Stochastic Demand Side Management in European Zonal Price Market

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***Abstract*—In this paper, demand-side management (DSM) is performed through demand response aggregators (DRAs) in an uncertain environment within zonal price market framework. The proposed scheme aims to allow cross-border electricity trading and optimize interconnections usage as well as to obtain optimum DR volume from the perspective of the Market Coupling Operator (MCO). The market consists of several zonal price markets as Nominated Electricity Market Operators (NEMO) who run their day-ahead and balancing market internally and communicate the information to the MCO to provide the cooperation with other NEMOs. To this end, a stochastic two-stage model is formulated in which the total operation cost from MCO's viewpoint is minimized. Accordingly, the model aims to consider day-ahead decisions in the first stage and balancing decisions in the second stage. Furthermore, the intermittent nature of renewable sources generation is handled by scenario generation with Monte-Carlo Simulation (MCS) method. NEMOs are physically connected as radial network. Therefore, all relative network constraints are taken into account as a linear power flow for radial networks. The results of the implementation of the proposed model demonstrate the effectiveness of various DR biddings on hourly DR volume, hourly DR cost and power exchange between different NEMOS.**

***Index Terms*—Demand response, stochastic modeling, European electricity market, zonal price markets.**

I. NOMENCLATURE

A. Indices (sets) and abbreviations

n,n' (NN)	Index (set) of nodes of NEMOs.
s (NS)	Index (set) of scenarios.
$Scen$	Superscripts for scenarios.
$NEMO$	Superscripts for normal NEMOs.
$LNEMO$	Superscripts for slack (large) NEMO.
t (NT)	Index (set) of time-step.
$\bar{U} \in P.EX, P.IM, Q.IM, Q.EX$	Superscripts for power.

B. Parameters

$C_{t,n}^{MBP}$	Power export cost for each NEMO.
C_t^{reg}, Cs_t^{reg}	Regulation cost for day-ahead and real-time market.
$C_{t,n}^{UMP}$	Uniform market price.
$P.IM_{t,n}^{NEMO}, Q.IM_{t,n}^{NEMO}$	Imported active and reactive power in each NEMO.
$P.PV_{t,n}^{NEMO}$, $P.PV.s_{t,n,s}^{NEMO}$	Forecasted and scenario PV export from each NEMO.
$P.WF_{t,n}^{NEMO}$, $P.WF.s_{t,n,s}^{NEMO}$	Forecasted and scenario WF export from each NEMO.
$\lambda_{t,n}$	DR bidding from DRA on behalf of NEMO.
ξ, ξ'	Percentage of DR trading within the same NEMO and other NEMOS, respectively.
$prob$	Probability of scenarios

C. Variables

$P\_DR_{t,n}$	Scheduled DR for DRA in the same NEMO.
$P\_DR_{t,n,n'}^{m}$	Scheduled DR for DRA in other NEMOs.
$P_{t,n}^{LNEMO}$, $Q_{t,n}^{LNEMO}$	Active and reactive power exchange for slack NEMO.
$P_{t,n}^{NEMO}$, $Q_{t,n}^{NEMO}$	Active and reactive power export in normal NEMO.
$reg_{t,n}^{LNEMO}$, $regs_{t,n,s}^{LNEMO}$	Active and reactive power flows in downstream directions day-ahead (real-time) (kW).
$PF_{t,n}^{p}, PF_{t,n}^{q}$	Active and reactive power flows in day-ahead market.
$PF.s_{t,n,s}^{p}$, $PF.s_{t,n,s}^{q}$	Active and reactive power flows in real-time market.

II. INTRODUCTION

A. Motivation and Background

THE European electricity market, specifically day-ahead market, is being developed based on zonal price market scheme which is in the opposite side of nodal price market (as e.g. in the United States) [1].

According to this scheme, each EU country can run their own electricity market as Nominated Electricity Market Operator (NEMO) and they all are integrated and run by a Market Coupling Operator (MCO) as a unique day-ahead market [2].

