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Hybrid time representation for the scheduling of energy supply and demand in smart grids

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Abstract

A new optimization model is presented for the short-term management of the energy supply and demand in smart grids. The detailed model includes a flexible demand profile in order to manage the energy requirements by incorporating penalizations in the economic objective function for delays in satisfying energy demand. The MILP model for the optimization of deterministic scenarios is reformulated in order to incorporate discrete and hybrid time representations. This approach allows considering a different granularity of the problem. Finally, the improved performance of the hybrid approach introduced is shown by comparing the performance of these two time representations.

Keywords: Energy systems; Energy management, control and optimization; Distributed generation and active demand; Energy storage; Smart cities and smart buildings.

1. Introduction

The interest in energy from renewable sources has increased in recent years, due to the price of fossil fuels, energy losses in long-distance transmission and environmental concern. These aspects involve the traditional power grid model, which is based in a static network, where large power plants generate electricity to be used posteriorly at industrial or domestic level (Wang, 2009).

Smart grids are typically decentralized systems and located near the consumption points. These grids usually generate energy from renewable sources. The use of these sources with low greenhouse emissions can be used in order to solve the massive energy demand with a tolerable climatic impact. However, renewable sources are not fully exploited, due to their intermittent behaviours and the unreliability of current forecast techniques, especially in photovoltaic panels systems and wind turbine systems.

Moreover, smart grids use information and communication technology to fully monitor and control production and demand levels. Thus, smart meters (Krishnan, 2008) have been developed for the availability of reliable information. The benefits of smart meters include, the proactive maintenance, the reduction of adverse events, as blackouts, or customer savings (Krishnamurti, 2012), and finally customers access to real-time information could allow smart consumption behaviour. The use of these devices allows the demand side management, by introducing the possibility of shifting some loads in order to optimize the production and distribution profiles in terms of efficiency, economics and sustainability.

The use of storage systems is a requirement to decouple production and demand, and to cope with the fluctuating availability of the related renewable resources, providing more flexibility to the system. Hence, it is essential an energy planning and scheduling tool, considering generation, storage and consumption of energy, and allowing an integrated management of energy demand and energy production.

Energy planning in process industries using aggregated models has also been presented (Zondervan, 2010). Also, an energy management system in order to determine the production and storage levels to satisfy a deterministic energy demand (Zamarripa, 2011) is related to this article. And finally Mehleri *et al.* (2012) presented a mixed-integer linear programming approach for the optimal design of a smart grid, considering heat and power demand

The system under study consists of a set of physical elements which includes resources and demands and a set of decisions that define the managerial problem. Moreover, it is worthy to mention that, in the presented case study, although data related to production and storage is obtained every 15 minutes, each device can start its consumption in any time. This is a hybrid time representation that has been included in the mathematical model in order to determine the short-term scheduling producing the optimal energy management.

2. Problem statement

The problem and its formulation considers not only the production and storage levels to be managed by the smart grid, but also the management of the energy consumption in order to minimize the total cost.

The mathematical model contemplates the energy balance equations or constraints, which describes the energy flows, generation, storage and consumption, and also the unit constraints associated to the equipment and technologies involved in the smart grid. Energy production is specified by equation 1: for each source (*i*) and time interval (*t*) the binary variable ($X_{i,t}$) indicates if the source is being used or not. Equation 2 represents the energy flow through the storage system (*k*) where storage level ($SE_{k,t}$) and the input energy flows ($SP_{k,t}$) and supply flows ($Load_{k,t}$) are represented. The energy required for each consumer (*j*) at every consumption repetition (*f*) is calculated by equation 3. Equation 4 is the general energy balance constraint.

$$P_{i,t}{}^{min} \cdot X_{i,t} \leq P_{i,t} \leq P_{i,t}{}^{max} \cdot X_{i,t} \qquad \forall i,t \tag{1}$$

$$SP_{k,t} - Load_{k,t} = SE_{k,t-1} - SE_{k,t} \qquad \forall k,t \tag{2}$$

$$Dem_t = \sum_{j=1}^{J} \sum_{f \in J_f}^{J_f} Cons_{j,f} \cdot DT \cdot TDem_{j,f,t} \qquad \forall t \tag{3}$$

$$\sum_{k=1}^{K} SP_{k,t} + \sum_{i=1}^{I} P_{i,t} \cdot DT - DemTot_t - \sum_{k=1}^{K} Load_{k,t} = 0 \qquad \forall t \tag{4}$$

Time representation of this formulation is a hybrid combination between a discrete supply treatment and continuous demand behaviour. The fixed discrete time representation is based in a previous approach (Silvente, 2012), where decisions in terms of production, storage and consumptions are taken every 15 minutes. However, a hybrid time representation has been developed to incorporate the possibility of starting any consumption at any time, and having time consumptions larger or smaller than a given set of time intervals.

