IET Generation, Transmission & Distribution

Research Article

Towards a fully integrated market for demand response, energy and reserves

ISSN 1751-8687
Received on 13th April 2016
Revised on 2nd August 2016
Accepted on 19th August 2016
doi: 10.1049/iet-gtd.2016.0567
www.ietdl.org

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Abstract: There is a trend for demand response (DR) market as a dedicated competitive environment for trading DR. In this market, aggregators participate as DR providers, while system operator, retailers and distributors are the DR buyers. Scheduling DR through the DR markets leads to a fair allocation of the benefits and payments across all participants. However, the integration of the DR markets into the existing power markets leads to technical and economic challenges. Those challenges associated with the integration of the DR markets into the energy/reserve markets are addressed in this study. To clear the DR markets jointly with the energy/reserve market, a bilevel approach is proposed in which the upper level belongs to energy/reserve market problem and the lower level includes DR market clearance. The proposed bilevel programming problem is then recast as a mixed-integer linear programming problem which can be solved using commercially available software. Finally, numerical results are provided to illustrate the performance of the proposed approach, demonstrating it brings about lower reserve price and higher social welfare compared with the existing markets.

Nomenclature

The main notation used in the paper is stated below. Some of the following constants and variables incorporate superscript U or D when referring to the upward or downward reserve/DR, respectively.

Indices and numbers

- n index of system buses, running from 1 to $N_{\rm B}$
- i index of generating units, running from 1 to $N_{\rm U}$
- j index of load points, running from 1 to $N_{\rm L}$
- m index of energy blocks offered by generating units, running from 1 to N_{Oi}
- g index of costumer groups, running from 1 to $N_{{\rm G}j}$
- b index of DR buyers, running from 1 to $N_{{\rm B}j}$
- l index of aggregators, running from 1 to $N_{{\rm A}j}$
- c index of customers, running from 1 to N_{Cl}

Variables

- $p_{Gi}(m)$ power output scheduled from the mth block of energy offered by unit i (MW). Limited to $p_{Gi}^{\max}(m)$
- R_{gi} spinning reserve scheduled for unit i (MW). Limited to $R_{gi}^{\max}$
- R_{dj} demand-side reserve scheduled at load point j (MW)
- SR spinning reserve demand (MW)
- P_{gi} power output of unit i (MW)
- P_{dj} power consumption at load point j (MW)
- s_{jbg} DR supplied to buyer b from costumer group g at load point j (MW)
- q_{jlc} DR provided by customer c of aggregator l at load point j (MW). Limited to $q_{jlc}^{\max}$
- $f(n, r)$ power flow through line (n, r). Limited to $f^{\max}(n, r)$
- δ_n voltage angle at node n (rad)
- u_i 0/1 variable that is equal to 1 if unit i is scheduled to be committed

Dual variables

Dual variables below are associated with the following constraints:

- γ_j DR supply–demand for transmission system operator and load j
- λ_{jbg} DR supply–demand for retailer/distributor b and costumer group g of load j
- $\bar{\mu}_{jlc}$ upper bound on DR provided by customer c of aggregator l at load point j
- $\underline{\mu}_{jlc}$ lower bound on DR provided by customer c of aggregator l at load point j

Constants

- $\lambda_i^{\rm S}$ start-up offer cost of unit i (\$)
- $\lambda_{Gi}(m)$ marginal cost of the mth block of energy offered by unit i (\$/MWh)
- $c_{gi}^{\rm R}$ offer cost of spinning reserve of unit i (\$/MWh)
- $c_{dj}^{\rm R}$ offer cost of DR reserve at load point j (\$/MWh)
- λ_{Lj} utility of consumer j (\$/MWh)
- $P_{gi}^{\min}/P_{gi}^{\max}$ minimum/maximum power output of unit i (MW)
- $P_{dj}^{\min}/P_{dj}^{\max}$ lower/upper elastic bound on P_{dj} (MW)
- σ fraction of total load, defining a lower bound of SR
- α_{jbg}/β_{jbg} coefficients of DR demand function of buyer b from costumer group g of load j(\$/MWh^2)/(\$/MWh)
- a_{jlc}/b_{jlc} coefficients of DR supply function offered by customer c of aggregator l at load point j (\$/MWh^2)/(\$/MWh)
- θ_{jlc} willingness of customer c of aggregator l at load point j to provide DR
- $B(n, r)$ absolute value of the imaginary part of theadmittance of line (n, r) (p.u.)

Sets

- Λ set of transmission lines
- $M_{\rm U}$ mapping of the sets of generating units into the set of buses

M_L mapping of the set of loads into the set of buses
M_C mapping of the sets of costumer groups into the set of loads

1 Introduction

Operating reserve plays a crucial role in maintaining an acceptable level of security in modern power systems. The random generator outages, stochastic nature of the renewable generations and demand and so on necessitate the reserve scheduling in power systems in order to reduce the risk of blackouts. In electricity markets, transmission system operators (TSOs) are responsible for secure and efficient operation of the power system. Hence, the TSO must procure an appropriate level of reserve with the aim of secure operation.

The real-time operation of a power system requires that the TSOs ensure a continuous balance between supply and demand. Therefore, a balancing mechanism should exist in electricity markets with the aim of maintaining the balance in the power system. The purpose of the balancing markets is to provide short-term operational security of the supply and grid operation in a market-oriented way. The time scale of the balancing markets extends from months before the trading (to ensure capacity allocation) to the day ahead and real time. These balancing markets are known by different names in power systems. For example, it is referred as real-time balancing market in Pennsylvania-New Jersey-Maryland (PJM) [1], real-time energy markets in Independent System Operator of New England (ISO-NE) [2], regulating market in the Nordic system [3] and frequency control ancillary services market in Australia [4]. In the European electricity markets, provision of balancing services is shared between balance responsible parties (BRPs) and the TSOs. A BRP is a private legal entity that takes up the responsibility to compose a balanced portfolio. In the balancing markets, different types of reserves are procured by the TSOs or BRPs such as, frequency containment reserves, frequency restoration reserves and replacement reserves.

In the existing electricity markets, there are different approaches for the procurement and settlement of the operating reserves. In some markets, such as New York Independent System Operator (NYISO) [5] and Midwest Independent System Operator (MISO) [6], energy and reserve prices are determined simultaneously through an integrated co-optimisation of the energy and reserve [7]. Separate optimisations for energy and reserve are carried out in some other markets, e.g. PJM, for scheduling the reserve. However, these optimisations include coupled constraints. Finally, some TSOs, such as ISO-NE, run separate parallel optimisations for scheduling the energy and reserve. The joint scheduling of the energy and reserve has been addressed in the literature [8–11]. In these models, beside the energy offers, the generating companies bids for providing reserves. Then, the TSO allocates the system reserve requirements according to the submitted offers.

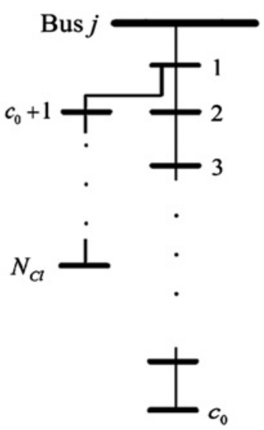

Fig. 1 *Customer load points at distribution level*

In some of the existing markets, demand response (DR) resources are permitted to participate in the energy/reserve market as well as the supply side (e.g. MISO). The demand-side reserve offer in the energy/reserve markets has been studied in [12–14]. A joint clearing model for the energy/reserve market with DR reserve offers was proposed in [12]. The effects of DR on a market with probabilistic reserve were investigated in [13]. Karangelos and Bouffard [14] investigated the impacts of the load recovery in energy/reserve markets with demand-side participation. The use of DR in the security-constrained unit commitment was investigated in [15–17], showing that the DR can reduce the system operation costs, air pollution and transmission congestion. In [18–21], it was shown that the DR can facilitate the integration of the renewable energy resources in the power systems.

In practice, the DR has been implemented successfully for large industrial customers. However, the application of DR in residential sector is a challenging task. This paper focuses on the DR provided by the small businesses and domestic consumers. As these customers have distinct characteristics, they should be treated differently from the major industrial loads.

