Energy resources management in three distinct time horizons considering a large variation in wind power

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Abstract

The intensive use of distributed generation based on renewable resources increases the complexity of power systems management, particularly the short-term scheduling. Demand response, storage units and electric and plug-in hybrid vehicles also pose new challenges to the short-term scheduling. However, these distributed energy resources can contribute significantly to turn the short-term scheduling more efficient and effective improving the power system reliability.

This paper proposes a short-term scheduling methodology based on two distinct time horizons: hour-ahead scheduling, and real-time scheduling considering the point of view of one aggregator agent. In each scheduling process, it is necessary to update the generation and consumption operation, and the storage and electric vehicles status. Besides the new operation condition, more accurate forecast values of wind generation and consumption are available, for the resulting of short-term and very short-term methods. In this paper, the aggregator has the main goal of maximizing his profits while, fulfilling the established contracts with the aggregated and external players.

Nomenclature

Δt	Elementary period (h)
$\eta_{c(ST)}$	Storage charge efficiency
$\eta_{c(V)}$	Grid-to-vehicle efficiency
$\eta_{d(ST)}$	Storage discharge efficiency
$\eta_{d(V)}$	Vehicle-to-grid efficiency
$\theta_{i(t)}$	Voltage angle at bus i in period t (rad)
θ_i^{max}	Maximum voltage angle at bus i (rad)
θ_i^{min}	Minimum voltage angle at bus i (rad)
$\theta_{j(t)}$	Voltage angle at bus j in period t (rad)
φ	Phase angle of the load L
B_{ij}	Imaginary part of the element in admittance matrix corresponding to the row i and column j (S)
C	VPP operation costs (m.u.)
f	Objective function (m.u.)
G_{ij}	Real part of the element in admittance matrix corresponding to row i and column j (S)
In	VPP income (m.u.)
L^i	Set of line connected to bus i
$c_{Cut(L,t)}$	Demand response curtailment cost of load L in period t (m.u./Wh)
$c_{Dch(ST,t)}$	Discharge cost of storage ST in period t (m.u./Wh)
$c_{Dch(V,t)}$	Discharge cost of electric vehicle V in period t (m.u./Wh)
$c_{DG(DG,t)}$	Generation cost of DG unit in period t (m.u./Wh)
$c_{GCP(DG,t)}$	Generation curtailment power cost of DG unit in period t (m.u./Wh)
$c_{NSD(L,t)}$	Non-supplied demand cost of load L in period t (m.u./Wh)
$c_{Red(L,t)}$	Demand response reduction cost of load L in period t (m.u./Wh)
$c_{SP(SP,t)}$	Energy price of the external supplier SP in period t (m.u./Wh)
$E_{BatCap(ST)}$	Battery energy capacity of storage unit ST (Wh)
$E_{BatCap(V)}$	Battery energy capacity of electric vehicle V (Wh)
$E_{MinCh(ST,t)}$	Minimum stored energy of storage unit ST (Wh)
$E_{MinCh(V,t)}$	Minimum stored energy to be guaranteed at the end of period t, for electric vehicle V (Wh)
$E_{Stored(ST,t)}$	Energy stored in storage unit ST at the end of period t (Wh)
$E_{Stored(V,t)}$	Energy stored in electric vehicle V at the end of period t (Wh)
$E_{Trip(V,t)}$	Energy consumption during a trip of the electric vehicle V in period t (Wh)
$MP_{Ch(ST,t)}$	Market price for the charge process of storage ST in period t (m.u./Wh)
$MP_{Ch(V,t)}$	Market price for the charge process of vehicle V in period t (m.u./Wh)
$MP_{Load(L,t)}$	Market price of load L in period t (m.u./Wh)
$MP_{Sell(t)}$	Market price of selling energy to the market unit in period t (m.u./Wh)
N_B	Total number of buses
N_{DG}	Total number of distributed generators
N_{DG}^i	Total number of units DG for bus i
N_L	Total number of loads
N_L^i	Total number of loads L for bus i
N_K	Total number of lines
N_{ST}	Total number of storage units
N_{ST}^i	Total number of storage units ST for bus i

