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Near real time load shifting control for residential electricity prosumers under designed and market indexed pricing models ☆

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HIGHLIGHTS

- Design of an energy management system for residential electricity prosumers.
- Both designed and market indexed pricing models are considered.
- Optimal load-shifting, self consumption and automated demand side management.
- Simulation of relevant scenarios which will characterize future residential nodes.

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ABSTRACT

This paper presents an event driven model predictive control approach for a local energy management system, enabling residential consumers to the automated participation in demand side management (DSM) programs. We consider a household equipped with smart appliances, a storage unit, electric vehicles and photovoltaic micro-generation. Resources are coordinated according to the needs of maximizing self-consumption and minimizing the cost of energy consumption, in a contractual scenario characterized by designed or market indexed pricing models, with DSM options. The control action (appliances' start times, the storage charging profile and the IEC 61851 compliant charging profile of the electric vehicles) is updated every time an event triggers the controller, such as a user request, a price/volume signal or the notification of a new forecast of micro-generation from the photovoltaic unit. The control framework is flexible enough to meet the real dynamics of a household and short-term grid requirements, while taking into account user preferences, contractual and technical constraints. A proper set of simulations validates the proposed approach.

1. Introduction

The future electricity grid will feature rapid integration of distributed and renewable energy sources (RES) as a priority for a sustainable growth of the industrialized countries [1]. The implications of such a trend are widely being investigated and the availability of negative and positive balancing power is commonly recognized as a basic requirement in order to mitigate the effects of RES volatility on grid stability and reliability [2,3]. Depending on the size and placement of distributed generators from consumption, the balancing task can be performed at different levels, according to the basic principle "the smaller the distance between RES and consumption, the higher the benefit for the grid." As a matter of fact, when talking about micro-generation at residential level, a local energy management system (EMS) matching generation with consumption appears as a meaningful and cost-effective technological solution both in the consumer and distribution system operators (DSOs) perspective. Further, when considering larger amounts of energy, extended control architectures implementing automated demand side management (DSM) strategies and several forms of storage devices installed along the distribution lines are complementary, clean and cost

Abbreviations: DAP, day ahead pricing; DER, distributed energy resources; DSM, demand side management; DSO, distribution system operator; EMS, energy management system; EV, electric vehicle; MILP, mixed integer linear programming; MPC, model predictive control; PV, photovoltaic; RES, renewable energy sources; RTP, real time pricing; SHC, smart home controller; ToU, time of use; UP, user preference; V2G, vehicle to grid; VPT, virtual power threshold.

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Nomenclature

T	discretization time step
ct	first time step of problem definition
ch	last time step of problem definition
dt	departure time of the electric vehicle (EV)
$\widetilde{C}$	pricing parameter
C	electricity tariff
P^*	estimate of power from non-plannable loads
P^{pln}	estimate of power from planned loads
P^{pv}	estimate of micro-generated power
VPT	virtual power threshold
M	set of appliances to be planned
S_m	first possible start-time interval for the mth plannable appliance (set by the user)
E_m	last allowed end-time interval for the mth plannable appliance (set by the user)
N_m	duration of the mth plannable program
$\overline{P}_m$	mean consumption of the mth plannable appliance
$\widehat{P}_m$	peak consumption of the mth plannable appliance
u_{mk}	Boolean control variable related to the activation of the mth appliance
x	state of charge of the electric energy storage
ξ^{st}	efficiency coefficient of the storage
ΔP^{st}	charging/discharging rate of the storage
u_k^{st}	Boolean control variable related to storage charging operations at kth time interval
v_k^{st}	Boolean control variable related to storage discharging operations at kth time interval
y	state of charge of the EV
ξ^{ev}	efficiency coefficient of the EV
ΔP^{ev}	maximum charging/discharging rate of the EV
u_k^{ev}	semi-continuous control variable related to EV charging operations at kth time interval
v_k^{ev}	semi-continuous control variable related to EV discharging operations at kth time interval
st, ev, pv	superscripts referred to, respectively, the electricity storage, the EV and the photovoltaic panel
max, min, 0	superscripts referred to, respectively, a maximum and minimum allowed value, and an initial value

