Energy 108 (2016) 119–131

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Energy management in a domestic microgrid by means of model predictive controllers

G. Bruni, S. Cordiner, V. Mulone, V. Sinisi, F. Spagnolo*

Department of Industrial Engineering, University of Rome Tor Vergata, Italy

ARTICLE INFO

Article history:
Received 11 March 2015
Received in revised form
3 August 2015
Accepted 4 August 2015
Available online 29 August 2015

Keywords:
Distributed generation
Microgrids
Model predictive control
Fuel cells

ABSTRACT

The need to increase renewable energy sources deployment and to reduce consumption of fossil fuels has led to the diffusion of small-scale DG (Distributed Generation) systems, which may be effectively integrated in micro-grids. The role of control logic in defining microgrid performances and reliability is predominant and can be improved by using advanced control logics such as the ones based on MPC (Model Predictive Control).

In a previous paper, a MPC logic, based on the use of weather forecasts to improve the performances, has been applied to the analysis of power management in a domestic micro-grid system composed by: PV (Photovoltaic panels), FC (Fuel Cells) and a battery pack; in that case, the system was not affected by real uncertainties. In this paper the same system has been considered for domestic microgrid applications. The system control logic has been implemented by assuming real weather forecast as input data. DMPC and SMPC (Deterministic and Stochastic Model Predictive Control) concepts have been applied to the system and results have been compared to both MPC and to a standard RBC (Rule Based Control) logic. The impact of forecast uncertainties has been evaluated showing the advantages of a stochastic approach. In that case, the SMPC showed encouraging performances compared to standard control logics, primarily in terms of primary energy savings and downsizing potential of the power-delivering subsystems using programmable energy sources.

1. Introduction

One of the current evolutions of the energy market foresees the diffusion of the microgrid concept [1,2] (or Hybrid Power Systems, HPSs) as a technical solution enhancing the Distributed Generation of energy. Such complex systems, including RES (Renewable Energy Sources), FES (Fossil Energy Sources) and storage devices, require accurate management strategies in order to optimize the energy use [3], through the control of subsystems [4], or to minimize capital and operating costs [5]. In such systems, the renewable energy production during a given period (typically a year) depends mainly on its sizing: the amount of available RES, in fact, strongly affects the use of fossil energy and the FES conversion plants working hours. The HPS management strategy, although has less impact on FES utilization than system sizing, may allow for a better use of the sub-systems. An optimal use of the sub-systems has in fact a double effect: the first is related to improved component durability and lower costs [6]; the second concerns component downsizing [7].

Among the sub-components, HPSs usually include FCs (Fuel Cells) as FES conversion plant: this mainly depends on the recent developments of FC technology. FCs, in fact, are a good option for the energy conversion in stationary or mobile applications in the mid or long term, for two main reasons: the greater efficiency if compared to thermal engines, also showing low operating costs [8], and environmental impact. Hydrogen is mainly produced by reforming processes of natural gas or, more in general, hydrocarbons; even taking into account all the intermediate conversion steps, FCs still present fairly high efficiency. However, hydrogen is expected to be produced in the future from renewable energy sources, thus helping the widespread diffusion of HPSs including RES conversion plants, FCs and electrolyzers. Therefore, great research efforts have been done during the last years in the field of FCs [9–11], in order to overcome some of their technological issues and improve their reliability and efficiency. Such research efforts included membrane development, referring to proton exchange membrane FCs [9], with the aim of solving durability issues, CFD-

* Corresponding author. Tel.: +39 0672597125; fax: +39 0672597158.
E-mail address: francesco.spagnolo@uniroma2.it (F. Spagnolo).

http://dx.doi.org/10.1016/j.energy.2015.08.004
0360-5442/

based studies to avoid slug formation in FC flow channels [10], or optimize FC performances [11]. However, FCs still have relatively short durability [12] and, therefore, need accurate load management, especially if they are included in complex systems such as microgrids. The control strategy may also be used for such purposes, to limit the number of start-up and shut-down procedures.

