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Intelligent control for energy-positive street lighting

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ABSTRACT

The paper investigates the application of solar energy in public lighting for realizing a street lighting sub-grid with positive yearly energy balance. The focus is given to the central controller, which ensures the adaptive behavior of the overall system and provides smart city services to the end users via its web-based user interface. A functionality of the controller of special interest is the optimization of the energy management of the system, i.e., determining when to sell and buy electricity to/from the grid, in order to minimize the cost of electricity (or to maximize the profit) subject to a given, time-of-use variable energy tariff. This requires precise forecasts of the energy produced and consumed, as well as appropriate robust optimization techniques that guarantee that the system bridges potential power outages of moderate duration in island mode. The algorithms implemented in the controller are presented in detail, together with the evaluation of the operation of a deployed physical prototype with 191 luminaries over a horizon of six months, based on the monitoring data collected by the proposed controller.

1. Introduction

This research has been motivated by the application of solar energy in public lighting with the intention to achieve an energy-positive street lighting sub-grid, briefly named *E + grid*. The proposed system architecture exploits all of the four possible approaches defined in Ref. [1] to minimize the energy consumption and the operating costs of the lighting system: advances in technology (i) by applying energy-efficient *LED luminaries*, *photovoltaic* (PV) panels for energy production, and *batteries* for intermediate energy storage; changes in use patterns (ii) by adjusting the daily switch on/off times to current *meteorological conditions*; modification in the basis of design (iii) by applying *adaptive lighting* that concentrates the lighting service to locations and times with vehicle or pedestrian traffic; and finally, changes in contracts (iv) by *optimizing the energy management* of the system subject to a *time-of-use variable energy tariff*. Hence, the proposed system can fully unfold its benefits if deployed in areas with low traffic during the night, such as residential areas, industrial parks, or supermarket car parks. To the best of our knowledge, the proposed system is the first in the literature to integrate all these technologies in a single street lighting system.

This paper focuses on the *central controller* (CC) of the E + grid system that ensures the adaptation of the lighting system to the actual environmental conditions and user requirements, including the control of the daily switch on/off times and the dimming levels of the luminaries. Special attention is given to the energy management of the system: battery storage, bi-directional grid connection and intelligent control enable the system to buy and sell electricity when it is the most profitable, taking into account forecasted energy production and consumption, as well as a variable, time-of-use energy tariff. The controller is also responsible for delivering smart city services to end users by means of its web-based graphical user interface (GUI), such as the visualization of the current status and historical operational data, which are crucial for the efficient operation and maintenance of the overall system.

The physical prototype of the E + grid system has been developed and deployed recently by an industry-academy consortium formed by General Electric Hungary, the Budapest University of

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This paper content is organized as follows. First, a review of the recent literature on intelligent, energy-efficient street lighting and on renewable energy management systems is given. Then, Section 3 formulates the objectives that led to the specification of the proposed controller, and it also presents the architecture of the overall E + grid system. Section 4 gives a detailed account on the services of the CC. The algorithms for forecasting and optimizing the flow of energy are discussed separately in Section 5. Finally, the lessons learnt during a half-a-year operation of the physical prototype are summarized (Section 6) and conclusions are drawn (Section 7).

2. Literature review

A recent review on the opportunities and challenges in solid-state lighting, including technological development, policy options, environmental impact, as well as future trends, is presented in Ref. [2]. The potential approaches to reducing the energy consumption of street lighting systems, such as changes in technology (e.g., light sources), in use patterns (e.g., applying a twilight switch and remote dimming), and changes to standards and design criteria have been investigated in Refs. [1,3]. These trends and the applicable technological solutions are review in detail below.

Adaptive lighting, i.e., the adjusting of the intensity and the distribution of light to the environmental conditions and user behavior, received significant attention recently, due to the favorable dimming performance of LED light sources. An optimization approach to balancing light quality and energy efficiency in color turnable adaptive lighting systems is proposed in Refs. [4], whereas the psychological effects of adaptive lighting have been studied by Haans and de Kort [5]. Pizzuti et al. [6] proposed reducing the energy consumption of street lighting by adjusting the dimming levels to the forecasted traffic intensity, and using an ensemble of artificial neural networks (ANNs) to derive such a forecast.