Each zone or NEMO is not necessarily a single country. For example, the Operator del Mercado Iberico (OMIE) operates Portugal and Spain electricity market and EPEX spot runs central Europe including Germany, France, Netherlands, Austria, Switzerland and Belgium market [3].

As depicted in Fig. 1, EPEX spot can interact with several other markets as NEMOs to build up a cross-zonal electricity exchange market.

The physical connection of this integrated market can be as similar as a radial network in a way that the largest market (e.g. EPEX spot) can be considered as the main network and other networks (e.g. OMIE, Nord Pool etc.) are connected to it for power exchange under MCO's viewpoint and Capacity Allocation and Congestion Management (CACM) regulations.

Meanwhile, a suitable strategy to exchange demand response (DR) among NEMOs by MCO should be formed in order to mitigate congestion problems and handle the intermittent nature of huge penetration of weather-dependent renewable energy sources (RESs) such as photovoltaic farms (PVs) and wind farms (WFs) as the main concern of CACM regulations.

B. Relevant literature

As some studies (see e.g. [4], [5]) indicate, Germany has 6.4 GW/h technical potential DR, in which 3.5 GW/h of this potential is viable through the current regulation and market scheme. Another study [6] states, in case more suitable market and regulation framework run, DR could substitute up to 10 GW of power plants. Accordingly, the measures the German Federal Ministry for Economic Affairs and Energy (BMWi) offered are mostly associated with changing the market rules to facilitate the access of DR sources to balancing market [2], [4].

Moreover some studies about DR implementation in Portugal [8], [9] concluded that it is necessary to open up the market by the Energy Services Regulatory Authority (ESRA) and include DR in balancing markets because of the already existing large capacity of renewable energy sources (RESs) and very active customers in retail market, which will help to push forward this procedure. Thus, according to these examples, suitable market structures for demand-side management for both NEMOs and MCO are highly required.

The interconnection among different zone price markets can be, physically, supposed as a radial network so that MCO will deal with radial network constraints for power flow. A number of studies have addressed how DR is used by different markets and utilities like DSO, which is possible to be inspired, conceptually, for this need.

For example, operation scheduling of microgrids has been studied in [10] via a two-stage stochastic program while considering an ancillary service demand response program (ASDR).

Therein, network constraints have been neglected. Nevertheless, there are some works in networks while considering network constraints as linear power flow without DR implementation [11]–[15] in a deterministic environment.

Moreover, DR scheduling has been conducted from demand response aggregator (DRA)'s viewpoint in some literature. For example, authors in [16] have applied two DR options including load curtailment and load shifting to maximize DRA profit.

A DR trading framework for DRAs has been proposed in [17] in which time-of-use (TOU) and reward-based DR program have been applied for trading with the customer. DR option agreements have been employed for DR trading with DR purchasers similar to the wholesale market.

Competitive scheduling for DRAs to sell the pre-stored energy through storage devices has been conducted in [18]. In [19], DRA has been optimized in a two-stage problem that aims to minimize the total operation cost from DSO's viewpoint while considering incentive-based DR programs.

All aforementioned papers mainly focus on how to implement DR in a radial network which is a good inspiration to form the MCO framework.

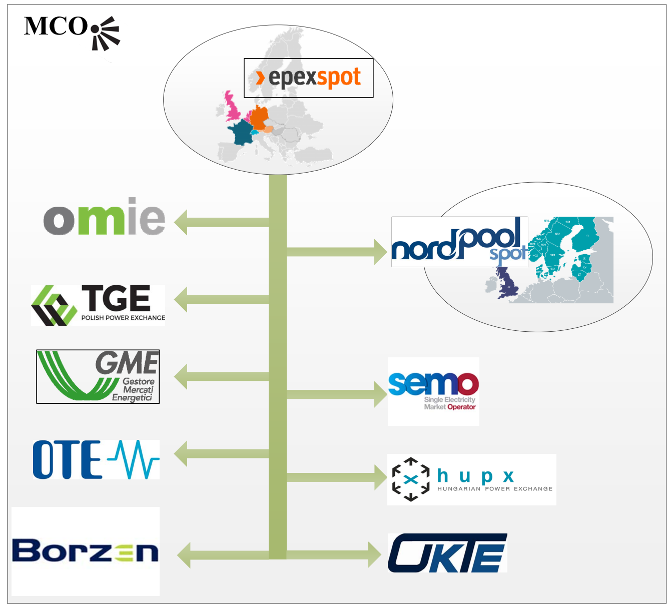

Fig. 1. Different NEMOs in European electricity sector.

