Combined Operations of Renewable Energy Systems and Responsive Demand in a Smart Grid

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***Abstract*—The integration of renewable energy systems (RESs) in smart grids (SGs) is a challenging task, mainly due to the intermittent and unpredictable nature of the sources, typically wind or sun. Another issue concerns the way to support the consumers' participation in the electricity market aiming at minimizing the costs of the global energy consumption. This paper proposes an energy management system (EMS) aiming at optimizing the SG's operation. The EMS behaves as a sort of aggregator of distributed energy resources allowing the SG to participate in the open market. By integrating demand side management (DSM) and active management schemes (AMS), it allows a better exploitation of renewable energy sources and a reduction of the customers' energy consumption costs with both economic and environmental benefits. It can also improve the grid resilience and flexibility through the active participation of distribution system operators (DSOs) and electricity supply/demand that, according to their preferences and costs, respond to real-time price signals using market processes. The efficiency of the proposed EMS is verified on a 23-bus 11-kV distribution network.**

***Index Terms*—Active management, demand side management (DSM), energy management systems (EMSs), smart grid (SG), wind turbines.**

I. Introduction

TODAY, the integration of large amounts of renewable energy systems (RESs) with the grid [1]–[6] is widely studied by many researchers, but only few of them address these problems in connection with a consumers' potential participation to the electricity market [7]–[9], or analyze the additional balancing costs due to intermittent and partially predictable availability of RESs [10]–[12]. On the other hand, continuous changes of power system generation capacity impose significant energy reserves, imported energy, and the use of efficient storage systems [13]–[15], thus higher costs. Usually, stabilization of the available power is based on automatic resources such as primary and secondary frequency control devices, reacting within seconds up to minutes, and fast manual resources (spinning and nonspinning reserves), usually provided by diesel generators, responding within 10–15 min.

Generation and load forecast systems can provide adequate solutions to face these problems even if they usually are affected by errors requiring suitable regulation capabilities. Prediction errors can be strongly reduced if wind-forecasting errors are independent of those on the demand forecasting [16], and short forecast lead time can generally ease the need for standby balancing resources [17].

One further element that could reduce balancing requirements is the flexibility of load demand which can be obtained by issuing price-based signals, and allowing customers to decrease the energy demand according to their real-time availability [17], [18].

Demand side management (DSM) includes mechanisms of both price responsive demand and demand response programs [19]. The first one refers to those changes applied by consumers to their electric load profile in response to energy market price signals for improving the economic efficiency of their energy consumption. This mechanism increases the economic effectiveness of electricity markets by encouraging the energy load demand when the real-time price is low and discouraging it when the price is high. As a consequence, the peak demand can be decreased and the additional generation and transmission infrastructures may be avoided or reduced [20] and new eco-friendly standard of living encouraged [21].

Demand response, instead, is defined as the customers' ability to alter their own electricity demand in response to signals forecasted by the system when reliability is put at risk. Essentially, it refers to curtailment service programs actualized by paying end-users to take their electrical load off the grid when it is deficient in capacity or operating reserves. There are many different potential balancing resources, for instance the management of space heatings, air-conditioners, refrigerators, washing/drying machines, electric vehicles, etc. [17]. Thousands of such potential balancing loads can quickly provide (within seconds up to one minute) stable and predictable response without any early warning of curtailment. However, a common characteristic of such a kind of load storage is that it is limited in duration as customers may not accept a sustained outage period of discomfort, considering that the value of lost load is always a very important issue [22]. Whereas real-time pricing options are already available for large industrial and commercial consumers [23], such schemes have limited implementations for domestic customers [24]–[26], where not all the types of loads are able to participate in responsive demand programs. Some researches pointed out that active control of consumer loads could enable

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additional on-shore wind farms [27]. In [28], it has been demonstrated that fast/emergency reserve can be provided by responsive loads such as residential and small commercial air-conditioners; in [29] the control of residential heaters and pumps have been applied for managing daily peak demands. In [17], it has been reported that the value of the implementation of real-time pricing in the U.K. would be at least £ 2.6 to £ 3.6 billion, due to peak loads reductions during low wind speed, thus justifying the expense of installing and operating smart meters.

These new mechanisms require active management schemes (AMS) as well as end-user-level complex communication systems, necessary for making available information on real-time-pricing and availability of the electrical energy. Due to the previous considerations, this paper proposes an energy management system (EMS) for smart grid (SG) management through DSM and AMS [30]. In the following, Section II describes the EMS and a scheme for the active control of an SG, and Sections III and IV present and analyze the proposed method and different case studies, respectively. Conclusions are drawn in Section V.

