2016

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Keywords

Wholesale electricity market, variable energy resources, contract design, swing (flexibility), optimization, mixed integer linear programming

Disciplines

Economic Theory | Electrical and Computer Engineering | Industrial Organization | Oil, Gas, and Energy | Power and Energy

Comments

Market Provision of Flexible Energy/Reserve Contracts: Optimization Formulation

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Working Paper No. 15019

ISU Department of Economics

Originally Posted: 12 November 2015

Latest Revision: 16 January 2017

A preliminary version of this working paper was published in the *Proceedings of the IEEE Power and Energy Society General Meeting, 2016 (electronic)*

Market Provision of Flexible Energy/Reserve Contracts: Optimization Formulation

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***Abstract*—The need for flexible service provision has dramatically increased in recent years due to the increased penetration of variable energy resources, as has the need to ensure fair access to service provision from an increasingly diverse array of resources. In response to these needs, this study develops a new analytic optimization formulation for the clearing of day-ahead markets based on swing contracts for the combined flexible provision of energy and reserve services. This new optimization formulation is a mixed integer linear programming (MILP) problem that can be solved using standard MILP solution software. A numerical day-ahead market example is presented to illustrate the potential of this new optimization formulation for real-world implementation.**

***Index Terms*—Wholesale electricity market, variable energy resources, contract design, swing (flexibility), optimization, mixed integer linear programming**

NOMENCLATURE

***Sets*:**

$\mathcal{B}$	Set of bus indices b
$\mathcal{M}$	Set of indices m for market participants (MPs) with dispatchable services
$\mathcal{M}_b \subset \mathcal{M}$	Market participants at bus b with dispatchable services
T	Set of time period indices $t = 1, 2, \ldots$
$\mathcal{L} \subset \mathcal{B} \times \mathcal{B}$	Set of transmission line indices ℓ
$\mathcal{L}_{E(b)}$	Subset of lines ℓ ending at bus b
$\mathcal{L}_{O(b)}$	Subset of lines ℓ originating at bus b

***Parameters and Functions*:**

$A_m(t)$	1 if m in period t is within its contract service period; 0 otherwise
$B(\ell)$	Inverse of reactance (pu) for line ℓ
$E(\ell)$	End bus for line ℓ
F_ℓ^{max}	Power limit (MW) for line ℓ
$NL_b(t)$	Net load (MW) at bus b in period t
$O(\ell)$	Originating bus for line ℓ
P_m^{min}	Lower power limit (MW) of m
P_m^{max}	Upper power limit (MW) of m
R_m^D	Ramp-down limit (MW/Δt) of m
R_m^U	Ramp-up limit (MW/Δt) of m
$RR^D(t)$	System-wide down reserve requirement (MW) in period t
$RR^U(t)$	System-wide up reserve requirement (MW) in period t
S_o	Positive base power (in three-phase MVA)
Δt	Length of time period t $\equiv [t, t + \Delta t)$
α_m	Availability price (\$) requested by m for a swing contract offering service availability
$\phi_m(t)$	Performance price (\$/MWΔt) requested by m for the ex post compensation of down/up power delivery in period t

***Variables*:**

c_m	1 if the contract offered by m is cleared; 0 otherwise
$v_m(t)$	1 if m is online in period t; 0 otherwise
$p_m(t)$	Power output (MW) for m in period t
$\overline{p}_m(t)$	Maximum available power output (MW) of m in period t
$\underline{p}_m(t)$	Minimum available power output (MW) of m in period t
$\theta_b(t)$	Voltage angle (radians) at bus b in period t
$w_\ell(t)$	Line power (MW) for line ℓ in period t

Originally Posted: 12 November 2015; Latest Revision: 16 January 2017.
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I. INTRODUCTION

THE increased penetration of variable energy resources in electric power markets has increased the volatility of net load (i.e., load minus non-dispatchable generation) as well as the frequency of strong ramp events. This, in turn, has led system operators to explore potential new products and market design features encouraging flexible service provision to enhance net load following capability.