C. Contributions and Organization

In this paper, MCO operates the integration of NEMOs while using a uniform market price (UMP). Accordingly, it is supposed that MCO is managing a uniform network in which each bus is representative of a zonal price market or NEMO. NEMOs just share the information of import power capacity, export conventional power capacity, export RESs capacity, their market bid price (MBP) as well as their DSM potential. MCO deals with the uncertainty of each zone' RESs by generating possible scenarios in real time through a Monte-Carlo Simulation (MCS) method. Moreover, MCO runs the market with a stochastic two-stage programming model to minimize the total operation cost. The aim is to acquire not only optimum electricity exchange among NEMOs but the optimum DR quantity for them. Therefore, the model captures day-ahead market decisions along with real-time market decisions. Meanwhile, NEMOs include an entity i.e. DRA to handle DSM issues. The rest of the paper is organized as follows. The structure and framework of the proposed model are stated in Section III. Mathematical formulation of the proposed DR market is presented in Section IV. The case study is introduced in Section V, and numerical results besides discussion are brought in this Section. Conclusions are given in Section VI.

III. PROBLEM STATEMENT

In this section, the framework of the proposed model is presented. The operation strategy applied for the MCO as well as the cooperation and coordination among NEMOs in day-ahead and balancing market are outlined. Besides, market approach for DR trading among NEMOs are elaborated. Moreover, the stochastic two-stage model which is applied for MCO to operate the cross-zonal electricity exchange market is briefly introduced in this section.

A. Operation strategy

The proposed central day-ahead market model is in line with the integration of European market operators based on CACM regulations and under MCO operation policies.

Different bidding zones or NEMOs can be, physically, connected as Fig. 2 depicts. Accordingly, each market indicates one zonal price or NEMO and provides all needed procedures for stable and sustainable operation of their network in a close cooperation with the relative TSOs. Since MCO performs fundamentally centralized task, NEMOs, who are responsible for computation of available transmission capacity, should have tight cooperation with MCO. Hence, NEMOs just deliver some information such as their MBPs, import and export capacity as well as DR prices. MCO collects all data and runs the cross-zonal day-ahead market as it is planned for the future European market [2].

The largest market (i.e. EPEX spot) can be considered as a slack network which is able to serve all other markets and provides reserve. In the proposed model, the only NEMO who is able to provide reserve for entire integrated network is the slack NEMO. Moreover, the NEMOs, who implements DR programs, has an entity called DRA in charge of DR trading among other NEMOs. DRAs can bid for DR trading on behalf of the relative NEMO.

The MCO runs a day-ahead market while clearing imbalances in a real-time market and handles cross-zonal power exchange among normal NEMOs and slack market operated by the EPEX spot. In other words, NEMOs interact by MCO to exchange power in a way that each NEMO can be power consumer or producer at each time step. The largest NEMO can play the role of covering imbalances when required. Thus, regulation is a commodity to be bought from the EPEX spot market to cover imbalances caused by weather-dependent renewable generations. Within this assumptive and possible future framework, the NEMOs' integration could be modelled in such a way that it can be modelled as a radial network with capacity constraints between them. The intermittent nature of WFs and PVs therefore can be considered in the second stage to schedule the required regulation by scenario generation.