II. EMS for SGs

As known, the term SG refers to a fully automated electric power system controlling and optimizing the operation of all its interconnected elements, in order to guarantee safe and efficient operations of energy generation, transmission, and distribution [31], [32]. Today, many interesting examples of SGs are available in many countries, including, for instance, the U.S., Canada, Germany, Japan, India, and Australia [33], [34]. Microgrids (MGs) are small-scenario versions of the centralized electricity systems that locally generate, distribute, and regulate the flow of electric energy to consumers. They are connected to the bulk power grid and allow higher reliability and energy cost reductions by encouraging the end consumers to locally purchase generated electric power with privileged tariffs [32].

Further initiatives towards the future SGs are concerned with the so-called virtual power plants (VPPs), i.e., aggregations of interconnected distributed generations (DGs) located in different places but managed in order to work as an unique virtual power plant managing a well defined amount of energy. This solution allows even the smallest DGs (aggregated in the VPP) to access the electricity market and contribute to the energy cost reduction process [35]. Examples of VPPs can be found in Germany, Australia, and the U.S. [36], [37].

Regardless of the possible different implementations, innovative EMSs are required to achieve a dynamic control of the different interconnected elements. A possible scenario for the implementation of this infrastructure is shown in Fig. 1. The main elements of this system are:

— Energy management system (EMS);
— Supervisory control and data acquisition (SCADA);
— Remote terminal units (RTUs);
— Advanced metering infrastructure (AMI);
— State estimation algorithms (SEAs);
— Generation and load forecast system (GLFS).

Optimization, monitoring, and control of the SG performances are entrusted to a suite of hardware/software applications constituting the EMS [38]. The SCADA system transmits the measurement data, provided by an AMI and by a set of remote collecting data devices (RTUs) placed in strategic positions along the SG, to the EMS. The latter determines the actions required for the optimum state of the SG by using SEAs and a GLFS.

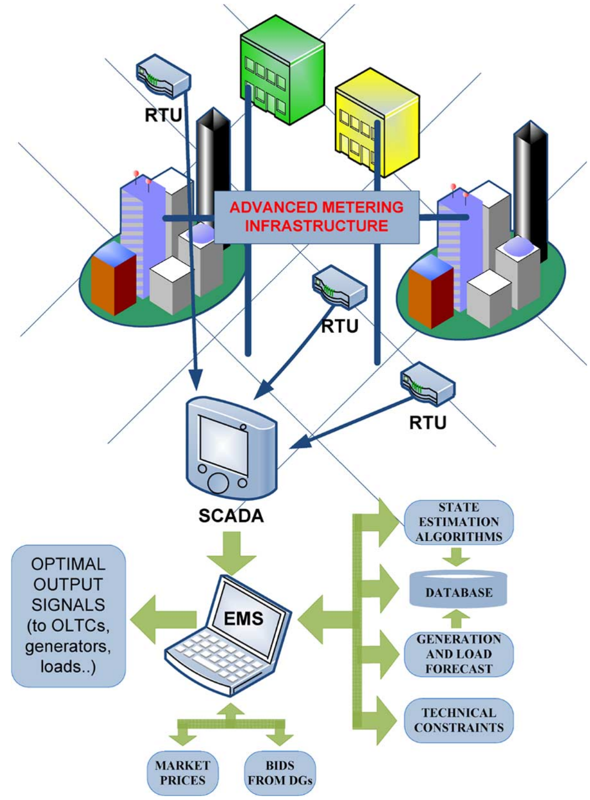

Fig. 1. EMS in the SG infrastructure.

III. Method Description

A. EMS Policy

According to the EU Directive EC 2006/32 on energy end-use efficiency and energy services [39], a mechanism of real-time pricing (RTP) tariff should be offered to the market. In this study, the hourly spot market price is assumed as the real-time electricity price for consumers available one day in advance, as adopted by Denmark and Ireland in Europe [26], [40]. Even if fluctuations between predicted and actual prices occur, this error usually goes to zero [41]. In order to reduce the electricity costs, those consumers with demand regulation capability can reschedule their bids according to the real-time electricity price. The scenario of Ireland Single Electricity Market (SEM) [41] demonstrated that DSM, optimized on one-day-ahead predicted electricity prices may promote the use of wind generated electricity. Moreover, variable service subscription (VSS)-type programs are assumed for customers that, under demand limiting and demand subscription service, subscribe to a demand threshold. The solution is a centrally controlled limiting load device: when the generation capacity is insufficient or due to reliability requirements, the EMS can limit the demand to the total subscribed capacity and responsive loads are paid by the distribution system operator (DSO) according to the VSS [42]. The EMS behaves as a sort of aggregator of distributed energy resources [43], that allows the SG (or MG) participating in the open market, buying and selling active and reactive power to the bulk grid and optimizing the local (renewable) production capabilities. It takes into account the bids received by energy producers and consumers.