The MPC (Model Predictive Control) concept has been widely applied for the management of final energy uses and of microgrids, both numerically and experimentally in order to achieve such results. In Refs. [13 and 14], describing a study on the improvement of MPC algorithms for the management of final energy use, the authors show the energy saving potential of MPC control strategies applied to building thermal control, also assuring lower CV (Comfort Violations) during the year compared to a simple RBC strategy. The study is focused on office buildings, integrating in the MPC controller actions on thermal and electric load modulation through the HVAC system control, window blinding and electric lighting system management. The authors apply three MPC strategies, under the assumptions of perfect weather forecasts, non-perfect weather forecasts and non-perfect weather forecast with characterization of uncertainties and affine feedback correction, respectively. Results all demonstrate the potential of the MPC strategy in comparison with a simpler RBC strategy in terms of fossil energy savings; they also show the importance of weather forecast accuracy. In these two papers the attention is focused only on thermal building management and then only on the energy consumption management without accounting its availability, or electric sources management. Weather forecast accuracy is also studied in Ref. [15]. In this work a microgrid was simulated by using a MPC control strategy taking into account weather forecast for load and RES predictions. In Ref. [16] Zong et al. implemented an MPC algorithm to manage the use of DERs (Distributed Energy Resources), such as solar energy, in a real smart domestic microgrid in SYLAB laboratory in Denmark. The management of final energy use consisted in load control related to the use of HVAC system to maximize the exploitation of the available RES. They demonstrated the capabilities of the predictive controller to maximize the use of the available RES and minimize costs. In this work, therefore, the target is twofold, regarding both costs and energy savings. Parisio et al. [17] presented a similar experimental application of the MPC algorithm, with an improvement in terms of robustness and the demonstration of the capabilities to optimize operating costs of the HPS. The authors tested the algorithm on an experimental microgrid, with the aim of minimizing costs. Recently, MPC has been applied to the study of multilevel controllers. In Ref. [18] (Trifkofic et al.) a MPC based supervisor controller has been implemented to schedule start up and shut down procedures for all the devices in the microgrid. After the start up procedure, microgrid components have been programmed to work at their rated power with no load modulation. A second controller has been set to manage the power balance mismatch in real time fashion.

The same microgrid model has been tested with a different control strategy [19], and, more specifically, a simple rule-based one. Several local MPC controllers have been defined to ensure optimal operation of the microgrid components to improve the overall system efficiency. In Ref. [20] a four level MPC controller has been proposed for the management of a grid-connected microgrid. This work presents an extended cost analysis, including capital costs effects, components ageing and variable grid energy costs. Multilevel MPC controller has then the objective of minimizing the overall operating costs. A single level MPC controller is presented in Ref. [21]. In this work, an optimization process is defined by considering a whole day forecast. The case study is defined on the poly-generation, grid connected microgrid of the University of Genova, in Savona campus. This analysis highlights the importance of storage systems when predictive controllers are adopted. In Ref. [22] a detailed model of a battery storage system is proposed and used within the model predictive control algorithm formulation. Although the authors state that there is room for improvements, it is already clear that the use of MPC allows for obtaining better results if compared to the use of more traditional control strategies. Ref. [23] proposed the use of MPC to solve the problem of uncertainties related to the PEVs (Plug-In Electric Vehicles) charging load into a Smart-Grid structure. They formulated the optimization problem with the target of minimizing operational cost and power losses of a fraction of the distribution grid, including distributed RES conversion plants and electric storage systems. Their work testifies the potential improvement in terms of operating costs and energy savings.

Another economic optimization was proposed by Kriett and Salani [24], who developed a mixed integer linear programming for the operation of a microgrid including both the electric and thermal layers. In Ref. [25] the authors, instead, describe an algorithm for the optimization of components sizing in a microgrid; they include the electric, thermal and economic aspects in the description of the microgrid dynamic behaviour and suppose that MPC is used in the microgrid management. They focus on three levels of complexity: single building, multiple buildings and larger microgrid layouts. The three levels may include a cogeneration power plant, PV modules, solar thermal panels, heat pumps, thermal and electric storage systems. Among their results, the optimal sub-component size may vary depending on the level of optimization procedure, as well as on the definition of constraints. The authors demonstrated that including the management strategy affects the optimal sizing of microgrid sub-components.

The mentioned papers have dealt with many concepts, such as: the management of final energy use [13,14,16,17,23–25]; the management of a whole microgrid [16–21,23–25]; improvements obtained with the help of weather forecast information [13–15,20,21]; the management of individual components [20]; energy savings [13,14,16,17,20,23–25]; cost savings [16,17,20,23–25]; dealing with multi-level controllers [20]. Many of such concepts are also considered in this work.

Following the approaches of similar papers [6,7,26], this paper is aimed at assessing, by means of models, the influence of the management strategy on the efficiency of a domestic microgrid. The focus is on the use of MPC algorithms for the management of the final energy use in domestic microgrids, with the aim of saving fossil energy and evaluate the potential for component downsizing. The case study is defined on a detached house equipped with a stand-alone microgrid including PV (Photovoltaic panels), FC (Fuel Cells) and a battery pack; the house thermal management is performed by means of heat pumps. In the presented case study the MPC manages both the electric load, by means of the HVAC load modulation, and the electric power output via the FC.

The main novelties of this paper, if compared to the previously cited ones, are based on the analysis of energy management [16,17,23–25], of savings in final and fossil energy for different renewable energy conversion plants sizes [7,26], of thermal load management of the house in order to assure thermal comfort [13,14]. Moreover, in comparison with [16], a trade-off between thermal comfort and energy savings is proposed. Similarly to reference [25], where it was shown that control strategies can affect the system sizing, this paper aims at demonstrating the impact of MPC strategies on the design (i.e. power output) of some components, and primarily of the FC subsystem, toward a minimization of the capital costs of the microgrid.

In Ref. [7] microgrid management and building thermal comfort management were the two targets: this was translated into a multi-objective MPC strategy aiming at increasing comfort conditions