N_{SP}	Total number of external suppliers
N_{SP}^{i}	Total number of external suppliers *SP* for bus *i*
N_{V}	Total number of electric vehicles
N_{V}^{i}	Total number of electric vehicles *V* for bus *i*
$P_{Ch(ST,t)}$	Active power charge of storage *ST* in period *t* (W)
$P_{Ch(ST,t)}^{i}$	Active power charge of storage units *ST* at bus *i* in period *t* (W)
$P_{Ch(V,t)}$	Active power charge of electric vehicle *V* in period *t* (W)
$P_{Ch(V,t)}^{i}$	Active power charge of electric vehicle *V* at bus *i* in period *t* (W)
$P_{ChLimit(ST,t)}$	Maximum active power charge of storage unit *ST* in period *t* (W)
$P_{ChLimit(V,t)}$	Maximum active power charge of electric vehicle *V* in period *t* (W)
$P_{Cut(L,t)}$	Active power of demand response curtailment of load *L* in period *t* (W)
$P_{Cut(L,t)}^{i}$	Active power of demand response curtailment of load *L* at bus *i* in period *t* (W)
$P_{Dch(ST,t)}$	Active power discharge of storage *ST* in period *t* (W)
$P_{Dch(ST,t)}^{i}$	Active power discharge of storage unit *ST* at bus *i* in period *t* (W)
$P_{Dch(V,t)}$	Active power discharge of electric vehicle *V* in period *t* (W)
$P_{Dch(V,t)}^{i}$	Active power discharge of electric vehicle *V* at bus *i* in period *t* (W)
$P_{DchLimit(ST,t)}$	Maximum active power discharge of storage unit *ST* in period *t* (W)
$P_{DchLimit(V,t)}$	Maximum active power discharge of electric vehicle *V* in period *t* (W)
$P_{DchMin(ST,t)}$	Minimum active power discharge of storage unit *ST* in period *t* (W)
$P_{DchMin(V,t)}$	Minimum active power discharge of electric vehicle *V* in period *t* (W)
$P_{DG(DG,t)}$	Active power generation of *DG* unit in period *t* (W)
$P_{DG(DG,t)}^{i}$	Active power generation of *DG* unit at bus *i* in period *t* (W)
$P_{Di(t)}$	Active power demand at bus *i* in period *t* (W)
$P_{DGMax(DG,t)}$	Maximum active power generation of *DG* unit in period *t* (W)
$P_{DGMin(DG,t)}$	Minimum active power generation of *DG* unit in period *t* (W)
$P_{GCP(DG,t)}$	Generation curtailment power by *DG* unit in period *t* (W)
$P_{GCP(DG,t)}^{i}$	Generation curtailment power by *DG* unit at bus *i* in period *t* (W)
$P_{Gi(t)}$	Active power generation at bus *i* in period *t* (W)
$P_{Load(L,t)}$	Active power demand of load *L* in period *t* (W)
$P_{Load(L,t)}^{i}$	Active power demand of load *L* at bus *i* in period *t* (W)
$P_{MaxCut(L,t)}$	Maximum DR curtailment of load *L* in period *t* (W)
$P_{MaxRed(L,t)}$	Maximum DR reduction of load *L* in period *t* (W)
$P_{MinCut(L,t)}$	Minimum DR curtailment of load *L* in period *t* (W)
$P_{MinRed(L,t)}$	Minimum DR reduction of load *L* in period *t* (W)
$P_{NSD(L,t)}$	Active non-supplied demand for load *L* in period *t* (W)
$P_{NSD(L,t)}^{i}$	Active non-supplied demand for load *L* at bus *i* in period *t* (W)
$P_{Red(L,t)}$	Active power of demand response reduction of load *L* in period *t* (W)
$P_{Red(L,t)}^{i}$	Active power of demand response reduction of load *L* at bus *i* in period *t* (W)
$P_{Sell(t)}$	Active power sell to market of VPP in period *t* (W)
$P_{Sell(t)}^{i}$	Active power sell to market of VPP at bus *i* in period *t* (W)
$P_{SP(SP,t)}$	Active power generation of the external supplier *SP* in period *t* (W)
$P_{SP(SP,t)}^{i}$	Active power generation of the external supplier *SP* at bus *i* in period *t* (W)
$P_{SPMax(SP,t)}$	Maximum active power of the external supplier *SP* in period *t* (W)
$P_{SPMin(SP,t)}$	Minimum active power of the external supplier *SP* in period *t* (W)
$Q_{DG(DG,t)}^{i}$	Reactive power generation of *DG* unit at bus *i* in period *t* (VAr)
$Q_{Di(t)}$	Reactive power demand at bus *i* in period *t* (VAr)
$Q_{DGMax(DG,t)}$	Maximum reactive power generation of *DG* unit in period *t* (VAr)
$Q_{DGMin(DG,t)}$	Minimum reactive power generation of *DG* unit in period *t* (VAr)
$Q_{Gi(t)}$	Reactive power generation at bus *i* in period *t* (VAr)
$Q_{Load(L,t)}^{i}$	Reactive power demand of load *L* at bus *i* in period *t* (VAr)
$Q_{NSD(L,t)}^{i}$	Reactive non-supplied demand for load *L* at bus *i* in period *t* (VAr)
$Q_{SP(SP,t)}^{i}$	Reactive power generation of the external supplier *SP* at bus *i* in period *t* (VAr)
$Q_{SPMax(SP,t)}$	Maximum reactive power of the external supplier *SP* in period *t* (VAr)
S_{Lk}^{max}	Maximum apparent power flow established in line *k* that connect buses *i* and *j* (VA)
T	Total number of periods
$\overline{U_{i(t)}}$	Voltage at bus *i* in polar form in period *t* (V)
$\overline{U_{j(t)}}$	Voltage at bus *j* in polar form in period *t* (V)
$V_{i(t)}$	Voltage magnitude at bus *i* in period *t* (V)
V_{i}^{max}	Maximum voltage magnitude at bus *i* (V)
V_{i}^{min}	Minimum voltage magnitude at bus *i* (V)
$V_{j(t)}$	Voltage magnitude at bus *j* in period *t* (V)
$X_{Ch(ST,t)}$	Binary variable of storage unit *ST* related to power charge
$X_{Ch(V,t)}$	Binary variable of electric vehicle *V* related to power charge
$X_{Cut(L,t)}$	Binary variable of DR curtailment of load *L* in period *t*
$X_{Dch(ST,t)}$	Binary variable of storage unit *ST* related to power discharge
$X_{Dch(V,t)}$	Binary variable of electric vehicle *V* related to power discharge
$X_{DG(DG,t)}$	Binary variable of *DG* unit in period *t* (connected or disconnected)
$\overline{y_{ij}}$	Series admittance of line that connect the buses *i* and *j* in polar form (S)
$\overline{y_{sh\_i}}$	Shunt admittance of line connected in bus *i* in polar form (S)
$\overline{y_{sh\_j}}$	Shunt admittance of line connected in bus *j* in polar form (S)

1. Introduction

The power system faces new challenges in this century due to the massive use of Distributed Energy Resources (DERs), mainly Distributed Generation (DG) based on Renewable Energy Sources (RES). The planning and operation of the electric network became more complex with the introduction of dispersed generators [1, 2]. In the past years, the investment in RES increased significantly and electric networks need to manage effectively these new resources. Therefore, it is essential to develop new methodologies to help managing the electric network considering an intensive use of DERs [3, 4].