Responding to this need for increased flexibility in service provision, a group of researchers has been working to develop a new form of swing (flexible) contracting for electric power markets that permits greater flexibility in service provision ([1], [2]). Roughly, a swing contract for energy and reserve is a contract whose contractual terms permit a diverse spectrum of services to be offered as ranges of values rather than as point values, thus permitting greater flexibility in their real-time implementation. These offered services might include, for example, ranges for possible start-up times, durations, power dispatch levels, and ramp rates.

Another important attribute of swing contracting is that it permits a full market-based compensation for service availability and service performance. The availability price of a cleared swing contract can compensate a contract issuer for service availability costs, while the service performance payment method included among the terms of the contract can ensure that the contract issuer is fully compensated ex post for any actual services rendered in real-time operations.

Left unresolved in this previous work, however, is whether the determination of optimal market clearing solutions for swing contracts can be reduced to a routine operation suitable for real-world application. The present study provides an affirmative answer to this question.

Specifically, this study reports on the development of a new optimization formulation for the market clearing of swing contracts. This new optimization formulation is a mixed integer linear programming (MILP) formulation expressible in analytic terms. It can be solved using the same MILP solution software currently in use for standard Security-Constrained Unit Commitment (SCUC) optimization formulations ([3], [4], [5], [6]). A numerical example is provided to illustrate the implementation of this new optimization formulation for the day-ahead market clearing of swing contracts that take a firm (non-optional) form.

II. Market Clearing of Swing Contracts

A. *Standardized Form of a Swing Firm Contract*

Four standardized contracts are proposed in [2] to facilitate energy and reserve trading: namely, firm contracts and option contracts taking either a fixed or swing form. A *firm contract (FC)* is a non-contingent contract that requires specific performance from both counterparties. In contrast, an *option contract (OC)* gives the holder the right, but not the obligation, to procure services from the issuer under contractually specified terms. The right can be activated by exercise of the OC at a contractually permitted exercise time, at which point the contractual terms of the OC become firm.

An FC or OC is a *fixed contract* if each of its contractual terms is expressed as a single value. An FC or OC is a *swing contract (SC)* contract if at least one of its contractual terms is expressed as a set of possible values, thus permitting some degree of flexibility in its implementation.

For clarity of exposition, this study will focus solely on SCs in firm form that offer a particular spectrum of services. The general form of these SCs is as follows:

$$\text{SC} = [b, t_s, t_e, \mathcal{P}, \mathcal{R}, \phi] \tag{1}$$

$b =$ location where service delivery is to occur;

$t_s =$ power delivery start time;

$t_e =$ power delivery end time;

$\mathcal{P} = [P^{min},\ P^{max}] =$ range of power levels p;

$\mathcal{R} = [-R^D,\ R^U] =$ range of down/up ramp rates r;

$\phi =$ Performance payment method for real-time services.

In (1), t_s and t_e denote specific calendar times expressed at the granularity of time periods of length Δt (e.g., 1h, 1Min), with $t_s < t_e$. The power interval bounds $P^{min} \leq P^{max}$ can represent pure power injections (if $0 \leq P^{min}$), pure power withdrawals or absorptions (if $P^{max} \leq 0$), or bi-directional power capabilities (if $P^{min} \leq 0 \leq P^{max}$). The down/up limits $-R^D$ and R^U for the ramp rates r (MW/Δt) are assumed to satisfy $-R^D \leq 0 \leq R^U$.

The location b, the start time t_s, and the end time t_e are all specified as single values in (1). However, the power levels p and the down/up ramp rates r are specified in swing form with associated ranges $\mathcal{P}$ and $\mathcal{R}$. As discussed in [2], the performance payment method ϕ designating the mode of ex post compensation for actual real-time service performance can take a wide variety of forms, such as a specified flat rate for energy and/or a power-mileage compensation for ramping.