Various authors investigated the application of adaptive lighting in indoor applications as well, with the objective of improving the perceived quality of light and saving energy at the same time. Parise and Martirano [7,8] suggest the integrated design of electric light and natural daylight systems, with the application of advanced sensor and information technologies. Petrov et al. [9] presents an approach to dynamically adjust the color temperature and illumination levels in an indoor lighting system to the observed natural outdoor light conditions using the DALI protocol and dedicated microcontrollers.

The basic services of a *remote monitoring and control system* for street lighting have been defined and a software architecture has been proposed in Ref. [10]. A three-layer control architecture, consisting of a backend server, multiple centralized controllers, as well as node controllers on individual luminaries, is proposed for intelligent street lighting in Ref. [11]. Formal graph models and a rule-based approach to controlling a complex adaptive lighting system are proposed in Ref. [12]. An intelligent communication and control system for street lighting, integrated into an experimental microgrid, is presented in Refs. [13,14]. proposes a controller architecture for individual, adaptive lighting points powered by PV panels mounted on the light pole, for off-grid applications.

The potential of *PV assisted street lighting* in off-grid and grid-connected systems is analyzed from the economic, ecologic, and energetic point of view using a simulation model in Ref. [15]. A thorough assessment of the effects of PV generation on the overall European electricity system, as well as recommendations for quantifying the full cost of PV generation are presented in Ref. [16]. An alternative methodology for the assessment of the economic value of PV generation is proposed in Refs. [17], where the calculation of the true market value, considering the temporal variability and geographical particularities of both PV generation and electricity demand, as well as time-of-use energy tariffs, is put forward, instead of the often used grid parity metric.

An important means for improving the yield of PV systems is the *maximum power point (MPP) tracking* algorithm in the power converter (inverter), which addresses the dynamic regulation of the operating voltage and current to maximize the power output. Recent improvements of the conventional *perturb and observe* (P&O) algorithm, often implemented in commercial systems, address the reduction of the oscillation around the MPP and the risk of divergence from the MPP [18,19]. The performance of the P&O and the incremental conductance (IC) algorithms is compared in Ref. [20]. In the experiments, IC yielded marginally better efficiency than P&O, but it was considerably more sensitive to parameter settings.

Energy management in microgrids addresses finding the optimal matching of power demand to power supply, potentially via intermediate storage, in such a way that the operating cost of the microgrid is minimized (or analogously, the profit is maximized) subject to a variable energy tariff. The integration of the capabilities to forecast power demand and supply, as well as to control loads, generators and storage in a single system is of utmost importance [21]. While the prediction of grid load has been a widely studied problem [22], PV production forecasts became of interest with the spreading use of renewable energy. Typical approaches combine dynamic time series methods with astronomic models, such as clear-sky approaches that estimate PV production under the assumption of a cloudless sky, based on the solar elevation angle and site altitude [23]. Methods for forecasting PV production on a short-term horizon include ANNs [24], time series models based on dynamic harmonic regression [25], or time series for spatial-temporal forecasts [26]. The adaptive aggregation of different time series models was investigated in Ref. [27].

Approaches to computing the *optimal control* based on given, deterministic or stochastic forecasts include [21], who introduced mixed-integer linear programming models for energy management in a microgrid, assuming non-cooperative users autonomously managing their own electricity demand, as well as for cooperative users targeting at a common objective. Elsied et al. [28] proposed a nonlinear optimization model for controlling distributed generators and storage systems. Provata et al. [29] introduced a genetic algorithm for minimizing the operating cost of a community microgrid, considering production and consumption forecasts generated using ANNs. Clastres et al. [30] proposed a two-step approach, in which the schedule of buying and selling electricity is computed first on a horizon of 24 h with the objective of maximizing the profit. The resulting active power bid is submitted to the distribution system operator. The second step is the real-time adjustment of the plan to the realization, with the objective of fulfilling the bid.

To cope with imperfect predictions, various papers investigate the application of *probabilistic forecasts* and *stochastic optimization*. Zavala et al. [31] propose an on-line stochastic optimization approach, applying model predictive control and a weather forecasting model. In Refs. [32], a similar approach is taken to the problem of controlling the production/distribution of a set of thermal power plants in order to compensate for the uncertain production of wind farms. Livengood and Larson [33] assume probabilistic weather and tariff forecast and apply stochastic dynamic programming to compute an optimal energy management policy in a residential or small office environment. Niknam et al.