[a], F. Spagnolo[a]*

[a]Dept. of Industrial Engineering, University of Rome "Tor Vergata"

Abstract

Distributed generation systems and microgrids are instrumental for a greater penetration of renewables to achieve a substantial reduction on carbon emissions. However, microgrids performances and reliability strongly depend on the continuous interaction between power generation, storage and load requirements, highlighting the importance in developing a proper energy management strategy and the relative control system. In this work a Model predictive Control (MPC) strategy, based on a Mixed Linear Integer Programming framework, has been applied to a residential microgrid case. Theoretical results obtained confirm that grid connected microgrids have potential capabilities in grid balancing allowing for a larger penetration of fluctuating renewable energy sources and thus producing economic benefits for both end-user and grid operators. A microgrid test bench to reproduce previous microgrid model is also presented in the paper. The experimental setup has been used to validate results obtained from simulation. Results obtained confirm the potential of this solution and its real applicability.

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Keywords:

1. Introduction

The novel concept of distributed generation requires the development and efficient implementation of advanced control strategies to manage microgrids. Several studies are available that improve microgrid performances by applying different control strategies [1]–[4]. Among these, Model Predictive Control concept [5]–[8] appeared appealing. The use of MPC in a MILP (Mixed Linear Programming) frameworks has been demonstrated to be suitable to manage smart loads, generators and storages taking into account weather forecast or electricity price forecast [7] [9]. An optimal value of the instantaneous power output as a result of the balance between power generation, energy storage and load dynamics, can be defined based on the results of an optimization process with rather different targets. Usually optimization is performed by

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* Corresponding author. Tel.:+39-06-72597125.
E-mail address: francesco.spagnolo@uniroma2.it.

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including rather large timescales. To allow the problem to be computationally feasible, fast system dynamics are not always taken into account into optimization since modeling is approached in a steady state fashion [10]. HIL (Hardware In the Loop) or SIL (Software In the Loop) simulations are then mandatory to prove that control strategies are not affected by transient dynamics, like devices' start up or shut down performances [6], [11]. In this work a MILP based MPC concept has been applied to the control of an grid-connected residential microgrid model, and compared to a more standard rule based control (RBC) strategy. The optimal power flow has been defined by scheduling smart loads with deferrable appliances, storage systems charge/discharge cycles, programmable power generators (Fuel cell) to pursue an economic optimum. Moreover, a microgrid test bench has been used to provide HIL validation of previous control strategy implementation as well as for the verification of numerical simulation results. Experiments have thus been carried out emulating same conditions as assumed in the model. Results have been then compared to show that assumption previously use are correct and the control logic real applicability is truly feasible. Respect to previous works a realistic domestic microgrid layout is considered and validated by considering both energy and economical aspects.

2. Case study

Case study is a grid connected domestic Microgrid. It includes a 3 kW peak photovoltaic (PV) power plant, 8 kWh Electric Storage System (ESS), a 1.2 kW PEM fuel cell (FC) connected to the natural gas standard distribution and avoiding thus any hydrogen storage system. Residential microgrid is considered as an active player in the distribution network. In this manner, the residential dwellings are controlled to meet an a priori electricity withdrawal profile, named reference profile, defined by the grid distribution provider. With this framework, an aggregation of domestic dwellings could allow for acting as a grid-balancing unit and also provide ancillary services to main grid as peak shaving and power quality control. Two management strategies have been applied to the system and compared each other. The first configuration, named A, is managed by a rule based control logic where control decisions, such as grid energy withdrawal and fuel cell operation, are chosen by means of instantaneous measurements and appliances are not deferrable. In the second configuration, named B, fuel cell operation, grid withdrawal and appliances starts up are defined by means of a predictive control logic based on a MILP algorithm and using weather forecasts. Moreover, the Demand Response concept adopted in configurations B allows for scheduling the deferrable loads as the washing machine, the dryer and the dishwasher by acting on their switching-on timings. The battery pack is directly connected to a 48V bus. The Microgrid size is thought to serve a family household. Results and power flow schedule have been defined based on cost minimization requirements. The following costs have been assumed: unbalance costs comparing to grid reference profile (195 €/MWh), fuel costs (methane for fuel cell, 0,8 €/smc), fuel cell operating and wear costs (fuel cell cost 1200 $/kW with rated durability of 40000 h), time variable grid electricity costs (0.25-0.30 €/kWh tax included), battery operating cost (1000 € per kWh, 10000 cycles lifetime). Fuel cell operating costs are related to the number of start-up and show-down events as well as the effective operating hours; a more detailed description of FC costs is also given in [10].