When buying active and reactive power from the grid, the EMS tries to maximize the benefit function of demand while minimizing the costs of energy and the costs paid to consumers for demand limiting. When selling active and reactive power to the bulk power grid, due to an excess of low price renewable generation, the EMS also tries to maximize revenues by exchanging power with the grid. The SG (or MG) can also relieve possible network congestions by transferring energy to the nearby feeders of the distribution network [44].

In other words, the complementary operations executed by the EMS are:

1) A one day-ahead schedule of distributed generators and responsive loads according to the market prices, with each trade day comprising 48 half hourly trading periods. All dispatchable generators and responsive loads bid the one day-ahead active and reactive power generation or load demand by providing price and quantity information for each trading period one day ahead. For each trading period the dispatch schedules are determined [45].
2) A real-time intraday optimization operation that every m minutes, e.g., 5 min, modifies the scheduling in order to consider the operation and economic requirements.

As both price and reliability demand response (e.g., ancillary service) are considered, the scheduling is modified according to both the real-time electricity price and the support offered by distributed generators and responsive loads to the active network operation.

B. Mathematical Problem Formulation

During each time interval, the objective function to be maximized is the sum of the total demand benefits, minus the sum of the total generation costs and the costs paid for load curtailing under VSS [46]

$$\begin{aligned}&\text{maximize}\left[f(\mathbf{x},\mathbf{u})=\sum_{c=1}^{N_c}B_c(\mathbf{d})-\sum_{g=1}^{N_g}C_g(\mathbf{s})-\sum_{l=1}^{N_{\mathrm{RL}}}C_l^C P_l^C(\mathbf{u})\right]\\&\text{subject to}\\&\mathbf{h}(\mathbf{x},\mathbf{u},\mathbf{s},\mathbf{d})=0\\&\mathbf{g}(\mathbf{x},\mathbf{u},\mathbf{s},\mathbf{d})\le 0\end{aligned}\tag{1}$$

where $\mathbf{x}$ is the vector of dependent variables, containing the amplitudes and angles of the buses voltages; $\mathbf{u}$ is the vector of control variables, including the secondary voltage of the on-load tap-changers (OLTCs) and the active and reactive power injected or absorbed by generators and loads; N_c is the set of pool load buses; N_g is the set of pool generator buses; N_{RL} is the set of responsive loads; C_l^C is the cost for curtailing 1 MWh of the lth responsive load under VSS; $P_l^C(\mathbf{u})$ is the curtailed energy for the lth responsive load; $\mathbf{d}=[\mathbf{d}_p,\mathbf{d}_q]$ is the demand vector; $B_c(\mathbf{d})=B_c(\mathbf{d}_p,\mathbf{d}_q)=B_{pc}(\mathbf{d}_p)+B_{qc}(\mathbf{d}_q)$ is the benefit of consumer c; $\mathbf{s}=[\mathbf{s}_p,\mathbf{s}_q]$ is the supply vector; and $C_g(\mathbf{s})=C_g(\mathbf{s}_p,\mathbf{s}_q)=C_{pg}(\mathbf{s}_p)+C_{qg}(\mathbf{s}_q)$ is the cost of supplier g. Subscript p and subscript q specify a relationship with active or reactive power, respectively. In the pool model, production costs and benefit functions are quadratic functions of active and reactive power of pool loads and generators, as follows:

$$C_{pg}(\mathbf{s}_p)=a_{0g}+a_{1g}s_{pg}+a_{2g}s_{pg}^2\tag{2}$$

$$C_{qg}(\mathbf{s}_q)=\alpha_{0g}+\alpha_{1g}|s_{qg}|+\alpha_{2g}s_{qg}^2\tag{3}$$

$$B_{pc}(\mathbf{d}_p)=b_{0c}+b_{1c}d_{pc}+b_{2c}d_{pc}^2\tag{4}$$

$$B_{qc}(\mathbf{d}_q)=-B_{q0c}[d_{qc}-\gamma d_{pc}]^2.\tag{5}$$

The price-dependent load is modeled with a consumer benefit function $B_c(\mathbf{d})$, concave and increasing, with $\mathbf{d}$ including both the real and reactive power demand [46].

In order to integrate the simulation of reactive power exchange, price-dependent reactive loads are considered. Since reactive power acts more as a service enabling the consumption of real power, a benefit function different from the real power benefit equation is determined. Accordingly, the benefit of the reactive power is considered as the avoidance of its shifting from a given desired level for a specified active power consumption. Desired reactive power demand is that required by the load at the given load level and can be defined as a function of the real power demand [46] $d_{q\mathrm{desired}}=f(d_p)$. Assuming the magnitude of the function increasing with d_p as $d_{q\mathrm{desired}}=\gamma d_p$ and considering a concave function for B_q as $k(x)=k(d_q-d_{q\mathrm{desired}})^2$ (5) is obtained.

In order to maximize the objective function, the nonlinear programming formulation of the OPF, described in [47]–[51], is modified including the AMS and DSM.