The following equations (5-8) locate the start consumption time ($Ts_{j,f}$) and the final consumption time ($Tf_{j,f}$) at the beginning and at the end of each consumption *jf*. The binary variable (Y_{jft}) is active when energy consumption *jf* starts at time slot *t*. Accordingly, (Z_{jft}) is active when energy consumption *jf* finishes at time slot *t*. These logical restrictions can be reformulated as a set of Big-M constraints:

$$\left(t - Ts_{j,f}\right) - \left(1 - Y_{j,f,t}\right) \cdot M \leq 0 \qquad \forall j, f \in J_f, t \tag{5}$$

$$\left(t + 1 - Ts_{j,f}\right) + \left(1 - Y_{j,f,t}\right) \cdot M \geq 0 \qquad \forall j, f \in J_f, t \tag{6}$$

$$\left(t - Tf_{j,f}\right) - \left(1 - Z_{j,f,t}\right) \cdot M \leq 0 \qquad \forall j, f \in J_f, t \tag{7}$$

$$\left(t + 1 - Tf_{j,f}\right) + \left(1 - Z_{j,f,t}\right) \cdot M \geq 0 \qquad \forall j, f \in J_f, t \tag{8}$$

The following equations represent the different ways to consider the demand of the discrete period. Taking into account the treatment of continuous demand, each consumption fraction needs to be assigned to its time interval. Equation 9 represents the possibility of a consumption active during the whole interval. The consumption started during the interval *t* is bounded by equation 10; the consumption finished during interval *t* is bounded by equation 11: and the energy consumption started and finished within interval *t* is constrained by equation 12.

$$TDem_{j,f,t} \geq \ (t + 1 - t) - M \cdot \left(1 - W_{j,f,t} + Y_{j,f,t} + Z_{j,f,t}\right) \qquad \forall j, f \in J_f, t \tag{9}$$

$$TDem_{j,f,t} \geq \ \left(t + 1 - Ts_{j,f}\right) - M \cdot \left(1 - W_{j,f,t} - Y_{j,f,t} + Z_{j,f,t}\right) \qquad \forall j, f \in J_f, t \tag{10}$$

$$TDem_{j,f,t} \geq \ \left(Tf_{j,f} - t\right) - M \cdot \left(1 - W_{j,f,t} + Y_{j,f,t} - Z_{j,f,t}\right) \qquad \forall j, f \in J_f, t \tag{11}$$

$$TDem_{j,f,t} \geq \ \left(Tf_{j,f} - Ts_{j,f}\right) - M \cdot \left(1 - W_{j,f,t} - Y_{j,f,t} - Z_{j,f,t}\right) \qquad \forall j, f \in J_f, t \tag{12}$$

Finally, the economic objective function to be minimized is subject to constraints regarding production, storage and penalty costs arising in case of deviation from the target for each energy consumer, as reported previously (Silvente, 2012).

$$Cost = CostPro + CostSto + CostPen \tag{13}$$

3. Case study

This case study (Silvente, 2012) takes into account several appliances, with different consumptions. These energy consumptions are modelled allowing a certain delay, depending on the availability and demand of energy. Each device has associated a penalty cost, to be applied in case of deviation from the target. The objective of this case study is to optimize the management of the energy generation, storage and consumption of the appliances within a single household.

The renewable energy sources include a set of photovoltaic panels and a micro-wind turbine. In addition to renewable sources, a diesel generator and the connection to the Grid are also considered. Moreover, batteries are also considered for energy storage.

The problem to be solved includes energy production, storage and consumption patterns. Data and decisions related to energy production are taken according to energy demand and a deterministic weather forecast.

Energy demand management has been addressed through two approaches: discrete and hybrid time representation. According the first point of view, decisions related to energy production are considered every 15 minutes, as well as energy demand decisions. The time horizon considered is 24 hours, thus resulting 96 time slots. However, the more realistic hybrid time approach considers that the energy consumptions can start and finish at any time, not only every 15 minutes, thus improving the flexibility of the model.

4. Results and discussion

The main advantage of this hybrid methodology is a greater flexibility with the demand management. Considering shifting demands is an achievement of this work, as well as the fact that consumptions are not forced to be located according to the time intervals. Therefore, the energy consumed is capable to be allocated proportionally at the corresponding interval.

Different scenarios have been considered in order to explore the possibilities of the problem formulation introduced. The scenarios are those obtained by having no energy demand management, by the totally discrete time approach and the hybrid approach proposed, which obtains an important improvement.

The power availability considered for this case study is observed in Figure 1.

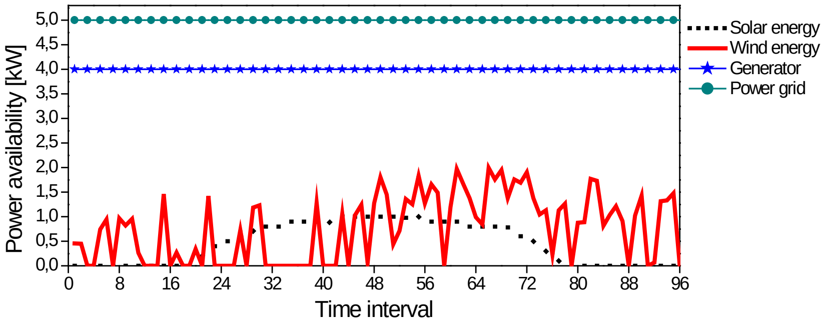

Figure 1. Power availability.

