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Modeling and optimization of a hybrid system for the energy supply of a "Green" building

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ABSTRACT

Renewable energy sources (RES) are an "indigenous" environmental option, economically competitive with conventional power generation where good wind and solar resources are available. Hybrid systems can help in improving the economic and environmental sustainability of renewable energy systems to fulfill the energy demand. The aim of this paper is to present a dynamic model able to integrate different RES and one storage device to feed a "Green" building for its thermal and electrical energy needs in a sustainable way. The system model is embedded in a dynamic decision model and is used to optimize a quite complex hybrid system connected to the grid which can exploit different renewable energy sources. A Model Predictive Control (MPC) is adopted to find the optimal solution. The optimization model has been applied to a case study where electric energy is also used to pump water for domestic use. Optimal results are reported for two main cases: the presence/absence of the energy storage system.

1. Introduction

The sustainable green building energy supply lead both developed and developing countries to make and implement new policies to improve efficiency in energy consumption, and to adopt new alternatives like RES. Variable energy demands, intermittent availability of renewable resources, different technological alternatives to satisfy the different demands, and the possibility of integrating storage and energy production systems give rise to the exigency of defining criteria and strategies able to improve efficiency and energy supply, and its environmental and economic sustainability. Methods and models able to optimize such hybrid systems for the specific case of a building are also welcomed because of the relevance that might have a "Green building" in terms of environmental sustainability and energy efficiency.

In fact, in the EU and US, energy consumption in buildings has even exceeded the energy consumption of the industrial and transportation sectors [1]. Energy consumption of buildings accounts for around 20–40% of all energy consumed in advanced countries. Over the last decade, more and more global organizations are investing significant resources to create sustainable built environments, emphasizing sustainable building renovation processes to reduce energy consumption and carbon dioxide emissions [1].

RES exploitation is one of the most important aspects of green buildings. RES are defined as sources of energy that can be derived from natural processes, and that can be replenished constantly, e.g. energy generated from sun, wind, biomass, geothermal, hydropower [2]. The wind and solar energies are freely available and environment friendly. The wind energy systems may not be technically viable at all sites because of low wind speeds and/or higher unpredictability with respect to solar energy. Moreover, the availability of a specific resource depends on the specific season and varies during the day. Integrating different RES in a hybrid system, allowing their combined exploitation, is therefore becoming increasingly attractive [3].

Hybrid renewable energy systems are becoming popular for remote area power generation applications due to advances in renewable energy technologies and rise in prices of petroleum products. Economic aspects of these technologies are sufficiently promising to include them in developing power generation capacity [4]. Effective energy management of hybrid energy systems is necessary to ensure optimal energy utilization and energy sustainability to the maximum extent [5]. Hybrid systems can be considered as a reasonable solution, capable to support systems that cover the energy demands of both stand-alone and grid connected consumers that can be integrated into residential, commercial, or institutional buildings and/or industrial facilities. Furthermore, the hybrid renewable energy systems are often the most cost-effective and reliable way to produce power as well as to attenuate fluctuations in power produced, thereby significantly reducing energy storage

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requirements [4]. In literature, the majority of papers have been focused on the sizing of hybrid renewable energy systems. Paska et al. [6] presented their experience of the design, build and exploitation of many hybrid power systems. The results show that the proposed hybrid plants are a good way to have available sources of electricity which optimize utilization of primary energy sources. Ashok [7] discussed different system components of hybrid energy system and developed a general model to find an optimal combination of energy components for a typical rural community minimizing the life cycle cost while guaranteeing reliable system operation. Ekren and Ekren [8] optimized an autonomous PV/wind integrated hybrid energy system with battery storage. Bakos and Tsagas [9] reported the technical feasibility and economic viability of a hybrid solar/wind grid connected system for electrical and thermal energy production, covering the energy demand of a typical residence in the city of Xanthi (Greece). Reichling and Kulacki [10] modeled the performance of a hybrid wind–solar power plant. They found that adding solar thermal electric generating capacity to a wind farm rather than expanding with additional wind capacity provides cost–benefit. Dagdougui et al. [11] presented an overall optimization problem in connection with a dynamic system model, which is controlled in real time to satisfy the hourly variable electric, hydrogen, and water demands. Ouammi et al. [12] presented a practical methodology to support decision makers in the evaluation of the wind exploitation on a territory and the sustainability of the installation of a wind power plant. Teleke et al. [13] developed a control strategy for optimal use of the battery energy storage. Papaefthymiou et al. [14] presented the wind-hydro-pumped storage hybrid power station of Ikaria Island. Karki et al. [15] developed a methodology for an energy limited hydro plant and wind farm coordination using a Monte Carlo simulation technique considering the chronological variation in the wind, water and the energy demand. Zhang et al. [16] presented a multistage stochastic mixed integer programming model for power generation in a day-ahead electricity market. Hyndman and Fan [17] proposed a new methodology to forecast the density of long-term peak electricity demand. Glanzmann and Andersson [18] investigated a decentralized optimal power flow control for overlapping areas in power systems. Abbey and Joós [19] studied the problem of energy storage system sizing for isolated wind-diesel power systems. In [20], authors presented a building automation system, where the demand-side management is fully integrated with the building's energy production system, which incorporates a complete set of renewable energy production and storage systems. Ruther et al. [21] assessed the potential of grid connected, building integrated photovoltaic generation in the state capital, Florianopolis, in south Brazil. Al-Salaymeh et al. [22] studied the feasibility of utilizing photovoltaic systems in a standard residential apartment in Amman city in Jordan. Hoes et al. [23] proposed a concept that combines the benefits of buildings with low and high thermal mass by applying hybrid adaptable thermal storage systems and materials to a lightweight building. Braun and Rüther [24] showed the role of grid-connected building-integrated photovoltaic in reducing the load demands of a large and urban commercial building located in a warm climate in Brazil.