DR produced by a single small customer is not tradable in the wholesale market, as it cannot match buyer requirements at the aggregated levels. For example, the TSO generally requires DR from customers in groups (corresponding to the different transmission load points), but does not need to know which customers are exactly the providers [14]. This has provided opportunities for the aggregators to join the electricity markets. The aggregators are independent agents that combine multiple consumers into a single unit to negotiate purchase from the retailers. In many real markets in Australia and the USA, aggregators developed dedicated systems for their customers to register, aggregate, schedule, dispatch and settle the DRs requested by the supply-side players [22]. They connect customers, as the DR sellers, to the DR buyers to trade a range of products or services. TSO, retailers and distributors are the examples of the DR buyers.

Following the growing trend of the DR-related business companies in real electricity markets, two serious concerns may arise about their technical and financial efficiency. One is related to the DR trading and scheduling. The DR as a virtual resource is conceptually different from the electricity, in the sense that each single DR quantity may be jointly used by multiple players. The TSO needs the DR to manage network congestion. These situations often happen in high loading conditions, i.e. peak hours. Similarly, distributors need the DR to resolve their distribution network problems such as, overloading of feeders and voltage violations. These critical conditions happen in high loading conditions, too. Finally, retailers purchase DR to reduce their risk against price spikes in the wholesale electricity markets. Price spikes often happen in peak hours. Therefore, there are situations, e.g. peak hours, where 1 MW of DR will benefit several buyers, at the same time. Hence, it seems that DR should be traded and settled in a different way from the electricity. This concern is addressed in [23] by proposing a separate market for trading the DR. In such DR markets, DR sellers (aggregators) and DR buyers (TSO, retailers and distributors) join a pool-based environment for exchanging DR as a public good.

Another concern towards retail DR trading is about the interactions between the DR markets and other existing markets. The main aim of the DR markets is to provide services to energy market participants, i.e. TSOs, retailers and distributors. Therefore, DR markets cannot operate effectively without interacting with the larger energy market. Moreover, the technical and physical constraints of the power system may influence the clearance of the DR markets. For the purpose of optimal coordination and management of the resources, i.e. energy, DR, reserves and so on, and also taking technical/physical constraints of the power system into account, the DR markets should be cleared jointly with the energy/reserve markets. This paper tries to integrate the retail DR markets into the wholesale energy markets, to address the following issues: How much is the DR needed by the TSO at each load point? How much is the price of the DR for each DR buyer? To what extent can the DR be integrated into the market in each load point? What is the effect of DR on the energy/reserve price at each load point? How does the DR influence the commitment and scheduling of the generating units?

Following the recent attempts for utilising DR markets to cover wind power uncertainty effects [24–26], this paper proposes a bilevel approach for joint clearance of the energy/reserve and DR markets. In the proposed bilevel model, the upper-level problem represents a deterministic model for energy/reserve market with the DR reserve offers. At this level, based on the system requirements for operating reserve and considering technical and economic aspects, the TSO's demand for the DR is determined. At the lower level, the clearance of the DR market is modelled considering all the market participants. At the lower level, the TSO's demand for the DR, determined at the upper level, and other DR buyers' demand (retailers and distributors) are allocated based on the aggregators' offers.

The proposed bilevel programming problem, which includes bilinear products of the decision variables, is linearised and formulated as a single-level mixed-integer linear programming (MIP) problem based on the Karush–Kuhn–Tucker (KKT) optimality conditions [27] and some linearisation rules. Using a commercially available software, such as CPLEX [28], a global optimal solution can be obtained for the resulting MIP formulation.

In summary, the contributions of this paper are twofold:

- Proposing a bilevel model where DR and energy/reserve markets are jointly cleared.
- Presenting case studies with realistic situations to show the interactions between the two markets in regards to the scheduled prices and qualities.

The rest of the paper is organised as follows. In Section 2, the energy/reserve and DR markets formulation are reported and the combination of these markets via the proposed bilevel model is described. Section 3 discusses on solution approach for the bilevel model. In Section 4, numerical examples are presented based on two test systems to illustrate the application of the proposed method. Relevant conclusions are drawn in Section 5. Finally, the complete formulation for the equivalent MIP problem of the proposed model is provided in the Appendix.

2 Model

2.1 Energy/reserve market

The energy and reserve market is jointly cleared by the TSO with the objective of minimising the system operation costs. To clear the energy/reserve market, the TSO collects selling and purchase offers from the generation companies and demand side, respectively. The generating companies can offer for the energy as well as the spinning reserves. The demand-side reserve offers are considered as well. Single-period scheduling, which is simpler to describe and analyse, is considered. For the sake of simplicity, deterministic criteria are used to derive system reserve requirements [12]. However, stochastic energy/reserve market clearing models [11] can also be implemented [29]. The energy/reserve market clearing problem is as follows.

Minimise

$$J_1 = \sum_{i=1}^{N_\mathrm{U}} \left(\lambda_i^\mathrm{S} u_i + \sum_{m=1}^{N_{Oi}} \lambda_{Gi}(m) p_{Gi}(m) + c_{gi}^\mathrm{RU} R_{gi}^\mathrm{U} + c_{gi}^\mathrm{RD} R_{gi}^\mathrm{D} \right) + \sum_{j=1}^{N_\mathrm{L}} \left(-\lambda_{Lj} P_{dj} + c_{dj}^\mathrm{RU} R_{dj}^\mathrm{U} + c_{dj}^\mathrm{RD} R_{dj}^\mathrm{D} \right) \quad (1)$$

subject to

$$\sum_{i:(i,n)\in M_\mathrm{U}} P_{gi} - \sum_{j:(j,n)\in M_\mathrm{L}} P_{dj} - \sum_{r:(n,r)\in \Lambda} f(n,r) = 0, \quad \forall n \quad (2)$$

$$-f^{\max}(n,r) \le f(n,r) \le f^{\max}(n,r), \quad \forall (n,r) \in \Lambda \quad (3)$$

$$f(n,r) = B(n,r)\left(\delta_n - \delta_r\right) \quad (4)$$

$$0 \le p_{Gi}(m) \le p_{Gi}^{\max}(m), \quad \forall m, \forall i \quad (5)$$

$$P_{gi} = \sum_{m=1}^{N_{Oi}} p_{Gi}(m), \quad \forall i \quad (6)$$

$$P_{gi}^{\min} u_i \le P_{gi} \le P_{gi}^{\max} u_i, \quad \forall i \quad (7)$$

$$P_{dj}^{\min} \le P_{dj} \le P_{dj}^{\max}, \quad \forall j \quad (8)$$

$$\sum_{i=1}^{N_\mathrm{U}} R_{gi}^\mathrm{U} + \sum_{j=1}^{N_\mathrm{L}} R_{dj}^\mathrm{U} = \mathrm{SR}^\mathrm{U} \quad (9)$$

$$\sum_{i=1}^{N_\mathrm{U}} R_{gi}^\mathrm{D} + \sum_{j=1}^{N_\mathrm{L}} R_{dj}^\mathrm{D} = \mathrm{SR}^\mathrm{D} \quad (10)$$

$$\mathrm{SR}^\mathrm{U} \ge P_{gi} + R_{gi}^\mathrm{U}, \quad \forall i \quad (11)$$

$$\mathrm{SR}^\mathrm{U} \ge \sigma^\mathrm{U} \sum_{j=1}^{N_\mathrm{L}} P_{dj} + \sum_{j=1}^{N_\mathrm{L}} R_{dj}^\mathrm{U}, \quad \sigma^\mathrm{U} \in (0,1) \quad (12)$$

$$\mathrm{SR}^\mathrm{D} \ge \sigma^\mathrm{D} \sum_{j=1}^{N_\mathrm{L}} P_{dj}, \quad \sigma^\mathrm{D} \in (0,1) \quad (13)$$

$$0 \le R_{gi}^\mathrm{U} \le P_{gi}^{\max} u_i - P_{gi}, \quad \forall i \quad (14)$$

$$0 \le R_{gi}^\mathrm{D} \le P_{gi} - P_{gi}^{\min} u_i, \quad \forall i \quad (15)$$

The objective function (1) indicates minimisation of operation costs, including the costs of units' energy production and start-up and scheduling reserve provided by supply and demand sides. This objective function is subject to the following constraints. DC power flow equations and transmission capacity constraints are included in (2)–(4). Constraints (5) and (6) approximate the energy offer cost function of the generating units by m-block price–quota curves. Limits on the produced and consumed energy are included in (7) and (8), respectively. Constraints (9) and (10) enforce the balance of up- and down-spinning reserves, respectively. The lower bound on the system requirements for up-spinning reserve is modelled in (11) and (12). Constraint (11) indicates that the up-spinning reserve should cover the loss of the largest committed generator ($n-1$ contingency criteria), while (12) considers the possibility of sudden increase of the total demand [12]. Lower limit on down-spinning reserve, unexpected decrease in total demand, is enforced in (13). Limits on up- and down-spinning reserves are shown in (14) and (15), respectively.