To understand the obligations of the seller and buyer of this swing contract, should it be cleared, a numerical example might be helpful. Consider the following SC offered into an ISO-managed day-ahead market by a market participant m at an availability price α=\$100, with Δt = 1h:

$b =$ bus b;

$t_s =$ 8:00am;

$t_e =$ 10:00am;

$\mathcal{P} = [P^{min},\ P^{max}] =$ [10MW, 40MW];

$\mathcal{R} = [-R^D,\ R^U] =$ [-38MW/h, 28MW/h];

$\phi =$ \$35/MWh.

Under this SC, market participant m offers to provide power at bus b from 8:00am to 10:00am on the following day. The power levels at which m is willing to be dispatched range from 10MW to 40MW, but the required down/up ramp rates r to achieve these power levels must satisfy -38MW/h $\leq r \leq$ 28MW/h. The performance payment method ϕ designates that m is to be paid the price ϕ=\$35/MWh for each MWh of energy it delivers under this SC. If the SC is cleared by the ISO, the GenCo is immediately entitled to receive its availability price α=\$100.

Figure 1 depicts one possible power path that the ISO could dispatch in real-time operations, in accordance with the terms of this SC. The (green) area under this power path is the resulting energy (MWh) delivery, compensated ex post at the rate of \$35/MWh.

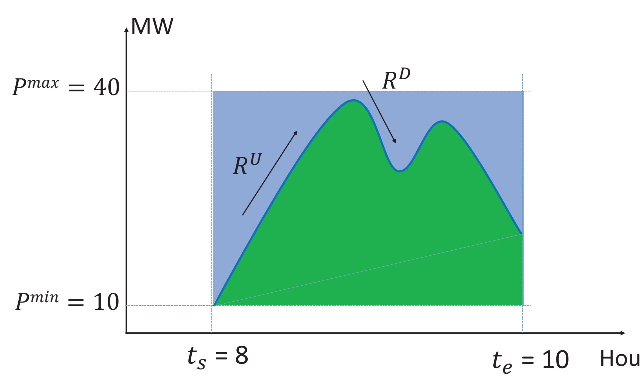


Fig. 1. A possible dispatched power path for the SC numerical example

It is the responsibility of market participant m to ensure it is able to fulfill the terms of this offered SC. For example, with regard to physical feasibility, the power delivery start time t_s=8:00am must precede the power delivery end time t_e=10:00am, which is clearly the case; but, in addition, $[t_e - t_s]$ = 2h must be at least as great as m's minimum up time.

With regard to financial feasibility, market participant m should make sure that its availability price α = \$100 is sufficient to cover all costs incurred in order to guarantee it is available to fulfill the terms of the SC. These costs should include avoidable fixed costs, such as start-up/shut-down costs and no-load costs, as well as lost opportunity costs arising from m's inability to receive revenues for its services in a next-best alternative use. Moreover, m should ensure that its offered performance price ϕ=\$35/MWh guarantees full coverage of all the variable costs (e.g., fuel expenses) it would incur if called upon to perform actual real-time services under this SC.

B. Market Design for the Support of SC Trading

As discussed in ([1], [2]), swing contract trading can be supported by a sequence of linked centrally-managed forward markets whose planning horizons range from years to minutes. Forward markets with very long planning horizons can be used to encourage new capacity investment while forward markets with very short planning horizons can be used to correct last-minute imbalances between available generation and forecasted real-time net loads.

In practice, US centrally-managed wholesale power markets are operated as two-settlement systems consisting of a day-ahead market (DAM) operating in tandem with a real-time market (RTM). Intra-day forward markets are then opened as needed between the DAM and the RTM to secure additional generation availability for reliability purposes.

In this study we show how an ISO-managed DAM could be designed to support SC trading. The subset $\mathcal{M}$ of market participants with dispatchable services is assumed to be able to fulfill the availability and performance commitments entailed by the sale and purchase of SCs. These entities could include generation companies (GenCos), load-serving entities (LSEs) with curtailable loads, demand response resources (DRRs), electric storage devices (ESDs), and dispatchable variable energy resources (VERs). Additional market participants could include non-dispatchable VERs and LSEs with fixed (must-serve) loads.