The renewable resources are characterized by an intermittent behavior, mainly the photovoltaic and wind generators [5]. This intermittent performance brings new problems to the dispatch of the resources to supply the demand, because the generation needs to be equal to the demand at each instant. Currently, the optimization methods are not adequate to face the challenges of DERs and even with all the undertaken research work some DER problems still remain [6]. In the short-term Energy Resource Management (ERM), the current state-of-the-art does not present the best answers to solve DER management problems, mainly due to the intermittent nature of the renewable resources.

Virtual Power Players (VPPs) are players that aggregate several energy resources, mainly at the distribution level [7]. The aggregation of DERs can be seen as an important strategy to improve the management of these resources. In the proposed methodology, it is considered that the VPP can manage a high number of DERs, such as DG units, storage units, demand response programs and electric vehicles [8, 9, 10].

The short-term ERM is essential to the future power systems, namely in the smart grid context. VPPs will require the use of a methodology to solve properly the short-term ERM problem [11, 12]. The short-term ERM obtains the optimal scheduling of the available DERs considering a short period of optimization (e.g., 5-minute periods). Other important aspect is the reschedule of the previously obtained schedule using the most recent forecast of the energy resources [11]. The hour-ahead scheduling serves as a set point to the short-term ERM, in which the results should be closer to the ones obtained in the hour-ahead scheduling. In the hour-ahead scheduling, the day-ahead results are used as a reference.

The main focus of this paper is to present a methodology to deal with the short-term management of DERs in a distribution network considering an intensive use of wind penetration. The wind power has a stochastic behavior, especially in the very short-term (e.g., over any given hour, 30-minute, 15-minute period) [12]. The proposed methodology solves the short-term optimal scheduling with the purpose of maximizing the VPP's profit.

The proposed methodology includes two phases. Firstly, the hour-ahead optimal scheduling solves the scheduling for the next hour considering the influence of the day-ahead schedule. Finally, the real-time optimal scheduling is conducted with 5 minutes of anticipation, taking into account the hour-ahead results and the most recent forecasts.

The paper is structured considering the following sections: section 1 presents the introduction; section 2 describes the proposed methodology and the mathematical formulation. Section 3 illustrates a case study involving the intensive use of wind generators in a distribution network. Finally, section 4 presents the most relevant conclusions of the paper.

2. ERM Methodology

The energy resource management has the purpose of finding the best scheduling for the available DERs of the VPP. The short-term ERM is important to improve the management of the DERs by the VPP. The short-term methodology helps the VPP changing the hour-ahead scheduling according to the most recent forecast values [6].

The massive integration of renewable resources introduces intermittency in the scheduling of the resources for the next day, that is, it is difficult to present an accurate day-ahead forecast of a wind generator. The short-term ERM improves the operation of the intermittent renewable resources with a more accurate control of the generation power.

2.1. Proposed methodology

The proposed methodology solves the short-term ERM problem with the objective of maximizing the VPP's profit. It is required to find a solution in a short period of time and to maximize the profit of the VPP.

As referred above, the proposed methodology manages DG units, storage units, demand response and electric vehicles. The architecture of the proposed methodology is shown in Figure 1, and it is divided into two phases: the Hour-ahead operation block and the Real-time operation block.

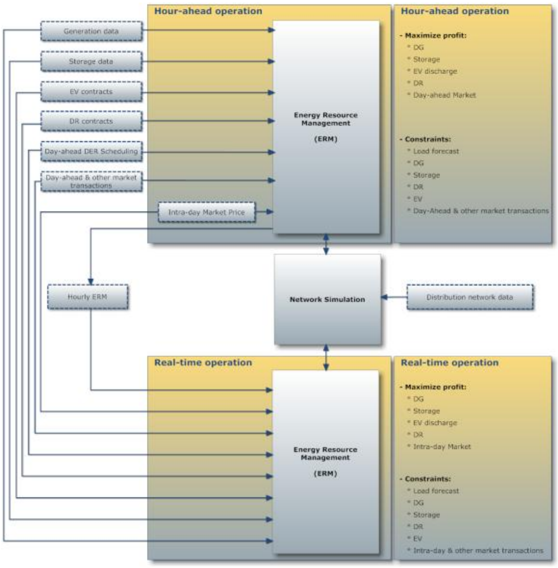

Figure 1: Proposed methodology (based on [13]).