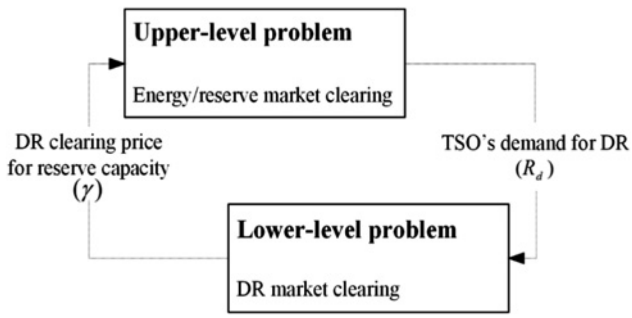

Fig. 2 *Proposed bilevel model*

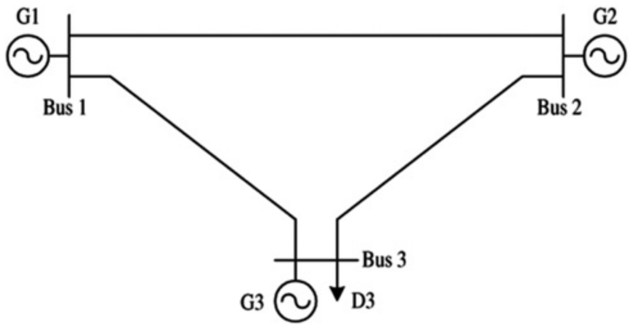

Fig. 3 *Test system*

Table 1 Generator data

Unit i	1	2	3
$P_{gi}^{\min}$, MW	10	10	10
$P_{gi}^{\max}$, MW	100	100	50
$\lambda_{Gi}(1)$, \$/MW	30	40	20
λ_i^{SU}, \$/MW	100	100	100
c_i^{RU}, \$/MW	5	7	8
c_i^{RD}, \$/MW	5	7	8

2.2 DR market

The DR market is cleared separately from the energy and reserve market. In a pool-based DR market, DR, as a virtual commodity, is exchanged between the buyers and sellers. The DR buyers may be the TSO, retailers and distributors while the DR sellers are aggregators. Via aggregators, retail electricity consumers can also participate in the DR market as the DR sellers. The aggregators are allowed to offer for both the upward and downward DR. The DR buyers can participate in the DR market to improve the reliability and efficiency of their network and markets. However, there are differences in modelling the DR buyers in the DR market. The TSO utilises DR for managing security of the transmission networks. Therefore, the TSO generally needs the DR provided by a group of customers corresponding to a transmission load point. However, retailers need the DR provided by small single customers at the distribution level who are in contract with them to cover risks caused by spot price volatility in the wholesale spot markets. Also, distributors need the DR to manage their network constraints at the distribution level. Hence, they may need DR provided by the certain customers connected at the certain distribution feeders.

The DR market operator is responsible for clearing the DR market with the aim of maximising DR buyers' benefits as well as minimising DR costs. The participation of the retailers and distributors in the DR market is modelled through quadratic benefit functions. Moreover, it is supposed that retailers and distributors reveal their DR benefit functions, honestly. Hence, 'obligatory contribution' constraint, proposed in [23] to enforce the DR buyers to honestly reveal their benefits, is not considered in this paper. The formulation of DR market clearing is as follows.

Maximise (see (16))

Table 2 Market clearing results

	Case I	Case II
P_{g1}, MW	10	10
P_{g2}, MW	10	0
P_{g3}, MW	35	45
R_{g1}^{U}, MW	25	40
R_{g2}^{U}, MW	10	0
R_{g3}^{U}, MW	0	5
R_{d3}^{U}, MW	0	5

subject to

$$R_{dj}^{\mathrm{U}} = \sum_{l=1}^{N_{\mathrm{A}j}} \sum_{c=1}^{N_{Cl}} q_{jlc}^{\mathrm{U}} : \gamma_j^{\mathrm{U}}, \quad \forall j \tag{17}$$

$$R_{dj}^{\mathrm{D}} = \sum_{l=1}^{N_{\mathrm{A}j}} \sum_{c=1}^{N_{Cl}} q_{jlc}^{\mathrm{D}} : \gamma_j^{\mathrm{D}}, \quad \forall j \tag{18}$$

$$s_{jbg}^{\mathrm{U}} = \sum_{l=1}^{N_{\mathrm{A}j}} \sum_{c=1}^{N_{Cl}} q_{jlc}^{\mathrm{U}} u_{lc}^{bg} : \lambda_{jbg}^{\mathrm{U}}, \quad \forall j, \forall b, \forall g \tag{19}$$

$$s_{jbg}^{\mathrm{D}} = \sum_{l=1}^{N_{\mathrm{A}j}} \sum_{c=1}^{N_{Cl}} q_{jlc}^{\mathrm{D}} u_{lc}^{bg} : \lambda_{jbg}^{\mathrm{D}}, \quad \forall j, \forall b, \forall g \tag{20}$$

$$0 \le q_{jlc}^{\mathrm{U}} \le q_{jlc}^{\mathrm{U,\max}} : \bar{\mu}_{jlc}^{\mathrm{U}}, \underline{\mu}_{jlc}^{\mathrm{U}}, \quad \forall j, \forall l, \forall c \tag{21}$$

$$0 \le q_{jlc}^{\mathrm{D}} \le q_{jlc}^{\mathrm{D,\max}} : \bar{\mu}_{jlc}^{\mathrm{D}}, \underline{\mu}_{jlc}^{\mathrm{D}}, \quad \forall j, \forall l, \forall c \tag{22}$$

The objective function of the DR market clearing problem in (16) represents the sum of the benefit function of the retailer and distributors minus the total DR cost. It is assumed that buyer b, who may be a retailer or a distributor, offers quadratic benefit functions for each of his/her associated customer group g [23]. Similarly, the aggregators' cost functions assumed non-decreasing quadratic functions. Constraints (17) and (18) state the upward and downward DR demand–supply balance for the TSO, respectively. The upward and downward DR demand–supply balance constraints for retailers and distributors are stated in (19) and (20), respectively. It should be noted that from the view point of the TSO, all aggregators located at a transmission bus are identical while for retailers and distributors the aggregators may be different in terms of contract types and feeder load point at the distribution level. To consider this fact in formulation of the DR market, customers of the aggregator l located at the transmission node j, are denoted by $c = 1, \ldots, N_{Cl}$ according to their location on the distribution network (see Fig. 1). Then, for buyer b who may be a retailer or a distributor, customer group $N_{\mathrm{G}b}$ is considered. The distributor can group the customers based on their geographical positions within a distribution feeder. For example, the distributor may choose one group of customers connected to the load point 1, one with load point 2, …, and the last one with load point N_{Cl} of the distribution networks in Fig. 1. For the retailer, customers holding the same type of contracts with him/her can be arranged in one group. For example, the retailer may choose one group of