C. Discrete Variables Handling

The OPF can be approached as a mixed discrete-continuous optimization nonlinear problem with a single integer variable: the OLTC transformer tap. The solution of this problem is implemented by a two-stage approach [52], [53]. First, a solution over the full range of variables is generated while assuming that all variables are continuous; then, the discrete variable is moved to the nearest discrete setting, and treated as constant during a second-stage solution.

D. Constraints

The equality constraints $\mathbf{h}(\mathbf{x},\mathbf{u},\mathbf{s},\mathbf{d})$ represent the static load flow equations such as Kirchhoff current law $\forall b\in B$, where B is the set of busses (indexed by b) and Kirchhoff voltage law $\forall l\in L$, where L is the set of lines (indexed by l) [51], [52]. The inequality constraints $\mathbf{g}(\mathbf{x},\mathbf{u},\mathbf{s},\mathbf{d})$ are listed in the following:

1) *Active and reactive power constraints for the interconnection to external network (slack bus)* $\forall n\in N$

$$\begin{aligned}s_{pn}^-\le s_{pn}\le s_{pn}^+\\ s_{qn}^-\le s_{qn}\le s_{qn}^+\end{aligned}\tag{6}$$

where N is the set of external sources (indexed by n), s_{pn} and s_{qn} are the active and reactive power outputs of n, respectively, and s_{pn}^-/s_{pn}^+ and s_{qn}^-/s_{qn}^+ are the min/max values they can assume.

2) *Active and reactive power constraints for generators*: $\forall g \in N_g$

$$s_{pg}^{-} \le s_{pg} \le s_{pg}^{+}$$
$$s_{qg}^{-} \le s_{qg} \le s_{qg}^{+} \tag{7}$$

where s_{pg} and s_{qg} are the active and reactive power outputs of g, respectively, and s_{pg}^{-}/s_{pg}^{+} and s_{qg}^{-}/s_{qg}^{+} are the min/max values they can assume.

3) *Active and reactive power constraints for consumers load*, $\forall c \in N_c$

$$d_{pc}^{-} \le d_{pc} \le d_{pc}^{+}$$
$$d_{qc}^{-} \le d_{qc} \le d_{qc}^{+} \tag{8}$$

where d_{pc} and d_{qc} are the active and reactive power absorbed by consumer c, respectively, and d_{pc}^{-}/d_{pc}^{+} and d_{qc}^{-}/d_{qc}^{+} are the min/max values it can assume.

4) *Voltage level constraints* $\forall b \in B$

$$V_b^{-} \le V_b \le V_b^{+} \tag{9}$$

where V_b is the voltage at b, V_b^{+} and V_b^{-} are the max/min values it can assume.

5) *Flow constraints for lines and transformers* $\forall l \in L$

$$\sqrt{\left(f_l^P\right)^2 + \left(f_l^Q\right)^2} \le f_l^{+} \tag{10}$$

where f_l^P and f_l^Q represent the active and reactive power injections onto l, respectively, and f_l^{+} the maximum power flow on l.

The additional constraints derived from the AMS are related to the coordinated OLTC voltage, the WTs and diesel generators (DGens) power factor angles.

1) *Coordinated OLTC voltage constraint*

$$V_{\text{OLTC}}^{-} < V_{\text{OLTC}} < V_{\text{OLTC}}^{+} \tag{11}$$

where V_{OLTC} is the secondary voltage of the OLTC, $V_{\text{OLTC}}^{-}/V_{\text{OLTC}}^{+}$ are the max/min values it can assume.

2) *Coordinated generator reactive power constraints*, $\forall g \in N_g$

$$\phi_g^{-} < \phi_g < \phi_g^{+} \tag{12}$$

where ϕ_g is the power factor angle of g, ϕ_g^{-}/ϕ_g^{+} are the max/min values it can assume.

IV. Case Studies

The proposed technique is applied to a 23-bus 11-kV radial distribution system, shown in Fig. 2. The three feeders are supplied by a 6-MVA 33/11-kV transformer; the tap position allows nine different voltages with a step $\Delta U = 0.0235$ p.u. Voltage limits are taken to be ±10% of the nominal value and feeder thermal limits are 1.5 MVA (81 A/phase). The phasor dynamic models for the WTs, the DGens, the OLTC and the other distribution system elements are implemented using Matlab SimPowerSystems.

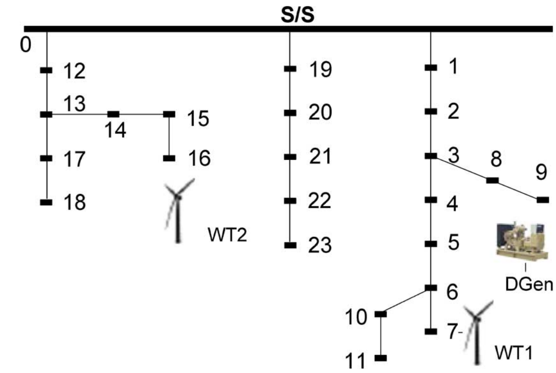

Fig. 2. Test network.