B. Stochastic two-stage model

According to CACM, the algorithms intends to maximize the economic surplus [2]. Therefore, the objective can be minimization of the total operation cost in the two-stage stochastic program from MCO's viewpoint. The first stage realizes day-ahead market decisions and the second stage balancing decisions in the real-time market. In the first stage, power exchange among EPEX spot market as the slack market and other NEMOs, scheduled regulation from slack market, NEMOs cross-border power exchange, and DR quantity to be bought from NEMOs are obtained according to UMP, MPC's regulation price, MBP, and DR bidding by DRAs. In the second stage, scenarios of wind and solar power outputs are generated from Monte-Carlo simulation method [20]. Real-time regulation in each scenario is defined based on real-time regulation price. Using historical data and given series of solar irradiance and wind speed, appropriate probability distribution functions (PDFs) for each variable are achieved. Based on the literature, Beta function and Rayleigh function are suitable for solar irradiance and wind speed, respectively. In other words, the parameters required to build up a specific PDF are extracted from historical data as depicted in Fig. 3 PDF production section. For example, there are two parameters in Beta function called α, β and they were defined based on mean value and variance value of the solar irradiance. Similar situation would be for Rayleigh function in a way that scale parameter c is defined based on mean value of wind speed data [10].

Each scenario as described in the third part of Fig. 3, is generated through assigning a random variable to the cumulative version of the relative distribution function. This task will be continued till the desired number of scenarios is generated.

Thoroughly, several scenarios with the same probability are generated. To overcome the computation burden, the scenarios are reduced to a few scenarios with forward reduction method. In this sense, the probability of preserved scenarios will not be the same anymore and the probability of omitted scenarios is added to the preserved ones. Afterwards, power generation of PVs and WFs are calculated from wind speed and solar irradiance scenarios according to [10].

All this procedure is explained in Fig. 3. For simplicity, here, all zones are supposed to have the same wind and PV pattern. Thus, these scenarios are applied in the second stage of the problem to achieve the required regulation. The integrated network is realized as a radial network in the proposed model based on the assumption of being all connected to one larger (balancing) network and some NEMOs being located at the border of the overall market area so that they are located at the end of a branch without further connections.

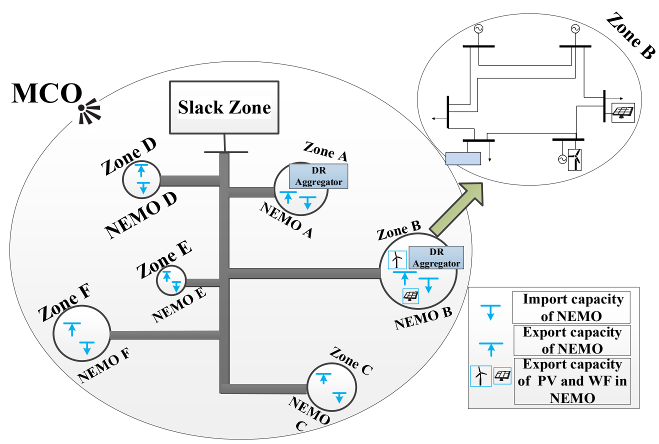

Fig. 2. The framework of the proposed market model.

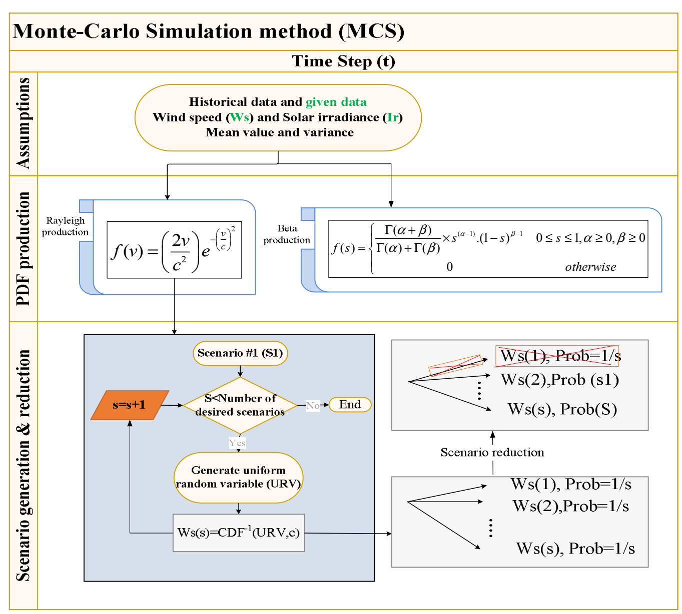

Fig. 3. Monte-Carlo Simulation method for scenario generation.