4.1. No demand side management

The first scenario is based in a discrete time formulation. In particular, energy demand management was not taken into account, so no energy load can be shifted. Optimal production is only determined by the lower cost energy available at the same fixed interval of consumption. The necessary purchase of energy to the grid is the main reason for increasing the total cost (objective function). This case has the highest cost as it shows Table 1.

4.2. Demand side management using totally discrete time representation

In the second scenario, the possibility of delaying consumptions is considered with the aim to use renewable and cheaper energy sources. This option includes a penalty cost for each load in case time bounds of each consumption are exceeded, which is still lower than the cost of power grid. In this case, energy purchases to the power grid are not required to satisfy the total energy demand which means a decrease in the power acquisition cost (Table1).

4.3. Demand side management using hybrid time representation

A third scenario is considered in which the model is solved for a more realistic case, considering that starting and finishing times and durations of consumptions may have non-integer values. Figure 2 illustrates that the purchase of energy to the power grid is not required to satisfy the energy demand, fulfilling the associated constraints. Moreover, the value of the objective function is increased, since each load can carry out any consumption at any instant of time (not only at the beginning of a time interval), reducing the penalty cost due to a decrease in the delay of consumptions (Figure 2). The demand schedule is observed also in Figure 2 and shows the optimal consumption interval for each energy device.

Table 1. Comparison of the different problems characteristics

	No demand side management	Discrete approach	Hybrid approach
Objective function	2.932770	0.5052077	0.0000653
Equations	82.715	82.715	459.704
Continuous variables	70,914	70,914	356,706
Discrete variables	33,338	33,338	33,338
Computational time	6,000	6,016	8,937

4.4. Discussion

The MILP model was implemented in GAMS (Rosenthal, 2012) and solved, using CPLEX, to optimality (gap of 0%) in Intel® Core™ i5 CPU 650 @ 3.20 GHz.

It is worthy to mention that the discrete model divides the whole day in 96 intervals of 15 min. The output variables and the characteristic parameters are related to these intervals. With the aim to adapt the common consumptions to this structure, important constraints are implemented. Furthermore, an overlap impediment constraint is created to avoid inconsistent results. Also, in the discrete model, the demand is fixed at the beginning or at the end of each period. This model allows only starting and finishing consumptions at the beginning and at the end of the time interval. Finally, in the hybrid model**,** the time demand is free to start in any moment. The discretization does not affect the consumption that belongs to real time. In the same way, the consumption durations are not required to be an integer value. Table 1 shows that, although the two representations involve the same number of discrete variables, the discrete time representation model requires fewer equations and less continuous variables that the hybrid representation, involving less computational time. Moreover, it is worthy to remark that for the same input parameters, the value of the objective function is the same for the two representations.

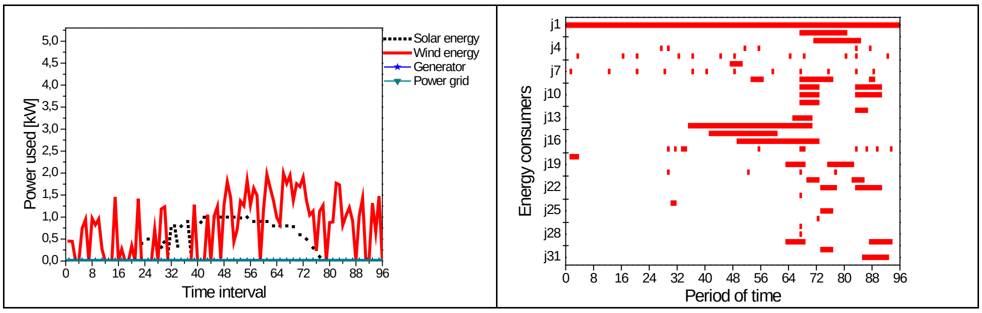

Figure 2. Power production and demand scheduling for 96 time intervals of the day.

5. Conclusions

This work addresses the short-term scheduling of a smart grid in order to determine optimal decisions in terms of energy production and consumption by minimizing the total economic cost, using discrete and hybrid time representations, which are compared. The results demonstrate that the system can be modelled, with high level of detail, for a short term horizon. Moreover, this approach proves the advantages of managing the energy demand, by reducing the total cost and improving its flexibility. In addition, modelling using hybrid time representation allows the incorporation of more realistic parameters, without discrete-value constraints, which improves the robustness of the model, but increases the computational time and the number of equations. Further work is required in order to improve the current model, by incorporating uncertainty related to weather conditions and electricity prices, and also to incorporate energy sales.

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