TABLE I
Network Loading

Load Band	Active Power [MW]	Reactive Power [MVAR]
Minimum	1.51	1.12
Medium	2.16	1.61
Normal	2.59	1.93
Maximum	3.02	2.26

TABLE II
WTS Generated Active and Reactive Power

Wind velocity [m/s]	0	6	8	10	12
Active Power [MW]	0	0.11	0.30	0.60	1.05
Maximum Reactive Power [MVar]	0	0.07	0.16	0.32	0.47

The load at each bus is assumed to track a load curve [30]: discrete load bands across one year are considered: maximum, normal, medium, and minimum load. The load levels for each band are summarized in Table I.

In the test network, two wind turbines (WT1 and WT2) are connected at nodes 7 and 16, respectively. Each WT generates about 1.05 MW at a wind speed of 12 m/s, operating within a power factor varying between 0.85 leading and lagging [54]. The power extracted from a WT is a function of the available wind power, the power curve of the machine and the ability of the machine to react to wind variations. The WTs generated active and reactive power dependence on the wind speed is given in Table II.

A high cost DGen generating a maximum active power of 600 kW is connected at bus 9. The cost curve used for the DGen is approximated by a second-order polynomial function [55], considering the diesel generator starting cost assessed at 15 euros [56]. The values of the cost coefficients are calculated considering the fuel consumption curve of a real diesel generator obtained from the data provided in [57], setting a fuel price of 1 euro per liter [58]. The diesel unit can operate between 25% and 100% of its rate capacity. As regards with the consumers, it

TABLE III
SUPPLIERS CHARACTERISTICS

SUPPLIER	a_{2g} [€/MWh^2]	a_{1g} [€/MWh]	a_{0g} [€]	α_{2g} [€/MVarh^2]	α_{1g} [€/MVarh]	α_{0g} [€]
Slack bus (Nor/Max load)	0.16	160	0	0	16	0
Slack bus (Min/Med load)	0.08	80	0	0	8	0
Wind turbine	0	40	0	0	4	0
Diesel Generator	153.90	123	48.40	15	12	5

TABLE IV
CUSTOMER CHARACTERISTICS SCENARIO 1

CUSTOMER BUS	LOAD VALUE	b_{2g} [€/MWh^2]	b_{1g} [€/MWh]	b_{0g} [€]
Slack bus	(Nor/Max load)	0	128	0
	(Min/Med load)	0	64	0
3	(Every load band)	-0.36	360	0
12-17	(Every load band)	-0.34	340	0
All other buses	(Every load band)	-0.9	900	0

TABLE V
CUSTOMER CHARACTERISTICS SCENARIO 2

CUSTOMER BUS	LOAD VALUE	b_{2g} [€/MWh^2]	b_{1g} [€/MWh]	b_{0g} [€]
Slack bus	(Nor/Max load)	0	128	0
	(Min/Med load)	0	64	0
3	(Nor/Max load)	-0.18	180	0
	(Min/Med load)	-0.36	360	0
12-17	(Nor/Max load)	-0.17	170	0
	(Min/Med load)	-0.34	340	0
All other buses	(Every load band)	-0.9	900	0

has been assumed that each consumer has both fixed and price responsive load.

Operation of the considered EMS endowed with AMS is first evaluated considering discrete load and wind speed states [30], varying in the range between minimum and maximum load and between 0 and 12 m/s, respectively.

The following analysis considers different DSM mechanisms such as Price Responsive Demand and Demand Response Programs [19] and aims at evaluating the benefits of real-time electricity price. Two different scenarios are analyzed as follows:

1) consumers are involved in a demand response program;
2) consumers are involved in a demand response program and also participate as price responsive demand.

Suppliers and customers coefficients are given in Tables III, IV, and V, respectively [59], [60].

In both minimum and maximum load scenarios, the suppliers and customer characteristics are equal, thus the supplied load and the total cost paid for energy delivering change only for normal and maximum loads.

A. Scenario 1: Consumers Involved in a Demand Response Program

In this scenario, consumers can be limited only for reliability requirements (i.e., for avoiding constraints violations) by means of a centrally controlled limiting load device. When, during maximum and normal load, demand is limited to the total subscribed capacity, consumers are paid by the DSO at 200 euros/MWh according to a VSS [43].