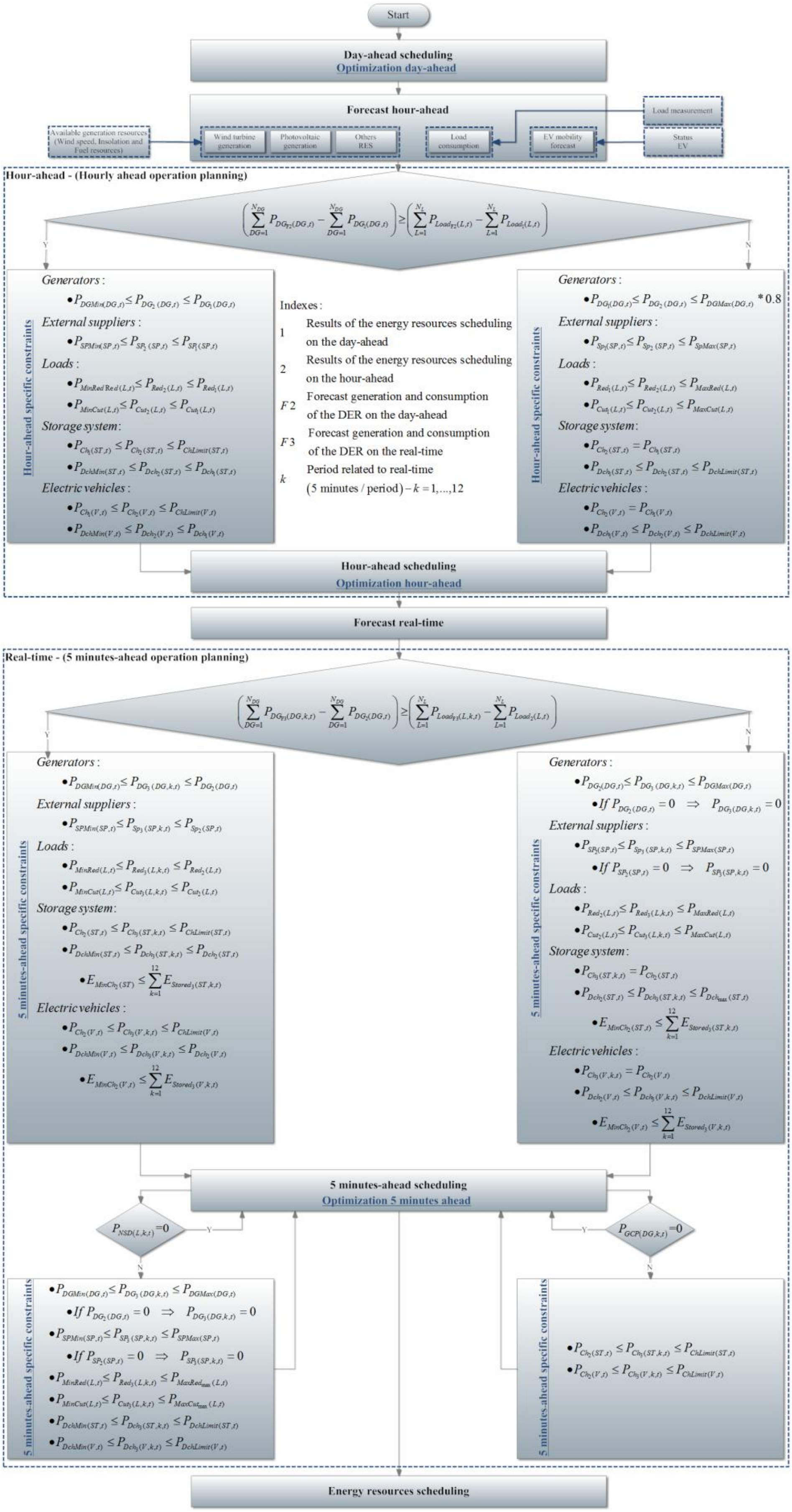

Figure 2: Flowchart of the constraints of the proposed methodology

The first block considers the day-ahead schedule and the most updated forecasts for the renewable resources and consumption. The optimization process regards the next hour, considering the objective of maximizing the VPP's profits. The second block runs for the following 5 minutes; the most updated forecasts are also considered. In this step, are only considered the resources that are connected to the network.

Figure 2 presents additional constraints which are added to the hour-ahead and real-time scheduling. The process begins by checking if the generation is greater than the consumption. It is necessary to determine the difference between the generation scheduling and forecast (the same happen to the consumption). This verification block divides the process into two different constraints blocks depending on a scenario with excess of generation or excess of consumption.

The behaviour of the resources in both scenarios is shown in Table 1. The DG units, external suppliers, demand response, storage discharge and EVs discharge reduce the power in the generation excess scenario and increase in the consumption excess scenario. The storage and EV charge must increase in the case of generation excess and must be equal in the consumption excess scenario.

Scenario **Resources**	**Generation excess**	**Consumption excess**
DG units	↙	↗
External suppliers	↙	↗
Demand response	↙	↗
Storage units charge	↗	–
Storage units discharge	↙	↗
Electric vehicles charge	↗	–
Electric vehicles discharge	↙	↗

Table 1: Hour-ahead and real-time conditions.

2.2. Mathematical formulation

The envisaged problem is a Mixed-Integer Non-Linear Programming (MINLP) problem. The VPP will be maximizing his own profits, which are determined by the income minus the operation costs, as shown in (1).

$$Maximize\ f = In - C \tag{1}$$

The VPP can receive his income from four sources, as illustrated in (2). The first source is the revenue from supplying the demand power to the consumers. The second one derives from selling energy to the electricity market. The third one is the revenue from the charging process of storage units. Finally, the last one also comes from the charging of electric vehicles.

$$In = \sum_{t=1}^{T} \begin{bmatrix} \sum_{L=1}^{N_L} MP_{Load(L,t)} \times P_{Load(L,t)} + MP_{Sell(t)} \times P_{Sell(t)} + \\ \sum_{ST=1}^{N_{ST}} MP_{Ch(ST,t)} \times P_{Ch(ST,t)} + \sum_{V=1}^{N_V} MP_{Ch(V,t)} \times P_{Ch(V,t)} \end{bmatrix} \tag{2}$$

Function *C* (3) calculates the operation cost of the resources managed by the VPP. It considers the cost with distributed generation, external suppliers, discharge of storage and EVs, demand response programs, penalization with non-supplied demand and penalization with *DG* units' generation curtailment.