C. DR trading

DRAs play the role of DR trading on behalf of relative NEMO in this framework. They are in connection with other eligible NEMOs who are capable of DR participation. Therefore, they bid DR prices to exchange DR with different NEMOs under a market scheme operated by MCO.

IV. Problem Formulation

In this section, the stochastic two-stage programming model is formulated. The objective function and relative constraints are formulated in (1) – (9). Accordingly, (1) is the objective function from the MCO's viewpoint which aims to minimize the total operation cost. The first two lines are related to the first stage of the two-stage problem in the day-ahead market. The decision variables are $P_{t,n}^{LNEMO}, P_{t,n}^{NEMO}, reg_{t,n}^{LNEMO}, P\_DR_{t,n}$. The first term of the first line includes the cost of power exchange among EPEX spot market as the slack market and other NEMOs with UMP. When $P_{t,n}^{LNEMO}$ is negative, EPEX spot market would receive power from other NEMOs and when $P_{t,n}^{LNEMO}$ is positive, EPEX spot market would send power to other NEMOs. The second term is the cost of cross-border power exchange for other NEMOs. It is supposed that other normal NEMOs are just able to sell the extra power to MCO and they receive power without payment. The third term is the regulation cost provided by the EPEX spot market. The second line is the total DR cost for all DRAs in different NEMOs. The first term in the second line is the DR cost for relative DRA in one NEMO regarding the providing internal DR in the relative NEMO and the second term is associated with DR exchange among two NEMOs. It means, MCO will decide if DR for a NEMO should be provided by the DRA in the same NEMO or other DEMOs. The third line is the second stage of the problem that corresponds to the security cost for buying regulation in real-time market from EPEX spot market. The decision variable here is $regs_{t,n,s}^{LNEMO}$ that is the scheduled regulation from slack NEMO for real-time market.

$$
\begin{aligned}
Minimize \sum_{t\in NT} \Bigg\{ & \sum_{n\in NN} (C_{t,n}^{UMP} P_{t,n}^{LNEMO} + C_{t,n}^{MBP} P_{t,n}^{NEMO} + C_{t}^{reg} reg_{t,n}^{LNEMO}) \\
& + \sum_{n\in N\_DR} (P\_DR_{t,n} \lambda_{t,n} + \sum_{\substack{n'\in N\_DR \\ n'\neq n}} P\_DR_{tnn'}^{m} \lambda_{tn}) \\
& + \sum_{s\in S} prob_{s} \Big[Cs_{t}^{reg} regs_{t,n,s}^{LNEMO} \Big] \Bigg\}.
\end{aligned} \tag{1}
$$

Subject to

First stage constraints

$$
\begin{aligned}
& P_{t,n}^{LNEMO} + P.EX_{t,n}^{NEMO} - P.IM_{t,n}^{NEMO} + P.PV_{t,n}^{NEMO} + P.WF_{t,n}^{NEMO} - PF_{t,n}^{p} \\
& + P\_DR_{t,n} + \sum_{\substack{n'\in N\_DR \\ n'\neq n}} P\_DR_{tn'n}^{m} = 0
\end{aligned} \tag{2}
$$

$$
Q_{t,n}^{LNEMO} + Q.EX_{t,n}^{NEMO} - PF_{t,n}^{q} = Q.IM_{t,n}^{NEMO} \tag{3}
$$

$$
0 \le P_{tn}^{\bar{U}} \le P_{tn}^{\bar{U},Max} \qquad P_{t,n}^{LNEMO}, P_{t,n}^{NEMO}, reg_{t,n}^{LNEMO}, P\_DR_{t,n} \tag{4}
$$

$$
PF_{t,n}^{\bar{U},Min} \le PF_{t,n}^{\bar{U}} \le PF_{t,n}^{\bar{U},Max} \tag{5}
$$

$$
P\_DR_{t,n} \le \xi \times P.IM_{t,n}^{NEMO},\ P\_DR_{t,n,n'}^{m} \le \xi' \times P.IM_{t,n'}^{NEMO} \tag{6}
$$