TABLE VI
TOTAL ACTIVE POWER ABSORBED BY DEMAND AT BUSES 3, 12, AND 17 [kW]

WIND SPEED [M/S]	LOAD			
	SCENARIO 1		SCENARIO 2	
	NOR	MAX	NOR	MAX
0	977	829	617	341
6	1091	1032	861	678
8	1257	1291	1257	1291
10	1462	1567	1462	1567
12	1462	1706	1462	1706

TABLE VII
SUM OF THE TOTAL NETWORK DEMAND [kW]

WIND SPEED [M/S]	LOAD			
	SCENARIO 1		SCENARIO 2	
	NOR	MAX	NOR	MAX
0	2106	2146	1746	1658
6	2220	2349	1990	1995
8	2386	2608	2386	2608
10	2591	2884	2591	2884
12	2591	3023	2591	3023

During normal operation each load is supplied at its maximum value for a wind speed equal to 12 m/s or when the load is minimum. When wind speed varies between 0 and 10 m/s, all consumers are supplied at their desired demand level, except those connected at buses 3, 12, and 17, which, are, instead, limited in order to satisfy reliability requirements, as shown in Table VI. Since variable loads operate at fixed power factor, the absorbed reactive power exhibits a similar trend. Due to the overall load increase, the active power absorbed by consumers connected at buses 3, 12, and 17 is limited by the thermal constraints on the wires 0–1 and 0–12. The sum of total network demand is shown in Table VII.

The percentage peak demand reduction is shown in Fig. 3 for wind speeds below or equal to 6 m/s. During maximum load, the total demand at buses 3, 12, and 17 decreases from 1706 to 1032 kW (or by 39%) and to 829 kW (or by 51%), when the wind speed is 6 and 0 m/s, respectively.

For instance, in case of maximum load and wind speed varying from 0 to 8 m/s, it is worth noting that:

— the total curtailed power decreases proportionally to the wind speed from 878 to 139 kW;
— the DGen always generates its maximum active power of 600 kW, except for a wind speed of 8 m/s, when it generates 320 kW.

The DGen supplies active power only during maximum and normal load states and wind speeds varying from 0 up to 8 m/s.

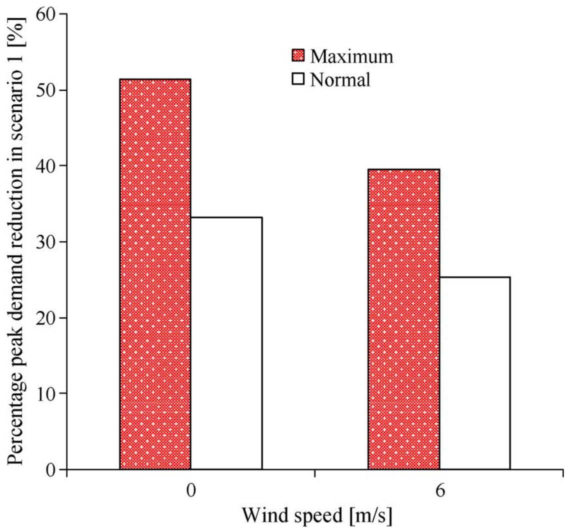

Fig. 3. Percentage peak demand reduction in Scenario 1.

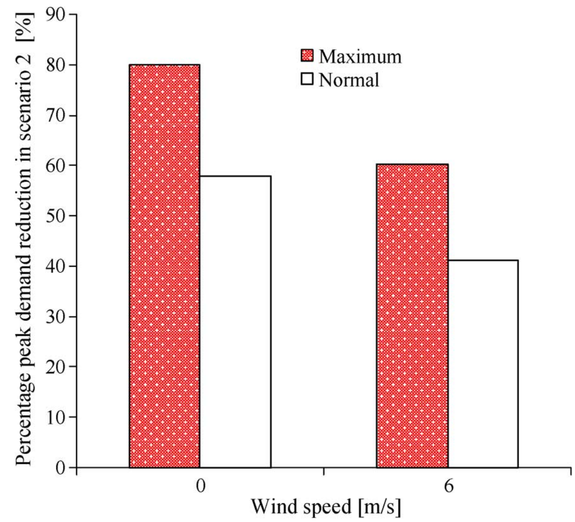

Fig. 4. Percentage peak demand reduction in Scenario 2.

Its output power varies from a minimum value around 293 kW, in case of normal load and wind speed of 6 m/s, to a maximum value of 600 kW, in coincidence with maximum load and wind speeds lower than 8 m/s.

The active and reactive power imported from the grid tend to increase while decreasing the wind speed and with an increasing load value. While this trend is always verified in case of reactive power, the relationship between the tendencies of the imported/exported active power in relationship with the load value is more complex as it depends on the active power generated by the WTs and the DGen and on the active power absorbed by variable loads. When the wind speed is equal to 12 m/s and the load is minimum, about 285 kW of active power are exported to the bulk power grid. Due to the implemented AMS and, in order to relieve the voltage constraints, the WTs always supply lead (capacitive) power.