$$J_2 = \sum_{j=1}^{N_{\mathrm{L}}} \sum_{b=1}^{N_{\mathrm{B}j}} \sum_{g=1}^{N_{\mathrm{G}b}} \left\{ \left(-\alpha_{jbg}^{\mathrm{U}} (s_{jbg}^{\mathrm{U}})^2 + \beta_{jbg}^{\mathrm{U}} s_{jbg}^{\mathrm{U}} \right) + \left(-\alpha_{jbg}^{\mathrm{D}} (s_{jbg}^{\mathrm{D}})^2 + \beta_{jbg}^{\mathrm{D}} s_{jbg}^{\mathrm{D}} \right) \right\} - \sum_{j=1}^{N_{\mathrm{L}}} \sum_{l=1}^{N_{\mathrm{A}j}} \sum_{c=1}^{N_{Cl}} \left\{ \left(a_{jlc}^{\mathrm{U}} (q_{jlc}^{\mathrm{U}})^2 + b_{jlc}^{\mathrm{U}} (1-\theta_{jlc}) q_{jlc}^{\mathrm{U}} \right) + \left(a_{jlc}^{\mathrm{D}} (q_{jlc}^{\mathrm{D}})^2 + b_{jlc}^{\mathrm{D}} (1-\theta_{jlc}) q_{jlc}^{\mathrm{D}} \right) \right\} \tag{16}$$

Table 3 DR clearing prices and energy/reserve market objective

	Case I	Case II
γ_3^{U}, \$/MW	50	22.5
$\lambda_{31}^{\mathrm{U}}=\lambda_{32}^{\mathrm{U}}$, \$/MW	0	15
J_1, \$	1895	1752.5

customers with load points $c = 1, \ldots, c_0$ who are in a specific contract, and one with load points $c = c_0 + 1, \ldots, N_{Cl}$ who are in another contract type. Binary coefficients u_{lc}^{bg} represent a relational status of each customer c of the aggregator l to the group g of the DR buyer b [23]. It must be noted that the dual variables of the DR demand–supply balance constraints, which are known as shadow prices [27], determine the price of the DR for TSO (γ_j) and retailers/distributors (λ_{jbg}). The upper and lower bounds on the upward and downward DR which can be provided by the aggregator l are enforced by constraints (21) and (22), respectively.

2.3 Combining DR market with energy/reserve market

In practice, DR cannot be exchanged in a separate market, omitting the interactions between the DR market and other electricity markets. In fact, DR is a minor resource beside the electricity, as the major resource, which may be integrated into the electricity markets to improve reliability of both network and market. In other words, demand for the DR depends on operating conditions of the electricity market. For example, the TSO's demand for DR cannot be predicted easily since it depends on the load as well as technical and physical conditions of the power systems.

To overcome the above-mentioned limitation of the DR markets, a bilevel approach is proposed with the aim of the simultaneous energy/reserve and DR markets clearing. In the proposed bilevel model, the upper-level problem belongs to the energy/reserve market clearing problem. The DR market clearing is considered as the lower-level problem. The interaction between these two levels is depicted in Fig. 2, where the TSO's demand for the DR is determined at the upper-level problem. The TSO's demand for the DR is determined based on the system requirement for the operating reserve. Then, at the lower level, the DR market is cleared and the DR prices are discovered. Therefore, the DR prices for reserve capacity, which are unknown at the upper level, are determined in the lower level. Hence, the parameters c_{dj}^{RU} and c_{dj}^{RD} in (1) is replaced by DR clearing prices for the reserve capacity, i.e. γ_j^{U} and γ_j^{D} which are the dual variables of (17) and (18), respectively. The objective function of the energy/reserve market can be rewritten as follows

$$J_1 = \sum_{i=1}^{N_{\mathrm{U}}}\left(\lambda_i^{\mathrm{S}} u_i + \sum_{m=1}^{N_{Oi}} \lambda_{Gi}(m) p_{Gi}(m) + c_{gi}^{\mathrm{RU}} R_{gi}^{\mathrm{U}} + c_{gi}^{\mathrm{RD}} R_{gi}^{\mathrm{D}}\right) + \sum_{j=1}^{N_{\mathrm{L}}}\left(-\lambda_{Lj} P_{dj} + \gamma_j^{\mathrm{U}} R_{dj}^{\mathrm{U}} + \gamma_j^{\mathrm{D}} R_{dj}^{\mathrm{D}}\right) \tag{23}$$

It should be noted that since the TSO's demand for DR is determined at the upper-level problem, the benefit function of TSO, as a DR buyer, is excluded from the objective function of the lower-level problem (16). Determination of the DR demand for other DR buyers, i.e. retailers and distributors, is out of the scope of this paper. Therefore, simple DR benefit functions are assumed for the retailers and distributors in (16). Finally, the proposed bilevel model for the joint clearance of DR and energy/reserve market is stated below

$$\underset{P_{gi}, R_{gi}^{\mathrm{U}}, R_{gi}^{\mathrm{D}}, R_{dj}^{\mathrm{U}}, R_{dj}^{\mathrm{D}}}{\text{Minimise}} \quad (23) \tag{24}$$

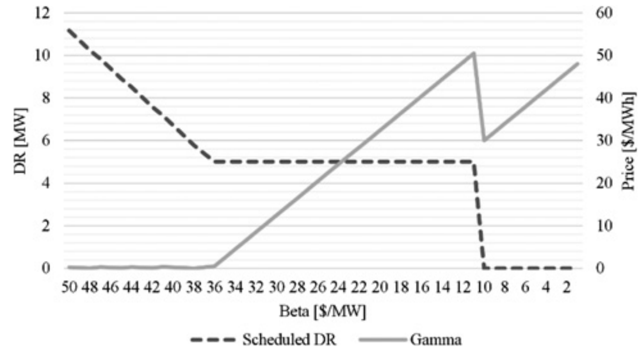

Fig. 4 *Effect of DR buyers' benefit function*

subject to

$$(1)-(15). \tag{25}$$

where

$$\gamma_j^{\mathrm{U}}, \forall j;\ \gamma_j^{\mathrm{D}}, \forall j \in \arg\left\{ \underset{\gamma_j^{\mathrm{U}}, \gamma_j^{\mathrm{D}}}{\text{Maximise}} \quad (16) \right. \tag{26}$$

subject to

$$\left. (17)-(22) \right\} \tag{27}$$

3 MIP formulation

In this paper, the presented benefit functions for the retailers and distributors are strictly concave while the DR cost functions of the aggregators in (16) are strictly convex. Consequently, the lower-level problem (16)–(22) is a convex optimisation problem with linear equality and inequality constraints. Hence, to transform the bilevel problem (1)–(22) into a single-level problem, the lower-level problem is replaced by its KKT optimality conditions [27]. The KKT conditions for the lower-level problem are stated below

$$2a_{jlc}^{\mathrm{U}} q_{jlc}^{\mathrm{U}} + b_{jlc}^{\mathrm{U}}(1-\theta_{jlc}) + \gamma_j^{\mathrm{U}} + \sum_{b=1}^{N_{bj}} \sum_{g=1}^{N_{Gb}} \lambda_{jbg}^{\mathrm{U}} u_{lc}^{bg} + \underline{\mu}_{jlc}^{\mathrm{U}} - \bar{\mu}_{jlc}^{\mathrm{U}} = 0, \quad \forall j,\ \forall l,\ \forall c \tag{28}$$

$$2a_{jlc}^{\mathrm{D}} q_{jlc}^{\mathrm{D}} + b_{jlc}^{\mathrm{D}}(1-\theta_{jlc}) + \gamma_j^{\mathrm{D}} + \sum_{b=1}^{N_{bj}} \sum_{g=1}^{N_{Gb}} \lambda_{jbg}^{\mathrm{D}} u_{lc}^{bg} + \underline{\mu}_{jlc}^{\mathrm{D}} - \bar{\mu}_{jlc}^{\mathrm{D}} = 0, \quad \forall j,\ \forall l,\ \forall c \tag{29}$$

$$-2\alpha_{jbg}^{\mathrm{U}} s_{jbg}^{\mathrm{U}} + \beta_{jbg}^{\mathrm{U}} - \lambda_{jbg}^{\mathrm{U}} = 0, \quad \forall j,\ \forall b,\ \forall g \tag{30}$$

$$-2\alpha_{jbg}^{\mathrm{D}} s_{jbg}^{\mathrm{D}} + \beta_{jbg}^{\mathrm{D}} - \lambda_{jbg}^{\mathrm{D}} = 0, \quad \forall j,\ \forall b,\ \forall g \tag{31}$$

$$\sum_{l=1}^{N_{Aj}} \sum_{c=1}^{N_{Cl}} q_{jlc}^{\mathrm{U}} - R_{dj}^{\mathrm{U}} = 0, \quad \forall j \tag{32}$$