competitive technologies in the balancing markets with respect to legacy generation, as they can reduce the reliance on expensive and pollutant power plants taken in stand by hot mode for the most of time. In the real case, characterized by a combination of small and medium size generating units from RES, a local energy management system working at residential level is the key element enabling the consumer to optimally benefit from the energy produced inside the dwelling and to participate in DSM programs in an automated way, then enlarging his/her level of responsiveness and the related economic benefit in reaction to proper signals [4,5]. Such a system is also promising with respect to the objective of minimizing the cost related to the energy that exceeds the local production from the micro-generation, in a scenario characterized by a time varying electricity tariff. Indeed the recognition of electricity product differentiation as a meaningful concept for the improvement of grid operation [6] has resulted in the possibility for consumers to choose among several pricing schemes characterized by different risk levels, based on their flexibility in electricity usage [7]; the higher the tariff variability during the day, and day by day, the higher the risk transfer from the retailer to the consumer [8], the higher the need of help for the consumer in order to optimize energy consumption [9]. Starting from designed tariffs such as the time of use (ToU) scheme, characterized every day by the same two or three fares (off-peak, on-peak and sometimes mid-peak [10]), the variability increases considering market indexed schemes such as day ahead pricing (DAP), where the hourly tariff is known on a day ahead basis, and real time pricing (RTP), where the cost of energy is updated during the day [11]. It is straightforward to look at ToU and DAP as basic forms of DSM; however, the implementation of the rigorous DSM concept, as defined in [12], requires the exchange of intra-day price/volume signals as additional feature, as a result of a trading in the balancing markets established in order to meet short-term requirements of the grid. As a matter of fact, RTP can be seen as a tariff scheme including DSM features. In the light of above, it is clear that a residential energy management system has to be able to manage loads taking into account information known in advance, and to react to real-time user needs and DSM signals, which implies the solution of a real time load shifting problem.

In this paper we establish an event driven model predictive control (MPC) approach for a local energy management system designed to optimally manage the resources of residential electricity prosumers, considering a dwelling equipped with a photovoltaic (PV) panel, a storage unit, smart household appliances and an electric vehicle (EV) with back-feeding capability. This paper provides the natural extension of the work presented in [13], which detailed the basic load-shifting control rationale of an EMS targeted for passive electricity consumers. The innovative contribution of the present paper regards the inclusion of the micro-generation unit, the electricity storage, and the EV into the EMS problem formulation, thus considering a reference scenario focused on electricity prosumers. Moreover, operation of devices is here coordinated according to different optimization criteria, such as cost minimization under ToU, DAP and RTP models, self-consumption maximization and automated overload avoiding. These objectives are met by dynamically assigning appliances start times, and optimally controlling the charging process of the storage unit and the EV. Our approach assures the respect of user preferences in the use of electric energy, and has the flexibility needed to meet the dynamics of real life in a household.

The remainder of the paper is organized as follows. In Section 2 the state of the art is discussed along with the proposed innovations. In Section 3 the system architecture is described. In Section 4 the control system is presented from a functional point of view. In Section 5 the mathematical formulation of the load shifting problem is given. Section 6 is dedicated to the presentation and discussion of simulation results. Finally, in Section 7 the conclusions are drawn.

2. State of the art and proposed innovation

Load management has received increasing attention from academics and industries during the last decade. Industry has been the driving sector, and the first one for which pioneer DSM programs have been deployed [14–16]. Even if load shifting criteria are strictly connected there to the productive process under control, the idea of re-optimizing arises as a way to manage disturbances and inaccurate system modeling. The same approach sounds reasonable also when thinking about load control in the residential sector, which is being faced at different scales with different granularity levels of control.