$$C = \sum_{t=1}^{T} \begin{bmatrix} \sum_{DG=1}^{N_{DG}} c_{DG(DG,t)} \times P_{DG(DG,t)} + \sum_{SP=1}^{N_{SP}} c_{SP(SP,t)} \times P_{SP(SP,t)} + \\ \sum_{ST=1}^{N_{ST}} c_{Dch(ST,t)} \times P_{Dch(ST,t)} + \sum_{V=1}^{N_V} c_{Dch(V,t)} \times P_{Dch(V,t)} + \\ \sum_{L=1}^{N_L} c_{Cut(L,t)} \times P_{Cut(L,t)} + \sum_{L=1}^{N_L} c_{Red(L,t)} \times P_{Red(L,t)} + \\ \sum_{L=1}^{N_L} c_{NSD(L,t)} \times P_{NSD(L,t)} + \sum_{DG=1}^{N_{DG}} c_{GCPDG,t)} \times P_{GCP(DG,t)} \end{bmatrix} \tag{3}$$

The optimization problem uses the following constraints:

- The network active (4) and reactive (5) power balance with power loss at bus *i* in period *t*

$$\begin{aligned} P_{Gi(t)} - P_{Di(t)} &= V_{i(t)} \times \sum_{j \in L^i} V_{j(t)} \times \left(G_{ij} \cos\theta_{ij(t)} + B_{ij} \sin\theta_{ij(t)} \right) \\ &\quad + G_{ii} \times V_{i(i)}^2 \\ P_{Gi(t)} &= \sum_{DG=1}^{N_{DG}^i} \left(P_{DG(DG,t)}^i - P_{GCP(DG,t)}^i \right) + \sum_{SP=1}^{N_{SP}^i} P_{SP(SP,t)}^i \\ &\quad + \sum_{ST=1}^{N_{ST}^i} P_{Dch(ST,t)}^i + \sum_{V=1}^{N_V^i} P_{Dch(V,t)}^i \\ P_{Di(t)} &= \sum_{L=1}^{N_L^i} \left(P_{Load(L,t)}^i - P_{Cut(L,t)}^i - P_{Red(L,t)}^i - P_{NSD(L,t)}^i \right) + P_{Sell(t)}^i \\ &\quad + \sum_{ST=1}^{N_{ST}^i} P_{Ch(ST,t)}^i + \sum_{V=1}^{N_V^i} P_{Ch(V,t)}^i \\ &\forall t \in \{1,...,T\};\ \forall i \in \{1,...,N_B\};\ \theta_{ij(t)} = \theta_{i(t)} - \theta_{j(t)} \end{aligned} \tag{4}$$

$$\begin{aligned} Q_{Gi(t)} - Q_{Di(t)} &= V_{i(t)} \times \sum_{j \in L^i} V_{j(t)} \times \left(G_{ij} \sin\theta_{ij(t)} - B_{ij} \cos\theta_{ij(t)} \right) \\ &\quad - B_{ii} \times V_{i(t)}^2 \\ Q_{Gi(t)} &= \sum_{DG=1}^{N_{DG}^i} Q_{DG(DG,t)}^i + \sum_{SP=1}^{N_{SP}^i} Q_{SP(SP,t)}^i \\ Q_{Di(t)} &= \sum_{L=1}^{N_L^i} Q_{Load(L,t)}^i - \sum_{L=1}^{N_L^i} Q_{NSD(L,t)}^i \\ &\forall t \in \{1,...,T\};\ \forall i \in \{1,...,N_B\};\ \theta_{ij(t)} = \theta_{i(t)} - \theta_{j(t)} \end{aligned} \tag{5}$$

- Voltage magnitude (6) and angle (7) at bus *i* in period *t*

$$\begin{aligned} &V_i^{min} \le V_{i(t)} \le V_i^{max} \\ &\forall t \in \{1,...,T\};\ \forall i \in \{1,...,N_B\} \end{aligned} \tag{6}$$

$$\begin{aligned} &\theta_i^{min} \le \theta_{i(t)} \le \theta_i^{max} \\ &\forall t \in \{1,...,T\};\ \forall i \in \{1,...,N_B\} \end{aligned} \tag{7}$$

- Line thermal limit (8) at line *k* in period *t*

$$\begin{aligned} &\left| \overline{U_{i(t)}} \times \left[\overline{y_{ij}} \times \left(\overline{U_{i(t)}} - \overline{U_{j(t)}} \right) + \overline{y_{sh\_i}} \times \overline{U_{i(t)}} \right]^* \right| \le S_{Lk}^{max} \\ &\left| \overline{U_{j(t)}} \times \left[\overline{y_{ij}} \times \left(\overline{U_{j(t)}} - \overline{U_{i(t)}} \right) + \overline{y_{sh\_j}} \times \overline{U_{j(t)}} \right]^* \right| \le S_{Lk}^{max} \\ &\forall t \in \{1,...,T\};\ \forall i, j \in \{1,...,N_B\};\ i \ne j;\ \forall k \in \{1,...,N_K\} \end{aligned} \tag{8}$$

- Active (9) and reactive (10) generation limit for the *DG* unit in period *t*

$$\begin{gathered} P_{DGMin(DG,t)} \times X_{DG(DG,t)} \le P_{DG(DG,t)} \le P_{DGMax(DG,t)} \times X_{DG(DG,t)} \\ \forall t \in \{1,...,T\};\ \forall DG \in \{1,...,N_{DG}\} \end{gathered} \tag{9}$$

$$\begin{gathered} Q_{DGMin(DG,t)} \times X_{DG(DG,t)} \le Q_{DG(DG,t)} \le Q_{DGMax(DG,t)} \times X_{DG(DG,t)} \\ \forall t \in \{1,...,T\};\ \forall DG \in \{1,...,N_{DG}\} \end{gathered} \tag{10}$$