Table 4 Energy/reserve market results

	Case I	Case II	Case III
number of committed units	22	19	16
spinning reserve, MW	400	324.75	288.95
DR reserve, MW	—	75.25	111.05
reserve price, \$/MW	7.60	7.60	5.68

Table 5 Market and participants outcome

		Case II	Case III
energy/reserve market	objective function, \$	43284.73	42561.43
DR market	TSO surplus, \$	297.29	1020.59
	retailers/distributors surplus, \$	71.78	145.39
	costumer surplus, \$	89.73	181.73
energy/reserve market with DR participation	total market surplus, \$	458.8	1347.71

$$\sum_{l=1}^{N_{Aj}}\sum_{c=1}^{N_{Cl}} q^{D}_{jlc} - R^{D}_{dj} = 0, \quad \forall j \tag{33}$$

$$\sum_{l=1}^{N_{Aj}}\sum_{c=1}^{N_{Cl}} q^{U}_{jlc}u^{bg}_{lc} - s^{U}_{jbg} = 0, \quad \forall j,\ \forall b,\ \forall g \tag{34}$$

$$\sum_{l=1}^{N_{Aj}}\sum_{c=1}^{N_{Cl}} q^{D}_{jlc}u^{bg}_{lc} - s^{D}_{jbg} = 0, \quad \forall j,\ \forall b,\ \forall g \tag{35}$$

$$0 \le q^{U}_{jlc} \perp \underline{\mu}^{U}_{jlc} \ge 0, \quad \forall j,\ \forall l,\ \forall c \tag{36}$$

$$0 \le (q^{U,\max}_{jlc} - q^{U}_{jlc}) \perp \bar{\mu}^{U}_{jlc} \ge 0, \quad \forall j,\ \forall l,\ \forall c \tag{37}$$

$$0 \le q^{D}_{jlc} \perp \underline{\mu}^{D}_{jlc} \ge 0, \quad \forall j,\ \forall l,\ \forall c \tag{38}$$

$$0 \le (q^{D,\max}_{jlc} - q^{D}_{jlc}) \perp \bar{\mu}^{D}_{jlc} \ge 0, \quad \forall j,\ \forall l,\ \forall c \tag{39}$$

The symbol $\perp$ is used to denote a complement condition in a compact form. The above-mentioned KKT conditions are necessary for the optimality of the DR market problem. Since the lower-level problem is convex, these conditions are sufficient for optimality. Therefore, by adding (28)–(39) as a constraint into the upper-level problem (1)–(15), the bilevel problem is transformed to a single-level mixed-integer non-linear programming problem. The non-linearities that may exist in the model and their equivalent linearisations are as follows:

- Bilinear products of the lower-level variables γ^{U}_{j} and γ^{D}_{j} and the upper-level decision variables R^{U}_{dj} and R^{D}_{dj} in (1). In order to linearise these bilinear products, a binary expansion [30] is applied to the variables R^{U}_{dj} and R^{D}_{dj}. For example, to linearise $\gamma^{U}_{j}R^{U}_{dj}$, the variable R^{U}_{dj} is approximated by a set of discrete values $\left\{R^{U}_{dj,h},\ h = 1, \ldots, H\right\}$, in which $H = 2^{K_1}$ for non-negative integer K_1. The binary expansion of R^{U}_{dj} is expressed by

$$R^{U}_{dj} = \Delta^{U}_{j}\sum_{k=1}^{K_1} 2^{k}x^{U}_{jk}, \quad \forall j \tag{40}$$

where $\Delta^{U}_{j} = \bar{R}^{U}_{dj}/H$, in which $\bar{R}^{U}_{dj}$ is an upper bound on R^{U}_{dj}, and x^{U}_{jk} is a binary variable.

Multiplying both sides of (40) by γ^{U}_{j}, we obtain

$$\gamma^{U}_{j}R^{U}_{dj} = \Delta^{U}_{j}\sum_{k=1}^{K_1} 2^{k}x^{U}_{jk}\gamma^{U}_{j}, \quad \forall j \tag{41}$$

Now, the product of variables in $z^{U}_{jk} = x^{U}_{jk}\gamma^{U}_{j}$ can be modelled by the following linear constraints

Table 6 Market results in congested case

	Reserve price without DR, \$/MWh	Reserve price with DR, \$/MWh	DR penetration, (%
base case	7.60	5.68	4.03
congested case	10.82	5.68	6.08

$$0 \le \gamma^{U}_{j} - z^{U}_{jk} \le G(1 - x^{U}_{jk}), \quad \forall j,\ \forall k \tag{42}$$

$$0 \le z^{U}_{jk} \le Gx^{U}_{jk}, \quad \forall j,\ \forall k \tag{43}$$

where $z^{U}_{jk} = x^{U}_{jk}\gamma^{U}_{j}$, and G is a large enough scalar for the relaxation of constraints (42) and (43) when $x^{U}_{jk} = 0$ and $x^{U}_{jk} = 1$, respectively.

- Products of dual variables of constraints (21) and (22) and lower-level decision variable q^{U}_{jlc} and q^{D}_{jlc} in complementary slackness conditions of the lower-level problem (36)–(39). As suggested in [31], these complementary slackness conditions can be formulated as mixed-integer linear expressions. For example, the linear formulation of (36) is as follows

$$q^{U}_{jlc} \ge 0, \quad \forall j,\ \forall l,\ \forall c \tag{44}$$

$$\underline{\mu}^{U}_{jlc} \ge 0, \quad \forall j,\ \forall l,\ \forall c \tag{45}$$

$$q^{U}_{jlc} \le \underline{w}^{U}_{jlc}M^{P}, \quad \forall j,\ \forall l,\ \forall c \tag{46}$$

$$\underline{\mu}^{U}_{jlc} \ge \underline{w}^{U}_{jlc}(1 - M^{P}), \quad \forall j,\ \forall l,\ \forall c \tag{47}$$

where $\underline{w}^{U}_{jl}$ is an auxiliary binary variable, and M^{P} is a large enough constant [31].

After substituting the lower-level problem by its KKT conditions and the above-mentioned linearisations, the bilevel model (1)–(22) can be presented as a single-level MIP (see Appendix) and then solved by a commercially available branch-and-cut software [28].

4 Numerical results

4.1 Small-scale study

The illustrative example presented in this section is based on a three-bus system shown in Fig. 3. Table 1 reports the generator data, extracted from [32]. A single block of the energy offer is assumed for the generating units. The transmission lines have no resistance but the reactance of 0.13 p.u. The demand on bus 3 is assumed 55 MW.

In the test system, there is one TSO, one retailer and one distributor. The aggregator is located on the bus 3 and offers for providing up-spinning reserve. To show the importance of the DR reserve in the energy and reserve scheduling, it is assumed that the cost of the DR is very high. The coefficients of the cost function of the aggregator are 0.25 \$/MWh^2 and 1000 \$/MWh with $\theta_{jl} = 0.95$. The coefficients of the supply function of the retailer and distributor are the same and assumed 1 \$/MWh^2 and 25 \$/MWh.

To reduce the number of problem constraints, only the lower bound on the up-spinning reserve (11), defined by the $n - 1$ security criterion, has been applied. The proposed bilevel problem is modelled using GAMS [28] and solved by CPLEX 12.5.0, while the upper bound on the duality gap is set to zero.