3. Model Predictive Control and Rule Based strategies

Two control strategies have been applied to the system: a Model Predictive Control with a MILP framework and a Rule Based Control. MPC is based on the representation of the system via a dynamic model representing the system power balance:

$$\frac{dS}{dt} = P_{PV} + P_{FC} + P_{grid} - P_{load} \tag{1}$$

Control actions, such as Fuel Cell (FC) operation storage system charge and discharge cycles and appliances use are decided by means of an optimization routine, based on an economic cost function, that takes in account both the current system state and predictions of future events, such as weather forecasts, for a finite time-horizon. MPC with MILP is able to consider into the optimization even discrete variable. For better understanding of the MPC MILP model see reference [8] [12].

Rule based control strategies are based on threshold values Vmin, and Vmax of the DC bus. Control actions are taken according to these values, current balance and depending on the period of the day (and thus the grid electricity price). A scheme of the RBC algorithm is presented in Fig 1.

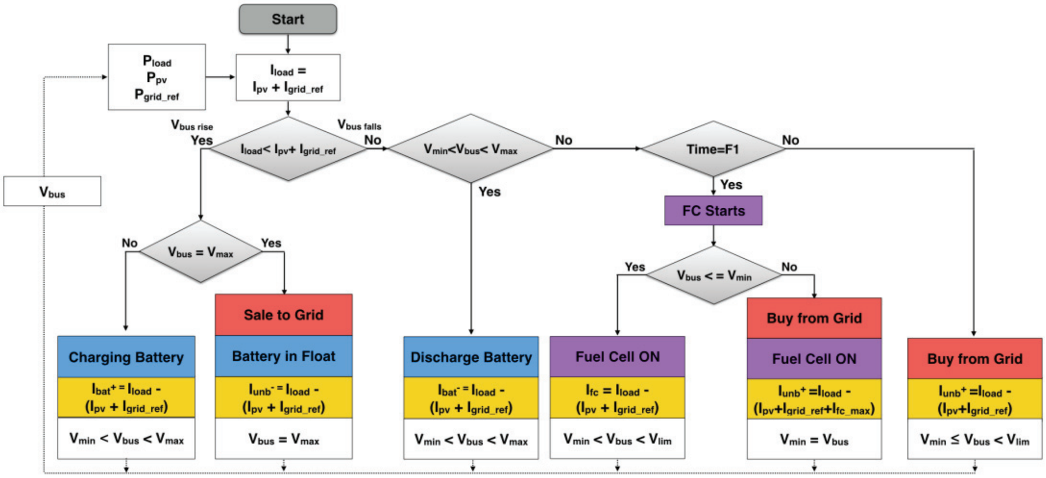

Fig. 1. Rule based control

4. Model Simulation, Results

Both configurations A and B have been operated under same conditions (reference profile, house consumption) and for the same time period (6th to 13th of January 2014). Same real weather data have been applied to both model configurations. The power flow profiles for configuration A and B for the third day of the simulation is given in the Figs below.