- Active (11) and reactive (12) generation limit for the external supplier *SP* in period *t*

$$P_{SP(SP,t)} \le P_{SPMax(SP,t)} \quad ; \ \forall t \in \{1,...,T\};\ \forall SP \in \{1,...,N_{SP}\} \tag{11}$$

$$Q_{SP(SP,t)} \le Q_{SPMax(SP,t)} \quad ; \ \forall t \in \{1,...,T\};\ \forall SP \in \{1,...,N_{SP}\} \tag{12}$$

- Demand response reduction (13) and curtailment (14) power limit for the load *L* in period *t*

$$\begin{gathered} P_{Red(L,t)} \le P_{MaxRed(L,t)} \\ \forall t \in \{1,...,T\};\ \forall L \in \{1,...,N_{L}\} \end{gathered} \tag{13}$$

$$\begin{gathered} P_{Cut(L,t)} \le P_{MaxCut(L,t)} \times X_{Cut(L,t)} \\ \forall t \in \{1,...,T\};\ \forall L \in \{1,...,N_{L}\} \end{gathered} \tag{14}$$

- Reactive demand power (15) for the load *L* in period *t*

$$\begin{gathered} Q_{Load(L,t)} = \left(P_{Load(L,t)} - P_{Red(L,t)} - P_{Cut(L,t)} - P_{NSD(L,t)}\right) \times \tan\varphi \\ \forall t \in \{1,...,T\};\ \forall L \in \{1,...,N_{L}\} \end{gathered} \tag{15}$$

- Battery balance (16) of storage unit *ST* in period *t*

$$\begin{gathered} E_{Stored(ST,t)} = E_{Stored(ST,t-1)} + \Delta t \times (\eta_{c(ST)} \times P_{Ch(ST,t)} \\ - \frac{1}{\eta_{d(ST)}} \times P_{Dch(ST,t)}) \\ \forall t \in \{1,...,T\};\ \forall ST \in \{1,...,N_{ST}\};\ \Delta t = 1 \end{gathered} \tag{16}$$

- Maximum stored energy (17) in the storage unit *ST* in period *t*

$$E_{Stored(ST,t)} \le E_{BatCap(ST)} \quad ; \ \forall t \in \{1,...,T\};\ \forall ST \in \{1,...,N_{ST}\} \tag{17}$$

- Charge and discharge processes are not simultaneous (18) in the storage unit *ST* in period *t*

$$\begin{gathered} X_{Ch(ST,t)} + X_{Dch(ST,t)} \le 1 \ ; \ \forall t \in \{1,...,T\};\ \forall ST \in \{1,...,N_{ST}\} \\ X_{Ch(ST,t)} \ and \ X_{Dch(ST,t)} \in \{0,1\} \end{gathered} \tag{18}$$

- Charge (19) and discharge (20) limits of the storage unit *ST* in period *t*

$$\begin{gathered} P_{Ch(ST,t)} \le P_{ChLimit(ST,t)} \times X_{Ch(ST,t)} \\ \forall t \in \{1,...,T\};\ \forall ST \in \{1,...,N_{ST}\} \end{gathered} \tag{19}$$

$$\begin{gathered} P_{Dch(ST,t)} \le P_{DchLimit(ST,t)} \times X_{Dch(ST,t)} \\ \forall t \in \{1,...,T\};\ \forall ST \in \{1,...,N_{ST}\} \end{gathered} \tag{20}$$

- Battery balance (21) of the electric vehicle *V* in period *t*

$$\begin{gathered} E_{Stored(V,t)} = E_{Stored(V,t-1)} - E_{Trip(V,t)} + \Delta t \times (\eta_{c(V)} \times P_{Ch(V,t)} \\ - \frac{1}{\eta_{d(V)}} \times P_{Dch(V,t)}) \\ \forall t \in \{1,...,T\};\ \forall V \in \{1,...,N_{V}\};\ \Delta t = 1 \end{gathered} \tag{21}$$

- Minimum and maximum stored energy (22) in the electric vehicle *V* in period *t*

$$\begin{gathered} E_{MinCh(V,t)} \le E_{Stored(V,t)} \le E_{BatCap(V)} \\ \forall t \in \{1,...,T\};\ \forall V \in \{1,...,N_{V}\} \end{gathered} \tag{22}$$

- Charge and discharge processes are not simultaneous (23) in the electric vehicle *V* in period *t*

$$\begin{gathered} X_{Ch(V,t)} + X_{Dch(V,t)} \le 1 \ ; \ \forall t \in \{1,...,T\};\ \forall V \in \{1,...,N_{V}\} \\ X_{Ch(V,t)} \ and \ X_{Dch(V,t)} \in \{0,1\} \end{gathered} \tag{23}$$

- Charge (24) and discharge (25) limits of the electric vehicle *V* in period *t*

$$\begin{gathered} P_{Ch(V,t)} \le P_{ChLimit(V,t)} \times X_{Ch(V,t)} \\ \forall t \in \{1,...,T\};\ \forall V \in \{1,...,N_{V}\} \end{gathered} \tag{24}$$

$$\begin{gathered} P_{Dch(V,t)} \le P_{DchLimit(V,t)} \times X_{Dch(V,t)} \\ \forall t \in \{1,...,T\};\ \forall V \in \{1,...,N_{V}\} \end{gathered} \tag{25}$$

3. Case study

This section presents a case study in a 33-bus distribution network. A projection for the year 2040 regarding the penetration of DG units is implemented in the network, as shown in Figure 3. It has been included a large wind farm in bus 1 of the distribution network to evaluate the impact of this wind farm in the short-term ERM problem. A single VPP is considered to manage the distribution network and the DERs connected to the network. The VPP can manage a large wind farm, 66 DG units, 10 external suppliers, 7 storage units, 218 consumers (with demand response programs) and 2000 electric vehicles. The information on all the DERs can be seen in Table 2.