Second stage constraints

$$
\begin{aligned}
& regs_{t,n,s}^{LNEMO} + \sum_{n\in PV} (P.PV.s_{t,n,s}^{NEMO} - P.PV_{t,n}^{NEMO}) + \sum_{n\in WF} (P.WF.s_{t,n,s}^{NEMO} - P.WF_{t,n}^{NEMO}) \\
& = PF_{t,n}^{p} - PF.s_{t,n,s}^{p}
\end{aligned} \tag{7}
$$

$$
\begin{aligned}
& Q.s_{t,n,s}^{LNEMO} + \sum_{n\in PV} (Q.PV.s_{t,n,s}^{NEMO} - Q.PV_{t,n}^{NEMO}) + \sum_{n\in WF} (Q.WF.s_{t,n,s}^{NEMO} - Q.WF_{t,n}^{NEMO}) \\
& = PF_{t,n}^{q} - PF.s_{t,n,s}^{q}
\end{aligned} \tag{8}
$$

$$
regs_{t,n,s}^{LNEMO} \le reg_{t,n}^{LNEMO},\ Q.s_{t,n,s}^{LNEMO} \le Q_{t,n}^{LNEMO} \tag{9}
$$

Equations (2) – (3) indicate active and reactive power balance. The second line of (2) is related to the DR quantity at each NEMO and time period. The first term (P_DR_{tn}) is DR quantity that DRA in the NEMO to provide DR from the own network at time step t and the second term ($P\_DR_{tn'n}^{m}$) is DR quantity that exchanges among different NEMOs. The limitation of power exchange among NEMOs in the network is represented in (4). Power flow limits are given in (5). The maximum possible DR quantity to be bought by each DRA in the same node and other nodes are presented in (6).

Equations (7) – (9) indicate the second-stage constraints of the two-stage problem. Balancing constraints for active and reactive power in different scenarios are in (7) – (8), and limitation for reserve is in (9).

V. Case Study and Numerical Results

In this section, the proposed method is evaluated in a symbolic European network. First, the case study is introduced, and then the result of implementing the proposed approach on the test system is brought and discussed.

A. Case study

It is assumed that the future integrated European market includes 15 NEMOs with nominal power 2300 GW as shown in Fig. 4. Four NEMOs are able to export conventional generation up to 690 GW to the integrated European network; two NEMOs have the capacity of 100 GW for PV farms to export. Two NEMOs have 100 GW for WFs export. UMP, MBP for each NEMO, and regulation price, Fig. 5.

In this work, three cases are considered to analyze different states of the proposed model. It is supposed that only two NEMOs are able to trade DR by relative DRAs. In this case, the DR interaction among these two NEMOs is studied with three different price schemes. The potential of DR participation would be twenty percent, moreover, ξ, ξ' are 10 and 4.5 percent, respectively.

The problem is solved by calling CPLEX solver in GAMS [23]. The simulation platform is a laptop with 2.7 GHz core i7 processor and 8 GB RAM. The solver time is 1.52 seconds.

B. Numerical results

Two DR-enabled NEMOs can trade DR in this case study. These NEMOs are able to provide DR from their own market or from the other NEMOs. With the definition of three cases which contain different DR prices for these two DR-enabled NEMOs, the interaction among them to exchange the DR is compared. In other words, according to the DR prices, the quantity of DR is scheduled.

It is noteworthy that in case 1 and 2, fixed DR prices for the whole day (24 hours - Table. I) are considered, while time-varying DR prices are considered for case 3 (Fig. 6).

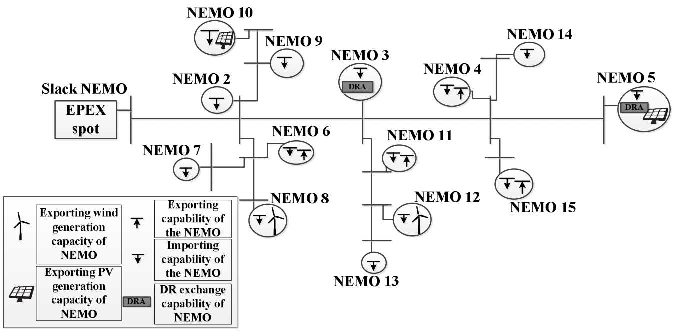

Fig. 4. Symbolic physical connection of future European market.