The aim of this paper is to define a dynamic optimization model that is able to support decisions related to the operational management of energy supply for a green building. Indeed, the model could also be used for a more general grid-connected microgrid characterized by different energy production plants and storage systems, and, unlike the majority of works reported in the literature, is related to a system already sized and to the optimal control of the overall system according to time-varying demands and resource availability.

The innovation carried out by this study consists in considering a mixed renewable energy sources and a storage system to feed a "Green" building for its thermal and electrical energy needs in a sustainable way. The system model is embedded in a dynamic decision model and is used to optimize a quite complex hybrid system connected to the grid. The optimization model has been solved for two main cases: the presence/absence of the energy storage system. Finally, unlike most contributions available in the literature, in this paper, an overall optimization problem is defined in connection with a dynamic system model, which is to be controlled in real time, on the basis of the (discrete time) observation of the system state. In particular, specific state and control variables are defined to formalize the dynamic hybrid system model, the objective function, and the constraints of the optimization problem. The problem considered in this paper is quadratic with linear constraints. A Model Predictive Control (MPC) approach is used in the problem formalization and solution in order to take into account updates in the system state, forecasts of the energy flows from renewable sources, and demand variations, which can be forecasted with some difficulties. The approach followed in this paper is based on the repeated formalization and solution of an optimization problem over a finite horizon, on the basis of the current observed state and on the available forecasts of the quantities of interest.

2. The control architecture

Intelligent buildings have attracted lots of attention in recent years. Recent papers [25,26] have focused on the inclusion in the Building Automation System (BAS) of algorithms based on control and optimization, with specific reference to a Model Predictive Control (MPC) scheme. Specifically, in [25], attention is focused on the heating system and state equations are formalized to describe the temperature behavior in the different buildings' rooms as a function of the external temperature and of the heat sources. Instead, in [26], authors developed an operational control platform for an intelligent building using a SCADA (Supervisory Control and Data Acquisition) system to control temperature and luminosity in huge-area rooms. Energy management systems require the integration and communication of different kinds of information. Thus, a specific communication network should be developed [27].

In this paper, a dynamic decision model for a green building is described in detail. The developed model is thought as a part of a general BAS based on a MPC controller that integrates plants, storage systems, energy demands (for electricity, heat, and water pumping), resource availability forecasts, through an appropriate communication system.

Fig. 1 reports the information flows necessary for the dynamic decision model application. A general architecture that can host such a dynamic decision model is reported in [26]. The optimization package used in this paper can be integrated with a supervisory system. Otherwise, the dynamic decision model can also be implemented in the Matlab Software (like in [26]). The results of the optimization algorithm can be sent to an actuator system that gives commands to the thermal, electrical, and water systems (i.e., inputs to production plants, inverters, storage system, air conditioning, water pumping, etc.).

The architecture is based on a centralized intelligence that receives forecasts for renewable resources availability, demands, prices, and system state (i.e., level of charge of the storage system), and, on the basis of an optimization model, gives commands to a sub-set of the production plants, to the storage system, to the pump, and to the connection between the building and the external net. The commands are given to typical hardware (i.e., inverters, switch with the external net, production plants, etc.) that can be present in the building. Moreover, the central controller is supposed to communicate with the local controllers present in the production plants and in the storage system. The primary control variables are those entities over which the central controller may