The Generic Algebraic Modeling System (GAMS) software has been used to optimize the short-term ERM problem [14]. The proposed methodology has been tested on a PC compatible with an Intel Xeon W5450 3.00 GHz processor, with 8 Cores, 12 GB of random-access-memory (RAM) and Windows Server Enterprise.

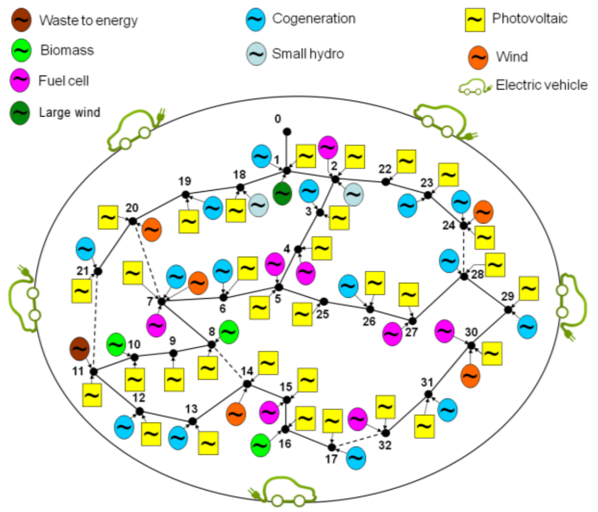

Figure 3. Network configuration adapted from [15]

Energy resources		**Availability (kW)**		**Prices (m.u./kWh)**
		min – max	**Total**	
Biomass		100 – 150	350	0.090
CHP		5 – 600	1150	0.060
Fuel Cell		10 – 50	235	0.150
Small Hydro		30 – 40	70	0.070
Photovoltaic		3 – 30	549	0.200
MSW		10	10	0.100
Wind		100 – 200	800	0.150
Large Wind		6000	6000	0.070
External Supplier		100 – 600	2400	0.600 – 0.150
Storage	Charge	150	–	0.086 – 0.158
	Discharge	100	–	0.106 – 0.178
Electric Vehicle	Charge	20 – 50	–	0.086 – 0.158
	Discharge	28 – 34	–	0.202
Demand Response	Red	2 – 172	3150	0.150 – 0.160
	Cut	0 – 206	2770	0.160
Load		–	–	0.086 – 0.158
Market		0 – 8000	–	0.100

Table 2: Energy resources data.

A scenario has been implemented to test the impact of the intermittent behavior of the large wind farm. The scenario considers an initial day-ahead forecast for the large wind farm and the day-ahead scheduling. In the hour-ahead scheduling, an unexpected change in the large wind forecast is considered. After hour 2, it is considered an unexpected increase in the generation power of the large wind farm. After hour 8, it is considered a huge drop in the generation power of the large wind farm. Figure 4 shows the forecast obtained in each step of the short-term ERM problem. It is possible to see the difference between the day-ahead forecast (blue line) and the hour-ahead forecast (red line).

Table 3 depicts the VPP's profit in each scheduling step, day-ahead, hour-ahead and real-time. The income keeps approximately equal in the three phases, even when unexpected changes in the large wind generation are considered. On the other hand, the cost increased significantly from the day-ahead scheduling to the hour-ahead scheduling, leading to a reduction in the VPP's profit.

Figures 5 and 6 present the scheduling of the resources in the three phases for hour 2 and 8 respectively. In Figure 5, the hour-ahead scheduling (middle figure) presented a higher generation power than the one in the day-ahead, because the large wind increased its own generation power (represented by the green line). In the real-time scheduling (right side figure), it was necessary to discharge storage units, because the large wind presented a small reduction in the generation power. In Figure 6, the day-ahead and hour-head scheduling presented a similar result. The real-time scheduling had to use more resources from 470 to 480 minutes. In these periods, the large wind had a reduction, leading no choice to the methodology than to select the storage discharge, electric vehicle discharge and demand response programs.

	Day-ahead scheduling	**Hour-ahead scheduling**	**Real-time scheduling**
Income (m.u.)	25 171	25 592	25 746
Cost (m.u.)	16 506	17 022	17 178
Profit (m.u.)	8 665	8 570	8 568

Table 3: Scheduling results.