Two cases are considered in the simulations, as follows:

- *Case I:* DR is directly scheduled in the energy/reserve market and only the TSO pays for the DR (TSO-based partial approach). In practice, the TSO-based partial approaches are utilised for trading the DR.

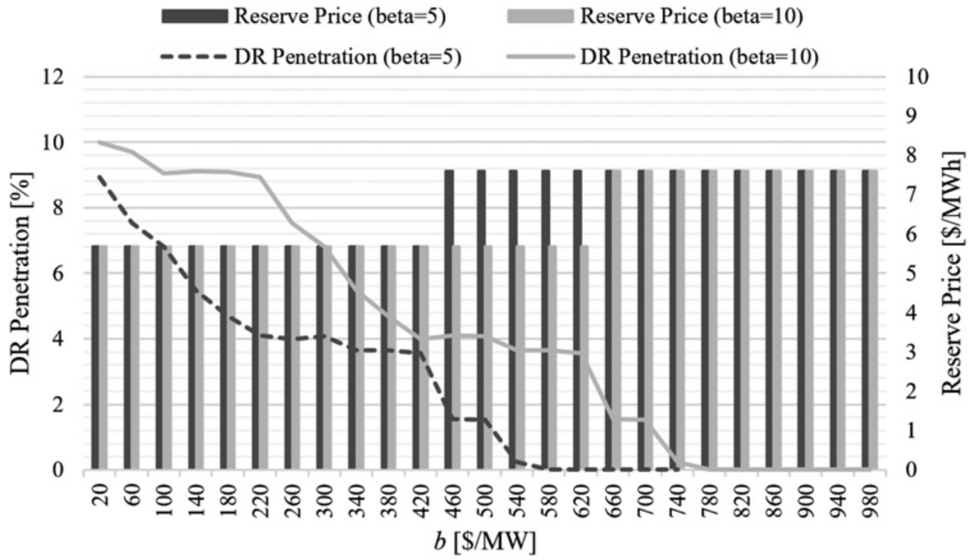

Fig. 5 *Effect of DR cost on scheduled DR*

- *Case II:* DR is scheduled through the DR market with all DR buyers and sellers considered (proposed bilevel model). The costs of DR are allocated between the DR beneficiaries, i.e. the TSO, retailers and distributors.

The results of the market clearance are reported in Table 2. As can be shown in Table 2, in case I while units 1 and 3 can supply the total load, but the expensive unit 3 is committed in the energy and reserve market to meet the reserve requirements in an economic way. In this case, no DR is scheduled in the energy reserve market due to the fact that only the TSO must pay the DR cost. In other words, utilising generating units is more cost effective than scheduling the expensive DR to meet the reserve requirements. Thus in case I, unit 2 with high energy/reserve price is operated at its minimum output. However, in case II since the DR cost is shared between the DR buyers, it is utilised in the energy and reserve market to avoid the expensive unit 2.

The DR clearing prices and the upper-level objective function (23) are reported in Table 3. It is seen in case I that no DR is scheduled in the energy/reserve market owing to the high DR clearing price for the TSO (γ_3^{U}). It should be noted that in case I (partial approach), the cost of DR is paid by one buyer, here TSO, and other DR buyers, i.e. retailer and distributor, do not pay. Therefore, the DR prices for retailer distributor in TSO-based partial approach are equal to zero and these buyers are free riders [23]. The clearing price of the DR capacity from the view point of the TSO (γ_3^{U}) and other DR buyers (λ_3^{U}) determines the contribution of each buyer in the DR payment. According to the DR clearing prices presented in Table 3, in case II, the TSO and other DR buyers pay $112.5 and $150 for the 5 MW of the scheduled DR. Therefore, the aggregator revenue is determined as the sum of the payments made by the DR buyers, i.e. $262.5.

According to the DR clearing prices, the surplus of the DR buyers and sellers from participating in DR market can be calculated. The retailer and distributor surplus (ψ_{jb}) can be calculated by subtracting the DR cost from the buyer's benefit as follows

$$\psi_{jb} = \sum_{g=1}^{N_{Gb}} \left[\left(-\alpha^{U}_{jbg} (s^{U}_{jbg})^2 + \beta^{U}_{jbg} s^{U}_{jbg} \right) - \lambda^{U}_{jbg} s^{U}_{jbg} \right] \qquad (48)$$

The TSO's surplus from participating in the DR market is equal to the difference between the objective function (23) with and without the DR participation. The surplus of the aggregator l located at the load point j (ξ_{jl}) and participating in the DR market can be calculated by subtracting the DR cost from his/her revenue

$$\xi_{jl} = \left(\gamma^{U}_{j} \sum_{c=1}^{N_{Cl}} q^{U}_{jlc} + \sum_{b=1}^{N_{bj}} \sum_{g=1}^{N_{Gb}} \sum_{c=1}^{N_{Cl}} u^{bg}_{lc} \lambda^{U}_{jbg} q^{U}_{jlc} \right) - \sum_{c=1}^{N_{Cl}} \left(a^{U}_{jlc} (q^{U}_{jlc})^2 + b^{U}_{jlc} (1 - \theta_{jlc}) q^{U}_{jlc} \right) \qquad (49)$$

It should be noted that the aggregator revenue is equal to buyers' payment at their associated prices. Based on the above-mentioned explanations, the surplus of the TSO and other DR buyers is obtained $142.5 and $50, respectively. The aggregator's revenue is obtained $262.5. In spite of high DR cost in this study, aggregator's surplus from participating in DR market is $6.25.

To show the interactions between the energy/reserve and DR market, some sensitivity analyses are carried out. First, the effect of DR buyers participating in the DR market, i.e. retailer and distributor, on the results of the energy/reserve market is evaluated. The coefficients of the DR buyers' benefit functions are input parameters that influence the results of the proposed bilevel model. To investigate the effect of DR buyers' benefit function on the market clearing results, the bilevel model is executed for different values of the coefficient β in the retailer and distributor's benefit function.

Fig. 4 illustrates the scheduled DR and the DR clearing price for the TSO, i.e. γ, for variations of β from 50 to 2 $/MW. It is seen in Fig. 4 that more DR is scheduled in the energy/reserve market for high values of β, as in such situations, retailer and distributor bid for purchasing the DR at high prices. Hence, the main portion of the DR cost is paid by these DR buyers and the DR price for the TSO will be low. Therefore, more DR is scheduled as reserves in the upper-level problem. By decreasing the coefficient β, the scheduled DR decreases down to 5 MW. This amount of the DR is the minimum required DR, able to prevent start-up of the expensive unit 2. Due to this economic benefit of the DR, the scheduled DR

Table 7 Impacts of DR market on energy and reserve prices

		Energy price, $/MW	Reserve price, $/MW
$\beta = 5$	$b = 100$	24.19	7.60
	$b = 200$	26.97	10.22
$\beta = 10$	$b = 100$	22.27	5.68
	$b = 200$	24.19	7.60

remains 5 MW even when β decreases. In other words, for $\gamma = 0.5$ to 50.5 \$/MW, no change occurs in the scheduled quantities of the energy/reserve market. For $\beta = 10$, according to (24), the price of the DR for retailer and distributor becomes zero. This indicates that the TSO must pay the whole DR cost at the high price of 52.5 \$/MW. Such a situation is similar to the partial approaches (case I) and no DR is scheduled. Therefore, the scheduled DR falls to zero and λ becomes 10 \$/MW for retailer and distributor. Hence, γwill decrease to 30 \$/MW based on (24).

Furthermore, operation condition of the energy/reserve market and its players' action may affect the DR market clearing. In other words, the TSO's demand for the DR, which is the input of the DR market, depends on the operating point of the power system. For instance, when unit 3 is out of service, 5 MW of DR is scheduled in the DR market even for the lowest value of β, i.e. $\beta = 10$ (see Fig. 4).

4.2 IEEE reliability test system (RTS) study

The IEEE RTS [33] is used to illustrate the applicability of the proposed bilevel approach. The system has 32 generating units and 17 load buses and the associated data have been extracted from [33]. The hydro units are considered as must-run generators and operate at half of their capacities. The generating units offer for selling energy via four incremental cost/power blocks as reported in [33]. It is assumed that all the generating units offer to provide spinning reserves at the rate of 25% of their highest marginal cost of energy production [32]. Similar to the small-scale test system, only the lower bound on the up-spinning reserve is applied.