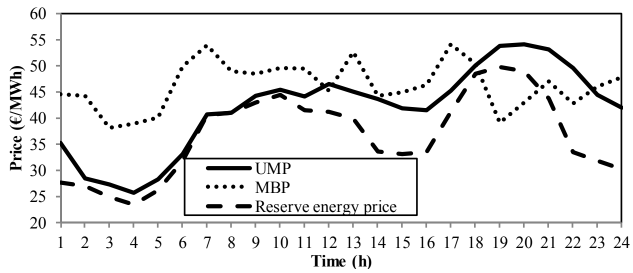

Fig. 5. Hourly different prices.

Table. I. Different DR prices for NEMO3 and NEMO5.

DR price (€/MWh)	Case 1	Case 2
DRA-3	40	40
DRA-5	40	35

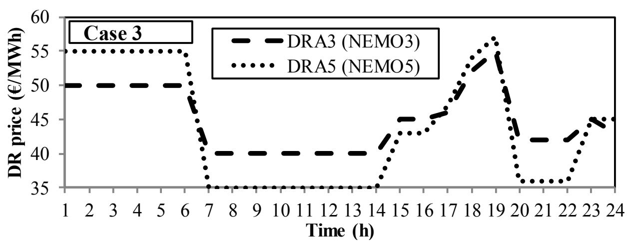

Fig. 6. DR prices for DRA3 and DRA5 in different hours. (case3).

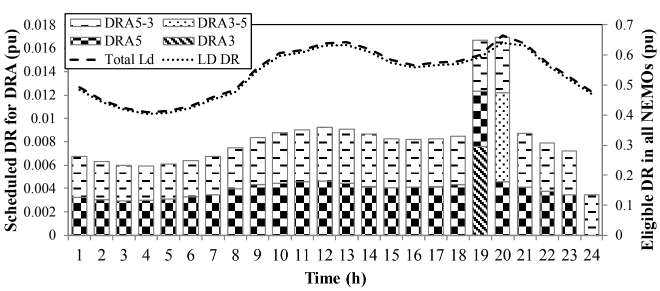

Fig. 7. Case 1 DR scheduling results.

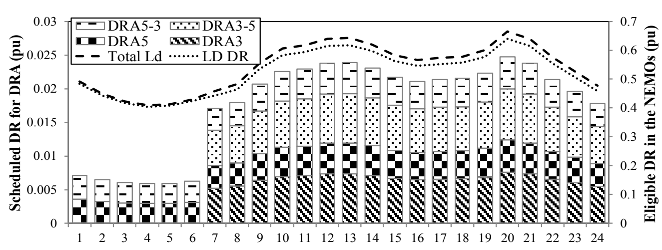

Fig. 8. Case2 DR scheduling results.

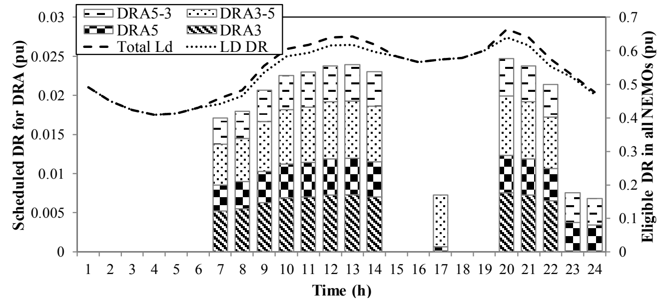

Fig. 9. Case 3 DR scheduling results.

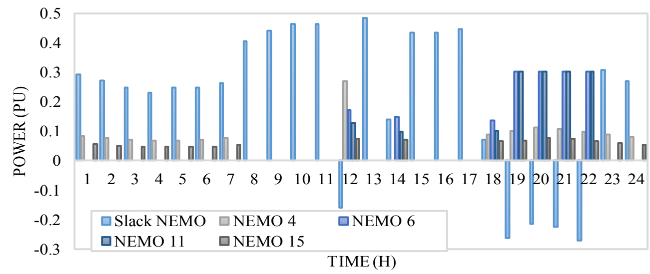

Fig. 10. Hourly scheduled power export for normal NEMOs and power exchange of slack NEMOs.