B. Scenario 2: Consumers Involved in a Demand Response Program also Participating as Price Responsive Demand

As in the previous scenario, consumers can be limited due to reliability constraints, moreover price responsive consumers under RTP tariff (at buses 3, 12, and 17) can modify their demand in response to high real-time electricity prices occurring during normal and maximum load.

Real-time electricity price signals, available to both consumers and producers, represent an effective coordination mechanisms suitable to drive both to change their bids/offers in both constrained and unconstrained feeder conditions.

While for wind speeds higher or equal to 8 m/s, the impact of price responsive demand and RTP tariff is negligible due to the low-price wind energy, consumers under RTP tariff adjust their demand bids in response to high real-time electricity price for wind speeds below 8 m/s. In the case of maximum load, RTP tariff induces consumers to move consumption away from costly peak hours and the total demand decreases from about 1706 kW to about 678 kW (−60%) and to about 341 kW (−80%) in correspondence of a wind speed of 6 and 0 m/s, respectively, as shown in Fig. 4.

RTP also allows reducing the power generated by the DGen, that is equal to about 240 kW during maximum load.

TABLE VIII
TOTAL COSTS [Euro/h]

WIND SPEED [M/S]	COST				COST REDUCTION	
	SCENARIO 1		SCENARIO 2			
	NOR	MAX	NOR	MAX	NOR	MAX
0	585	694	352	393	233	301
6	528	649	377	373	151	276
8	425	563	384	370	41	193
10	337	432	337	404	0	28
12	248	341	248	341	0	0

A reduction of the peak demand can be evidenced in Scenario 2 when compared to Scenario 1: for wind speeds below 8 m/s, the percentage decrease of the peak demand is within 21%–37% and 34%–60%, during normal and maximum load, respectively. This reduction leads to significant economic benefits for both consumers and DSO, that avoids paying consumers according to a VSS at 200 euros/MWh for demand limiting, as in Scenario 1.

A maximum cost reduction, varying from 301 to 28 euros/h, can be achieved during maximum load in Scenario 2 when compared with Scenario 1. The total cost reductions, if compared to the previous Scenario, are shown in Table VIII.

Moreover, RTP encourage consumers shifting consumptions during periods of high wind energy production and supporting the use of renewable energy resources.

C. Base-Year Analysis

The benefits of the AMS and price responsive consumers under RTP tariff during one year are assessed following the approach used in [61]. Based on their joint probability of occurrence, defining the number of coincident hours over the year, wind availability and demand have been aggregated into a number of wind/demand scenarios. Actual data for both demand and wind production have been taken from [61].

The set of scenarios obtained by combining wind availability and load demand real data for one year are shown in Fig. 5.

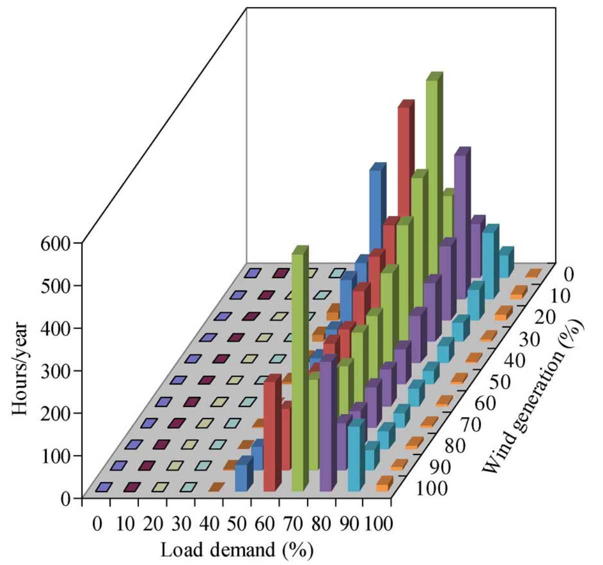

Fig. 5. Coincident hours for demand/generation scenarios.

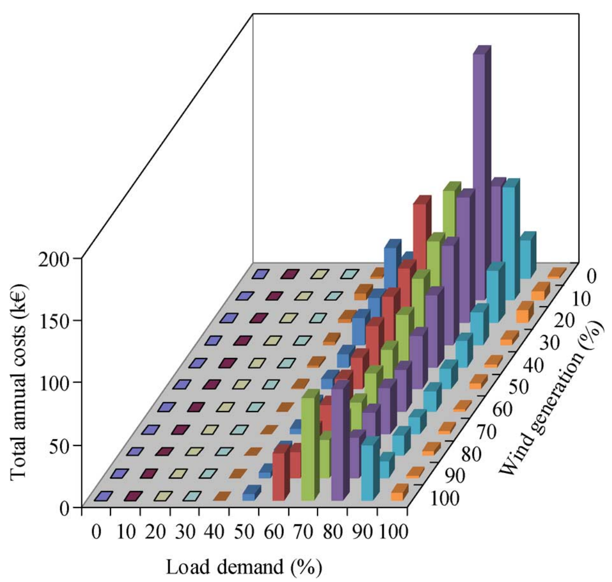

Fig. 6. Total costs without AMS.