The total system demand is 2750 MW. It is assumed that at each load bus there are one retailer, one distributor and one aggregator. It is assumed that loads can be curtailed from their normal levels up to 5% of their consumption to provide upward spinning reserves. The coefficients of the cost function of the aggregator are 0.25 \$/MWh^2 and 250 \$/MWh. The coefficient θ for all load buses are assumed 0.95. The coefficients of the DR buyers' supply functions are set to 0.1 \$/MWh^2 and 5 \$/MWh.

Three cases are considered to illustrate the advantages of the proposed model. In case I, only generating units provide spinning reserves. However, in cases II and III DR reserve offers are allowed in addition to the supply side. Moreover, partial approach from the TSO point of view is considered in case II while DR market is used to schedule the DR in case III. All these cases are modelled in GAMS and solved using MIP solver CPLEX 12.5.0 with the duality gap of 0.25%.

Table 4 reports some results of the energy and reserve market clearing for the IEEE RTS. In case I, some expensive units are forced to operate at their minimum output to meet the reserve requirements, i.e. 400 MW, and hence, 22 units (of 26 units) are committed. In case II, the demand-side participation results in the shutdown of several expensive units. In case III, implementation of the DR market increases the total DR participation in the energy and reserve market up to 4%. Consequently, the energy and reserve market can be cleared only with 16 generating units. According to Table 4, the demand side can provide 27.75% of required system reserve when the propose approach is pursued.

The reserve clearing price, i.e. dual variable of (9), is reported in the last row of Table 4. As can be seen, in case II although the DR is utilised in the energy/reserve market, but the clearing price of reserve is the same as in case I. Whereas, in case III, DR participation in energy/reserve market leads to 25.26% decrease in the reserve price. The reason for this decrement in the reserve price can be traced back to the shutdown of the expensive marginal units in case III, which set the reserve clearing prices in cases I and II.

In Table 5, the objective function of the energy/reserve market, surplus of DR buyers and sellers and total market surplus are compared between case II and case III. The optimal value for the objective function (1) is obtained \$43,582 in case I. In case II, although all of the DR costs are paid by the TSO, the surplus of retailers and distributors are lower compared with the case III. In other words, a DR buyer can obtain higher surplus if he/she participate in the DR market (instead of choosing to be free rider as in case II). On the other hand, due to the higher DR participation in case III, aggregators obtain higher surplus compared with case II. Since the DR costs are allocated across all the DR buyers in case III, more DR is traded and total market surplus increases compared with case II, and hence the benefit of the participants increases. Consequently, the proposed approach for trading DR leads to the increase in total market surplus and social welfare.

To evaluate the impact of network congestion on market results, the transmission line limits are decreased down to 50% of their original values. Table 6 compares the reserve prices and DR penetration in the base case and the congested case. As can be seen, transmission congestion leads to higher reserve price because of procuring reserve from the expensive combustion turbine U20. However, utilising the DR market for reserve procurement reduces the reserve price down to 5.68 \$/MWh by providing 6.08% of DR reserve.

To investigate the effect of the DR cost on the market clearing results, the parameter b is changed from 20 to 1000 \$/MWh for all the aggregators. Fig. 5 illustrates the DR penetration level and reserve price in the energy/reserve market for two different DR buyers' benefits, i.e. $\beta = 5$ \$/MWh and $\beta = 10$ \$/MWh. As can be seen in Fig. 5, if the DR buyers, i.e. retailers and distributors, submit higher benefit functions into the DR market, more DR is scheduled in the energy/reserve market. The DR penetration into the energy/reserve market leads to the decrement of the reserve price from 7.6 \$/MWh (without DR) to 5.6 \$/MWh. In the case of $\beta = 10$ \$/MWh, the DR is utilised in the energy/reserve market up to higher values of b ($b = 780$ \$/MW in comparison to $b = 580$ \$/MW in the case of $\beta = 5$ \$/MWh) due to more contribution of retailers and distributors in compensation of the DR costs.

Finally, the impact of the DR market on the energy and reserve prices for a critical situation, i.e. outage of one of oil/steam generators U197, is investigated. For this purpose, the bilevel model is run for different DR buyers' benefits (different values of β) and DR costs (different values of b). Table 7 reports the results of this investigation. It is seen in Table 7 that in such circumstances, the DR has a considerable impact on the clearing price of the energy and reserve. However, this DR impact is dependent on the DR price as well as the DR benefit functions of the retailers and distributors. Increasing β from 5 to 10 \$/MWh leads to the decrement of the energy and reserve up to 10 and 25%, respectively. As can be found from Table 7, this impact of increasing β on the energy and reserve prices is approximately equal to the impact of decreasing b from 200 to 100 \$/MWh. This shows the importance of involving all the DR buyers into the DR trading. In other words, trading DR through a DR market, where all DR buyers are participating, leads to the fair allocation of the DR costs among the DR buyers and brings more positive impacts on the energy/reserve markets.

5 Conclusions

In this paper, a bilevel approach for integrating the retail DR markets into the wholesale power market was proposed. The main aim of this study was to clear DR market and the energy/reserve market, jointly. In the proposed bilevel model, the energy/reserve market clearing was presented as the upper-level problem. To determine the system reserve requirements, deterministic criteria were used at this level. The lower-level problem belongs to the DR market clearing problem. By substituting the lower-level problem by its optimality conditions and adding them to the upper-level problem as constraint, the bilevel problem was transformed to an equivalent single-level optimisation problem. Some well-known linearisation techniques were used to re-state the problem into a MIP problem.

The applicability and effectiveness of the proposed bilevel model was illustrated using a simple case study and the IEEE RTS. It was shown that operation of the DR markets for scheduling DR in wholesale energy and reserve markets brings about higher social welfare. The future works will be focused on the application of the proposed approach in facilitating renewable energy integration, extension of the model to a stochastic programming and modelling load recovery effect in the DR market.

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7 Appendix

The equivalent single-level MIP problem of the proposed bilevel model is produced below.

Minimise

$$\begin{aligned} J = &\sum_{i=1}^{N_U}\left(\lambda_i^S u_i + \sum_{m=1}^{N_{Oi}} \lambda_{Gi}(m) p_{Gi}(m) + c_{gi}^{RU} R_{gi}^U + c_{gi}^{RD} R_{gi}^D\right) \\ &+ \sum_{j=1}^{N_L}\left(-\lambda_{Lj} P_{dj} + \Delta_j^U \sum_{k=1}^{K_1} 2^k z_{jk}^U + \Delta_j^D \sum_{k=1}^{K_2} 2^k z_{jk}^D\right) \end{aligned} \quad (50)$$

subject to

$$\sum_{i:(i,n)\in M_U} P_{gi} - \sum_{j:(j,n)\in M_L} P_{dj} - \sum_{r:(n,r)\in\Lambda} f(n,r) = 0, \quad \forall n \quad (51)$$

$$-f^{max}(n,r) \le f(n,r) \le f^{max}(n,r), \quad \forall (n,r)\in\Lambda \quad (52)$$

$$f(n,r) = B(n,r)\left(\delta_n - \delta_r\right) \quad (53)$$

$$0 \le p_{Gi}(m) \le p_{Gi}^{max}(m), \quad \forall m,\ \forall i \quad (54)$$

$$P_{gi} = \sum_{m=1}^{N_{Oi}} p_{Gi}(m), \quad \forall i \quad (55)$$

$$P_{gi}^{min} u_i \le P_{gi} \le P_{gi}^{max} u_i, \quad \forall i \quad (56)$$

$$P_{dj}^{min} \le P_{dj} \le P_{dj}^{max}, \quad \forall j \quad (57)$$

$$\sum_{i=1}^{N_U} R_{gi}^U + \sum_{j=1}^{N_L}\left(\Delta_j^U \sum_{k=1}^{K_1} 2^k x_{jk}^U\right) = SR^U \quad (58)$$