The results of the implementation of these cases with the proposed model are demonstrated in different figures and compared. Based on these figures, the hourly scheduled DR quantities during a day are compared with each other along with the total load curve without DR and after running DR. Noted that DRA3-5 is the purchased DR by NEMO 3 from NEMO 5. This definition is vice versa for DRA5-3.

The DR capacity in NEMO 3 is larger than one in NEMO 5 during a day, because NEMO 3 has more power input than NEMO 5. The results of case 1 and case 2 depicted in Fig. 7 and Fig. 8, show that fix DR tariffs have no meaningful DR scheduling because the DR potential is employed for all time steps. For example, in off-peak hours and also in hours with low UMC, there is no reason to pay for load curtailment. In case 1, as Fig. 7 shows, when DR tariff for both NEMOs are the same, NEMO 5 is scheduled to buy DR during even the off-peak hours and finally there is not enough DR to shave the load curve. In case 2 as Fig. 8 shows, however the DR tariffs are not the same, DR is again scheduled for off-peak hours (1-6) due to the lower DR price in NEMO 5 compared with UMP and MBP and even regulation price. Therefore, after comparison Fig. 7 and Fig. 8, it is concluded that load reduction in Fig. 8 with different DR tariff for DRAs is higher and also more reasonable than Fig.7 with similar DR tariff for DRAs.

The results shown in Fig. 9 demonstrate that once the DR prices are defined based on peak hours and UCM, the results are more desirable. Thoroughly, at off-peak hours and the hours with lower UMP including 1-6 and 15-19, almost no DR is scheduled because the DR prices are higher than the UMP. Moreover, at peak-hours, approximately, maximum possible DR quantities are exchanged among NEMOs, no matter which NEMO has the higher or lower DR price. At hour 17, although the UMP is lower than DR prices, DR is scheduled because the MBP is higher than the UMP and no power is bought from NEMOs at that hour. Thus, to overcome this power shortage, DR is the lowest-cost solution.

Fig. 10 demonstrates the hourly exported power from NEMOs purchased by MCO and hourly exchange power with the slack NEMO.

As it is obvious, when the UMP is higher, the operator prefers to buy from normal NEMOs and even sell the extra purchased power to slack NEMO/EPEX Spot market. Therefore, at hours 12 and 19-22, all NEMOs are exporting almost in their maximum potential to supply other normal NEMOs and also make a profit from selling to the EPEX spot market.

At other hours, depending on UMP and MBP, the required power is bought from the EPEX or from other normal NEMOs. For example, at hours 8-11 and 15-17, since the MBP is higher than the cross-zonal market price, the operator buys electric power from EPEX instead of using normal NEMOs.

VI. Conclusions

Within this work, a market structure with different market zones as currently realized in the European energy market is shown. Additionally to the zonal approach, an MCO coordinating the exchanges between the different zones as proposed in [2] is also assumed here. Within this implementation it is possible to lever possible synergies between the RES generation in different zones and coordinately optimize exchange powers between the different zones. Moreover, the proposed method is able to optimize the DR quantity to be bought by the MCO from NEMOs within the European cross-border electricity network. To this end, all the relative elements of such an integrated network as well as RESs uncertainties were modeled in a two-stage program. This model enabled MCO to buy DR from different NEMOs and seek for total operation cost minimization in day-ahead market while considering uncertainty of RESs generation in real-time. Results show that it would be beneficial to define the DR prices according to the UMP and peak hours. It means that the operator should have a look at different market prices to define the DR price in order to have an effective DR scheduling in the network. To this end, the operator proceeds to define the DR price after receiving the markets' information and send it back to relative markets. Moreover, the impact of UMP and MBP on the power exchange among NEMOs has discussed. For the future work, investigation about other physical connection in this market framework is suggested.

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