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Action dependent heuristic dynamic programming for home energy resource scheduling

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ABSTRACT

Energy management in smart home environment is nowadays a crucial aspect on which technologies have been focusing on in order to save costs and minimize energy waste. This goal can be reached by means of an energy resource scheduling strategy provided by a suitable optimization technique. The proposed solution involves a class of Adaptive Critic Designs (ACDs) called Action Dependent Heuristic Dynamic Programming (ADHDP) that uses two neural networks, namely the Action and the Critic Network. This scheme is able to minimize a given Utility Function over a certain time horizon. In order to increase the performances of the ADHDP algorithm, suitable Particle Swarm Optimization (PSO) based procedures are used to pretrain the weights of the Action and the Critic networks. The results provided by PSO techniques and by a non-optimal baseline approach are also used as elements of comparison. Computer simulations have been carried out in different residential scenarios. An historical data set for solar irradiation has been used to simulate the behavior of a photovoltaic array to obtain renewable energy and the main grid is used to supply the load and charge the battery when necessary. The results confirm that the ADHDP is able to reduce the overall energy cost with respect to the baseline solution and the PSO techniques. Moreover, the validity of this method has also been shown in a more realistic context where only forecasted values of solar irradiation and electricity price can be used.
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1. Introduction

In the last decade the price of oil and others fossil fuels has quickly increased and most of the world countries have been developed new policies to reduce the energy costs and the pollution impact. There is a certain variety of renewable resources that can provide energy production; however wind and solar power sources are undoubtedly the most used worldwide.

The former has recently increased its diffusion not only in U.S. [1] but also in several other countries. The main advantages of this technology are the high efficiency of the wind based systems, the absence of gas production, the short payback time and the very low costs of maintenance and dismantling of the wind system. On the other side, the main limitations are represented by the acoustic noise produced by the wind turbines and the fact that in several places the wind availability is sporadic or simply not enough.

The solar power is typically exploited by means of photovoltaic (PV) systems. With respect to other resources, the solar one has some relevant advantages, as the fact that all locations on earth receive predictable solar irradiation. Moreover, the PV systems can be easily scaled from large to small sizes, and they are often employed in home environments because they have no moving parts and they need only a little maintenance. Such systems typically present lower efficiency with respect to the ones exploiting wind power and thus a longer payback period. It follows that an important issue consists in optimizing the usage of produced PV electrical energy and its delivering to the grid in order to reduce the overall energy cost under different operating conditions.

Along this same direction, the aim of aligning the interests of electric utilities, consumers and environmentalists [2–9], the development of advanced technological solutions for the *smart grid* has encountered an increasing success within the research community in the last years. The advanced technologies find application in various grid environments, going from the micro scenarios, like houses and neighborhoods, to the large scale systems for production and distribution. Moreover, several commercial products have already appeared and more will come in the future, as confirmed by recent market trends [10].

This work deals with a domestic scenario where an electrical grid connection, a PV system and a suitable storage system (called

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simply battery from now on) coexist. The goal consists in satisfying the electrical load requirements over time by optimally managing the electrical power produced from the PV panel, the battery charge/discharge actions and the amount of electrical power acquired from the main grid. In this way the overall energy costs can be reduced.

In this paper we name the addressed problem as *Energy Resource Scheduling*, to differentiate it from the *Energy Task Scheduling* (or Energy Consumption Scheduling) one, whose main objective consists in allocating the temporal activity of household appliances according to some strategy. The large variety of solutions recently proposed for the Energy Task Scheduling issue, like [11–13] do not seem to include an optimal Energy Resource Scheduling policy therein. It represents thus an interesting topic to investigate in the near future.

Focusing on the specific problem addressed in this paper, several techniques have been proposed in the literature. A dynamic programming approach is used in [14,15] whereas a genetic algorithm is proposed in [16]. Moreover, Liu and Huang [17] have recently advanced an Adaptive Dynamic Programming (ADP) basic scheme using only a Critic Network and considering only three possible controls for the battery (charging mode, discharging mode, idle) choosing the best for every time slot. Venayagamoorthy and Welch also made use of the ADP paradigm to perform an Energy Resource Scheduling strategy in isolated electrical systems [18–20].