$$\sum_{i=1}^{N_U} R_{gi}^D + \sum_{j=1}^{N_L}\left(\Delta_j^D \sum_{k=1}^{K_2} 2^k x_{jk}^D\right) = SR^D \quad (59)$$

$$SR^U \ge P_{gi} + R_{gi}^U, \quad \forall i \quad (60)$$

$$SR^U \ge \sigma^U \sum_{j=1}^{N_L} P_{dj} + \sum_{j=1}^{N_L}\left(\Delta_j^U \sum_{k=1}^{K_1} 2^k x_{jk}^U\right), \quad \sigma^U \in (0,1) \quad (61)$$

$$SR^D \ge \sigma^D \sum_{j=1}^{N_L} P_{dj}, \quad \sigma^D \in (0,1) \quad (62)$$

$$0 \le R_{gi}^U \le P_{gi}^{max} u_i - P_{gi}, \quad \forall i \quad (63)$$

$$0 \le R_{gi}^D \le P_{gi} - P_{gi}^{min} u_i, \quad \forall i \quad (64)$$

$$0 \leq \gamma_j^{\mathrm{U}} - z_{jk}^{\mathrm{U}} \leq G(1 - x_{jk}^{\mathrm{U}}), \quad \forall j,\ \forall k \tag{65}$$

$$0 \leq z_{jk}^{\mathrm{U}} \leq Gx_{jk}^{\mathrm{U}}, \quad \forall j,\ \forall k \tag{66}$$

$$0 \leq \gamma_j^{\mathrm{D}} - z_{jk}^{\mathrm{D}} \leq G(1 - x_{jk}^{\mathrm{D}}), \quad \forall j,\ \forall k \tag{67}$$

$$0 \leq z_{jk}^{\mathrm{D}} \leq Gx_{jk}^{\mathrm{D}}, \quad \forall j,\ \forall k \tag{68}$$

$$2a_{jlc}^{\mathrm{U}} q_{jlc}^{\mathrm{U}} + b_{jlc}^{\mathrm{U}}(1 - \theta_{jlc}) + \gamma_j^{\mathrm{U}} + \sum_{b=1}^{N_{bj}} \sum_{c=1}^{N_{Cl}} \lambda_{jbg}^{\mathrm{U}} u_{lc}^{bg} + \underline{\mu}_{jlc}^{\mathrm{U}} - \bar{\mu}_{jlc}^{\mathrm{U}} = 0, \quad \forall j,\ \forall l,\ \forall c \tag{69}$$

$$2a_{jlc}^{\mathrm{D}} q_{jlc}^{\mathrm{D}} + b_{jlc}^{\mathrm{D}}(1 - \theta_{jlc}) + \gamma_j^{\mathrm{D}} + \sum_{b=1}^{N_{bj}} \sum_{c=1}^{N_{Cl}} \lambda_{jbg}^{\mathrm{D}} u_{lc}^{bg} + \underline{\mu}_{jlc}^{\mathrm{D}} - \bar{\mu}_{jlc}^{\mathrm{D}} = 0, \quad \forall j,\ \forall l,\ \forall c \tag{70}$$

$$-2\alpha_{jbg}^{\mathrm{U}} s_{jbg}^{\mathrm{U}} + \beta_{jbg}^{\mathrm{U}} - \lambda_{jbg}^{\mathrm{U}} = 0, \quad \forall j,\ \forall b,\ \forall g \tag{71}$$

$$-2\alpha_{jbg}^{\mathrm{D}} s_{jbg}^{\mathrm{D}} + \beta_{jbg}^{\mathrm{D}} - \lambda_{jbg}^{\mathrm{D}} = 0, \quad \forall j,\ \forall b,\ \forall g \tag{72}$$

$$\sum_{l=1}^{N_{Aj}} \sum_{c=1}^{N_{Cl}} q_{jlc}^{\mathrm{U}} - \Delta_j^{\mathrm{U}} \sum_{k=1}^{K_1} 2^k x_{jk}^{\mathrm{U}} = 0, \quad \forall j \tag{73}$$

$$\sum_{l=1}^{N_{Aj}} \sum_{c=1}^{N_{Cl}} q_{jlc}^{\mathrm{D}} - \Delta_j^{\mathrm{D}} \sum_{k=1}^{K_2} 2^k x_{jk}^{\mathrm{D}} = 0, \quad \forall j \tag{74}$$

$$\sum_{l=1}^{N_{Aj}} \sum_{c=1}^{N_{Cl}} q_{jlc}^{\mathrm{U}} u_{lc}^{bg} - s_{jbg}^{\mathrm{U}} = 0, \quad \forall j,\ \forall b,\ \forall g \tag{75}$$

$$\sum_{l=1}^{N_{Aj}} \sum_{c=1}^{N_{Cl}} q_{jlc}^{\mathrm{D}} u_{lc}^{bg} - s_{jbg}^{\mathrm{D}} = 0, \quad \forall j,\ \forall b,\ \forall g \tag{76}$$

$$q_{jlc}^{\mathrm{U}} \geq 0, \quad \forall j,\ \forall l,\ \forall c \tag{77}$$

$$\underline{\mu}_{jlc}^{\mathrm{U}} \geq 0, \quad \forall j,\ \forall l,\ \forall c \tag{78}$$

$$q_{jlc}^{\mathrm{U}} \leq \underline{w}_{jlc}^{\mathrm{U}} M^P, \quad \forall j,\ \forall l,\ \forall c \tag{79}$$

$$\underline{\mu}_{jlc}^{\mathrm{U}} \geq \underline{w}_{jlc}^{\mathrm{U}}(1 - M^P), \quad \forall j,\ \forall l,\ \forall c \tag{80}$$

$$(q_{jlc}^{\mathrm{U,max}} - q_{jlc}^{\mathrm{U}}) \geq 0, \quad \forall j,\ \forall l,\ \forall c \tag{81}$$

$$\bar{\mu}_{jlc}^{\mathrm{U}} \geq 0, \quad \forall j,\ \forall l,\ \forall c \tag{82}$$

$$(q_{jlc}^{\mathrm{U,max}} - q_{jlc}^{\mathrm{U}}) \leq \bar{w}_{jlc}^{\mathrm{U}} M^P, \quad \forall j,\ \forall l,\ \forall c \tag{83}$$

$$\bar{\mu}_{jlc}^{\mathrm{U}} \geq \bar{w}_{jlc}^{\mathrm{U}}(1 - M^P), \quad \forall j,\ \forall l,\ \forall c \tag{84}$$

$$q_{jlc}^{\mathrm{D}} \geq 0, \quad \forall j,\ \forall l,\ \forall c \tag{85}$$

$$\underline{\mu}_{jlc}^{\mathrm{D}} \geq 0, \quad \forall j,\ \forall l,\ \forall c \tag{86}$$

$$q_{jlc}^{\mathrm{D}} \leq \underline{w}_{jlc}^{\mathrm{D}} M^P, \quad \forall j,\ \forall l,\ \forall c \tag{87}$$

$$\underline{\mu}_{jlc}^{\mathrm{D}} \geq \underline{w}_{jlc}^{\mathrm{D}}(1 - M^P), \quad \forall j,\ \forall l,\ \forall c \tag{88}$$

$$(q_{jlc}^{\mathrm{D,max}} - q_{jlc}^{\mathrm{D}}) \geq 0, \quad \forall j,\ \forall l,\ \forall c \tag{89}$$

$$\bar{\mu}_{jlc}^{\mathrm{D}} \geq 0, \quad \forall j,\ \forall l,\ \forall c \tag{90}$$

$$(q_{jlc}^{\mathrm{D,max}} - q_{jlc}^{\mathrm{D}}) \leq \bar{w}_{jlc}^{\mathrm{D}} M^P, \quad \forall j,\ \forall l,\ \forall c \tag{91}$$

$$\bar{\mu}_{jlc}^{\mathrm{D}} \geq \bar{w}_{jlc}^{\mathrm{D}}(1 - M^P), \quad \forall j,\ \forall l,\ \forall c \tag{92}$$