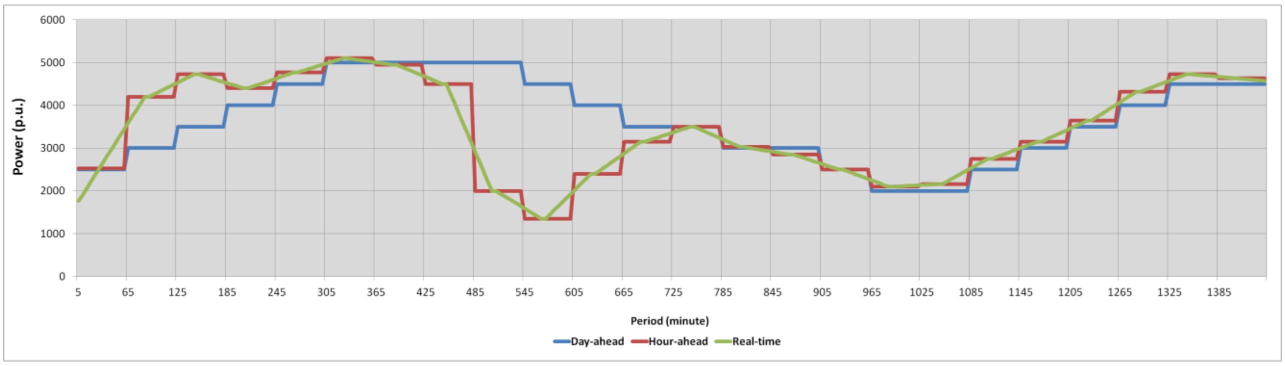

Figure 4. Forecast of large wind farm at bus 1 in the different time horizons

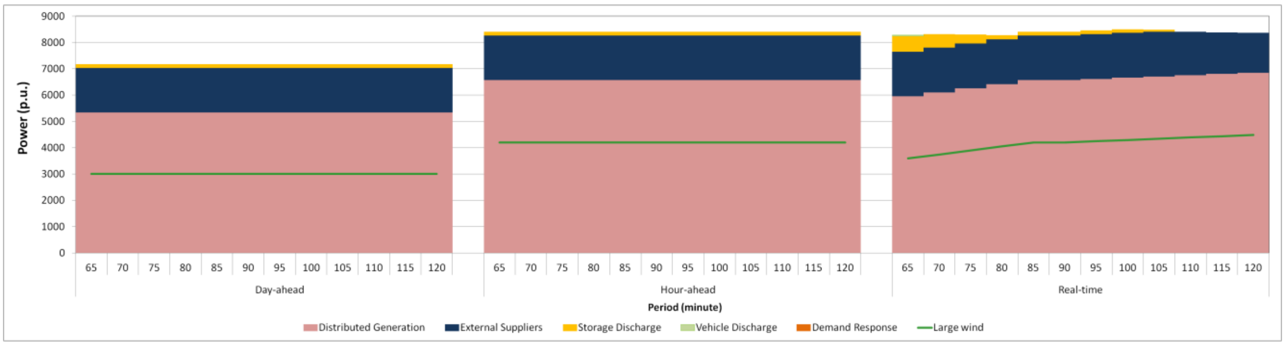

Figure 5. Scheduling results for hour 2 in the three time horizons

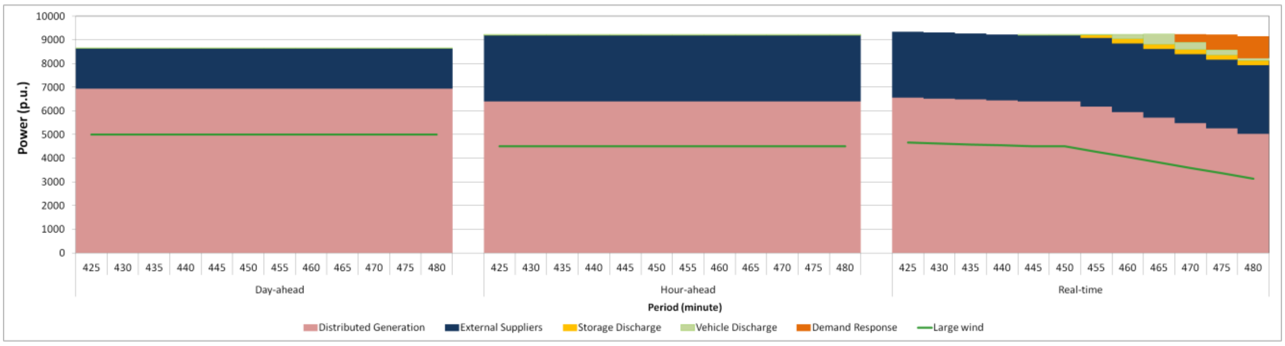

Figure 6. Scheduling results for hour 8 in the three time horizons

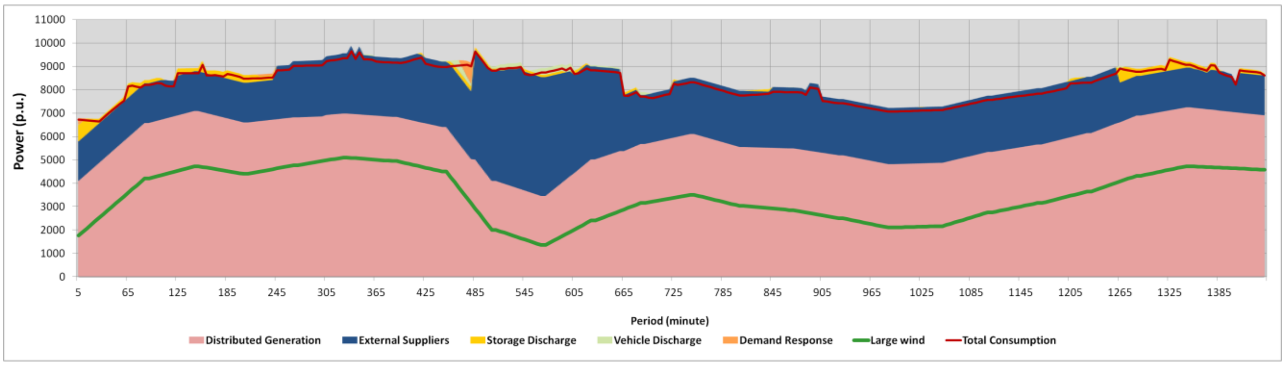

Figure 7. Real-time scheduling results

The real-time optimal scheduling of the resources for the complete day is presented in Figure 7. In periods with a low wind generation (green line), it was necessary to supply the load with energy from the external suppliers (blue area).

4. Conclusions

The paper proposes a short-term energy resource management methodology involving hour-ahead and real-time scheduling, taking advantage of the better accuracy of short-term and very short-term wind forecasting.

With this methodology, the VPP can manage his resources in very short period of time, improving his profits and fulfilling the established contracts. However, it is important to ensure a correct definition of the values for the spinning reserve to balance the distribution network in some periods, reducing in this way the use of demand response events.

The proposed methodology proved to be able to provide users with significant cost reductions, lowering resource use costs. Moreover, the system operators obtained higher profits.

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