Up to the authors' knowledge, the most performing approach to deal with the Energy Resource Scheduling problem is the Particle Swarm Optimization (PSO), available in the literature in its online version: given a Utility Function to minimize, given some constraints, through certain "particles" that explore all the solutions space, the algorithm is able to find the best solution for the problem under test. Gudi et al. in [21] proposed an optimal management of renewable resources with PSO using an Utility Function able to charge the battery only from the PV system, not considering the charging from the main grid; furthermore the battery is constrained to discharge itself only in fixed "peak hours", when the electricity price or the load demand are high. Although this method provides a solution at a low computational cost, it is not able to work over an extended temporal horizon, but only step by step.

To reach the same goal an operational scheme with self-learning ability can be developed to optimize home energy systems according to system configuration and user demand. This method is based on a class of Adaptive Critic Designs (ACDs) called Action Dependent Heuristic Dynamic Programming (ADHDP) and it has the capability to learn from the environment [22]. The ADHDP uses two neural networks, an Action Network (which provides the control signals) and a Critic Network (which criticizes the Action Network performance). An optimal control policy is evolved by the Action Network over a time period using the feedback signals provided by the Critic Network. The goal of the control policy is to minimize the amount of energy imported from the grid, represented in a Utility Function, according to some given constraints, managing the battery action and knowing the state of the system in terms renewable energy resources, load profile and electricity price. The chosen Utility Function must be an index of system costs, so that when such a function is minimized the Action Network is able to provide an optimal control to keep the energy costs over the work horizon low. From this perspective and at the light of the theoretical properties of the ADHDP optimization framework [23,22], the implemented strategy for smart home Energy Resource Scheduling can be considered optimal.

The innovative solution advanced in this paper (and preliminary investigated in [24]) is to consider an ADHDP based algorithm where the neural networks weights are pre-trained with online or offline PSO algorithms. The first one, mentioned above, cannot work over an extended horizon but only step by step, while the second one, here proposed for the first time, has to minimize an extended Utility Function and it can work over a larger time horizon. This combined technique, compared with a baseline approach, is able to provide relevant results in terms of monetary saving. The proposed PSO methods are used in this paper to pre-train the ADHDP neural networks and also as element of comparison in performed computer simulations.

Computer simulations show that results provided by the ADHDP algorithm, pre-trained with PSO Offline, are the best in terms of saving, if compared to ADHDP pre-trained with PSO Online. Naturally the results outperform also the ones obtained with the baseline approach and the PSO algorithms. All performed simulations are made considering historical data for solar irradiation, but in order to make the simulated scenario closer to real case studies also uncertain forecasted data have been considered. In this case the uncertainty of the data affects the final results and reduce the attainable saving; anyway the effectiveness of the approach is still ensured.

Moreover it must be said that the proposed algorithm is much more general of the aforementioned recent ADP based techniques for smart home energy management. Indeed, on one side it allows to apply a continuous control to the battery activity, rather than the discrete control in [17], and, on the other, it is able to work also in presence of grid-connected system, taking the electricity price into account, which is not the case of the algorithms in [18–20].

Here the outline of the paper follows. Section 2 describes the considered energy system in home environment, Section 3 proposes the PSO scheme with a brief theoretical preface. In Section 4 the optimal-control ADHDP scheme is shown, the used neural networks are described and the training algorithm is explained. The computer simulations, carried out using both historical and forecasted data for solar irradiation and unitary energy prize, are described in Section 5 and related results reported therein. Conclusions are drawn in Section 6, where some future works ideas are also highlighted.

2. Simulated home energy system

The simulated home energy system is composed of four different parts: main electrical grid, external PV array, the battery and a Power Management Unit (PMU). The main electrical grid and the external PV array (able to convert solar energy in electrical one) can supply the load and/or charge the battery. Furthermore the energy in surplus from photovoltaic system can be sold to the grid. On the other hand the battery system can operate in one of the following modes:

- Charge from the grid and/or from the PV: the battery is charged with an energy quantity according to the battery charging rate (Table 1).
- Discharge: the battery supplies the load discharging itself of an energy quantity according to battery discharging rate (Table 1).
- Inactive: no energy quantity is exchanged with external systems.

As reported in Fig. 1, the PMU unit manages the energy flows described above, assuring the meeting of load demand over time.

Table 1
Battery parameters. Operating voltage is assumed to be equal to 48 V.

η	BL_0	BL_{MIN}	BL_{MAX}	Ch_{rate}/Dh_{rate}
95%	5 kW h	0.5 kW h	10 kW h	±1 kW

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