Each scenario represents the combination between wind speed and load demand values, indicated in percentage terms (x-axis), and is characterized by a defined number of hours over the year (y-axis). Such a number represents the time (number of hours) during which each combination wind/demand occurs in the course of the year.

As shown in Figs. 6 and 7, by summing the costs of each scenario, the proposed EMS endowed with AMS allows a total annual cost reduction around 383 keuros, if compared to the scenario without AMS. The annual curtailed energy is equal to about 634 MWh/year without considering the AMS, while it decreases down to about 573 MWh/year when using the AMS, with a reduction of about 9% of the curtailed energy.

AMS, such as the coordinated voltage regulation of OLTC and the power factor control of WTs, are able, in fact, to increase the total energy absorbed by loads. For instance, when the load demand is within 70% and 100%, the power factor control of WTs can increase the energy absorbed by loads up to 10% if compared with the scenario in which only a regulation of the

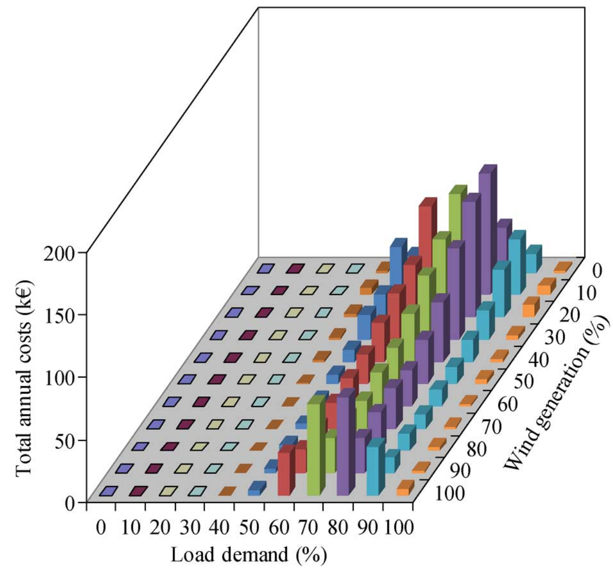

Fig. 7. Total costs with AMS.

OLTC is applied, and up to 20% if compared with the scenario without AMS.

Combining AMS with price responsive consumers under RTP tariff (at buses 3, 12, and 17) an additional 93 keuros annual cost reduction over the scenario with the sole AMS is achieved.

It is worth noting that, by mitigating network constraints, the sole use of AMS may increase the energy absorbed by loads up to 20%.

Moreover, real-time electricity price signals drive consumers to find a different time schedule of their consumptions, thus reducing expensive peak power demands further contributing to network constraints reduction.

Hence, a combination of both mechanisms through the active participation of producers and consumers, represents a good option for improving both resilience and flexibility of SGs and for supporting the use of renewable energy resources.

D. Computational Performances Evaluation

Simulation results demonstrate that the proposed method is fast enough to be executed in real-time: for the considered network, a personal computer with an Intel CoreTM i7 processor running at 2.67 GHz and with 8-GByte RAM requires less than 3 min for the solution of a single OPF.

The proposed optimization approach (i.e., Sequential Quadratic Programming), requires low computational resources while providing very good results, comparable with performances obtained using interior point method solution of OPF relaxation [53]. It is worth noting that this method, also coded in the AIMMS optimization modeling environment [30], is scalable, i.e., it can be used with a larger number of control variables.

V. Discussion and Conclusion

In this paper, an EMS for the optimization of SGs has been proposed.

The EMS behaves as a sort of aggregator of distributed energy resources allowing the SG participating in the open market in order to optimize the local production capabilities as well as to minimize the cost of bought energy.

The proposed system integrates AMS with DSM without requiring significant additional hardware.

Simulation results evidenced that the combined operations of RES and Price Responsive Demand mitigate network constraints while satisfying higher demand levels and reducing the energy costs.

AMS offer technical benefits: they allow a better coordination between DSOs and electricity supply and demand that, satisfying their preferences at minimum costs, can respond to real-time price signals using market processes.

It is worth pointing out that each active or DSM solution, or the combination of them, should be evaluated on a case-by-case basis as the implementation and cost-effectiveness of each solution depends on network characteristics. A combination of both mechanisms will, however, represent in most cases, the best option to improve the SG's resilience and flexibility through resource use optimization and peak loads reduction.

The implementation of AMS and DSM requires both a hardware as well as a software infrastructure that are expected to become standard in SGs. Conversely, the actual implementation of AMS and DSM also requires a new regulatory framework based on economic signals and providing incentives for both consumers and generator owners and special bilateral contracts between them and the DNOs.

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