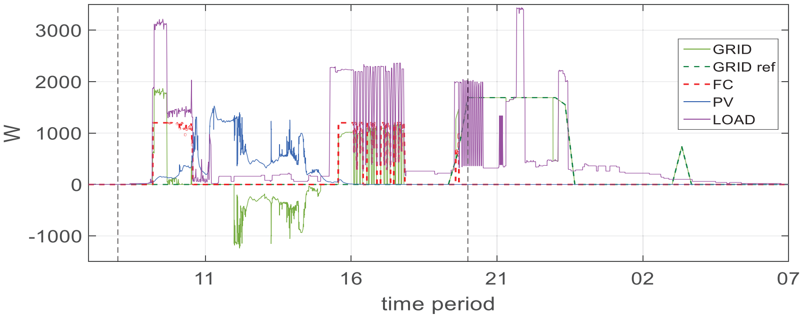

Fig. 2. Configuration A, power profile

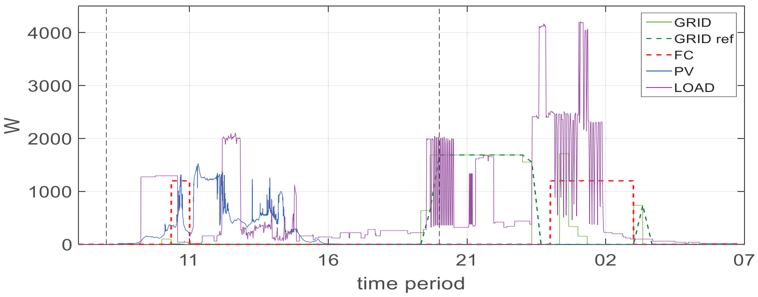

Fig. 3. Configuration B, power profile

The MPC strategy is able to better match grid reference profile, limiting the use of the fuel cell and maximizing the photovoltaic power self-consumption (no power is sold to the grid in configuration B). In the next Figs costs required to run the microgrid are reported. Figure 4 reports cost related to energy consumptions, while in Fig 5 are instead costs related to component operation and grid unbalance are given. In the Same figure (brown column) is shown the amount of energy withdrawn within the reference profile that can be accounted as a grid benefit.

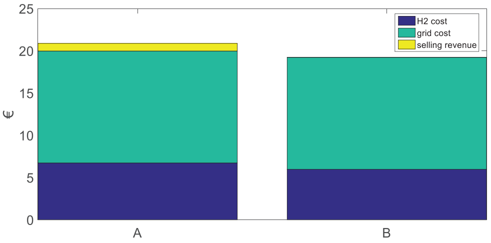

Fig. 4. Energy consumption costs

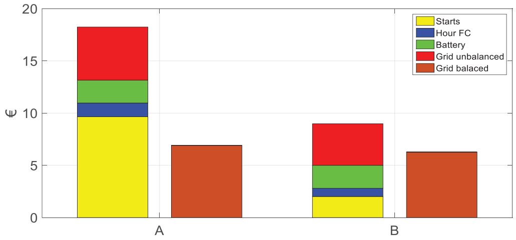

Fig. 5. Devices costs and grid benefit

5. Experimental Test Bench

A MG test bench has been developed to validate the model presented above. The MG layout has been experimentally emulated with a ratio 1:10, with a HIL (Hardware In the Loop) system. This is composed by: a 5 kW electronic load, a 3 kW power supply, a Ballard 1.2 kW PEM fuel cell, a dc/dc converter to connect the fuel cell to the dc bus, a battery bank composed by four 42 Ah lead-acid battery and used in the 50% to 100% SOC range to preserve its State of Health. The Battery pack is directly connected to the DC bus. The bus voltage may range between 42 and 60 V (maximum and minimum battery allowed voltage). The EMS has been implemented into the Simulink/Matlab® Environment and has been run in real time on a laptop. A Texas Instruments TIVA-C TM4C1294 microcontroller it is used to connect the Simulink control algorithm to instrument and vice versa. A more detailed description of the HIL system is available in [13].

6. Experimental Validation, results

A comparison between model (with MPC) and experimental results is provided below for a tested period of 26 hours. Results obtained by the model almost perfectly match the tested ones. The good match between

SOC and voltage profile means that not only the microgrid has been well represented by the model developed, but it also means that same control actions are taken during the period considered. This is clearly represented in Figs 6a and 6b. In Fig 7a it is shown that grid power withdrawals occurs at same time for model and HIL system. This is also proved by the simultaneous fuel cell start up (Fig 7b). In Fig 8 the house load is reported for both the model and HIL approaches. In the same figure general electric load that not include wet appliances consumption (Load no app.) is reported. Wet appliances have been instead scheduled according to the cost minimization routine of the MILP algorithm. In Fig. 8 it is evident that both model and HIL system have scheduled appliances at same timings.

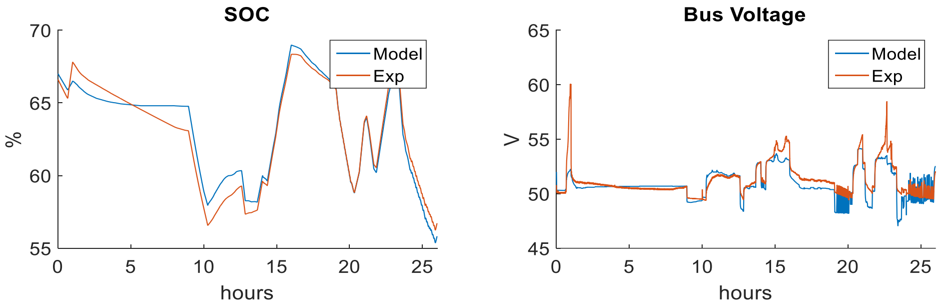

Fig. 6. a) SOC profile; b) Bus voltage profile

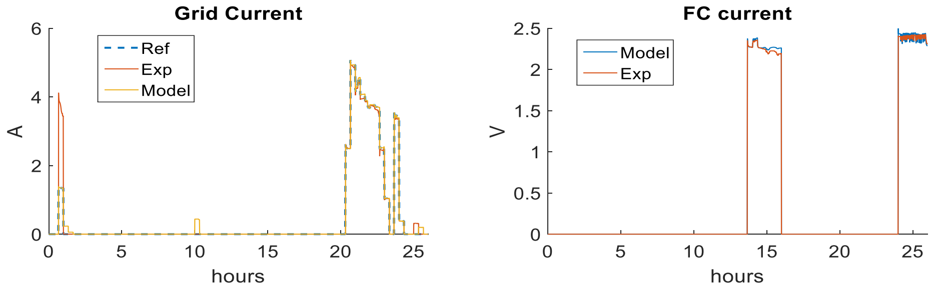

Fig. 7. a) grid current profile; b)FC current profile

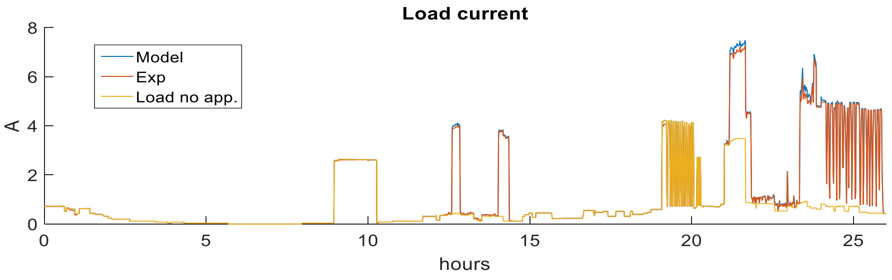

Fig. 8. House load consumption profile (current)

Conclusions

This paper presents an MPC based management strategy for the optimal control of a domestic microgrid. A comparison respect to standard control logic has been provided. Results obtained show how microgrids, when properly managed, are able to actively interact with main electricity grid. The capability to meet an a priori designed electricity withdrawal profile, externally defined by the distribution provider has been demonstrated to be technically and economically feasible. It means that the MG proposed is able to completely self-consume energy produced by renewables energy generators and thus increasing their penetration. At the same time, it empowers grid stability by matching the grid reference withdrawal profile. With this framework, an aggregation of domestic dwellings could allow for acting as a grid-balancing unit and provide a sort of ancillary services and thus allowing for a further increase of fluctuating renewable energy penetration. Numerical results have been validated by means of an experimental microgrid test bench and the control strategy adopted has been demonstrated to be truly implementable.

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