Figure 2 compares our proposed SC DAM design to current DAM designs, highlighting key similarities and differences. To understand this comparison, it is important to understand the following three attributes of SCs.

First, the swing in the contractual terms of SCs permits these contracts to function as both energy and reserve products. This eliminates the need to provide separate pricing and settlement processes for energy versus reserve services.

Second, the two-part pricing of SCs permits full separate market-based compensation for service availability and service performance. The availability price of an SC compensates the issuer for service availability, while the performance payment method included among the terms of an SC permits the issuer to be compensated ex post for any actual real-time service provision.

Third, SCs permit resources to internally manage unit commitment and generation capacity constraints. By offering an SC into an SC DAM, a resource is guaranteeing the ISO in charge of this SC DAM that it can feasibly perform the services represented in the SC if called upon to do so.

III. SC DAM Optimization Formulation

Current DAM designs rely on standard SCUC/SCED optimizations to determine unit commitment, economic dispatch, and pricing solutions. In a sharp break from this practice, we propose a new analytic optimization formulation for the SC DAM that permits the optimal clearing of SCs.

		Current DAM	**Proposed SC DAM**
Similarities		• Conducted day-ahead to plan for next-day operations • ISO-managed • MPs can include GenCos, LSEs, DRRs, ESDs, & VERs • Subject to same physical constraints: e.g. transmission, generation, ramping, & power-balance constraints	
Differences	• Optimization formulation	SCUC & SCED	Contract-clearing
	• Settlement	Locational marginal pricing	Contract-determined prices
	• Payment	Payment for next-day service before actual performance	Payment for availability now & performance ex post
	• Out-of-market payments	Uplift payments (e.g., for UC)	No out-of-market payments
	• Information given to MPs	UC, DAM LMPs, & next-day dispatch schedule	Which contracts have been cleared

Fig. 2. Comparison of the SC DAM design with current DAM designs

Fig. 3 highlights key distinctions between our proposed optimization formulation for the SC DAM and traditional SCUC/SCED optimization formulations. This section clarifies these distinctions by setting out, in concrete analytic terms, our proposed SC DAM optimization formulation.

To simplify the exposition, three assumptions are made. First, it is assumed that all LSEs service fixed (must have) loads, and all LSE bids have a simple block-energy form, i.e., the bids consist of a quantity demand (MW) for each period t that is not responsive to price. Second, it is assumed that each market participant m with dispatchable services submits only one SC offer,[1] and the performance payment method ϕ_m appearing in this SC takes the form of a specified flat rate for energy (\$/MWh). Third, it is assumed that only system-wide reserve requirements are imposed.

The objective of the ISO managing the SC DAM is to minimize total cost subject to constraints. Total cost is the summation of SC availability cost plus expected performance cost arising from the need to balance next-day net loads as determined by LSE bids and forecasted generation from non-dispatchable VERs. Total cost is expressible as follows:[2]

$$\sum_{m\in\mathcal{M}} \alpha_m c_m + \sum_{t\in T}\sum_{m\in\mathcal{M}} \phi_m(t)|p_m(t)|\Delta t \qquad (2)$$

The ISO's key decision variables for minimization of (2) are:

- *Market participant contract clearing indicators:*

$$c_m \in \{0,1\}, \quad \forall m \in \mathcal{M}$$

[1]See [2] for a discussion of the more general case in which each market participant with dispatchable services can submit a portfolio consisting of multiple SCs.

[2]The absolute value terms $|p_m(t)|$ in the objective function (2) can be handled as follows: (i) Introduce new decision variables for the ISO, $p_m^a(t), t = 1, \ldots T,\ m \in \mathcal{M}$; (ii) In the objective function (2), replace $|p_m(t)|$ by $p_m^a(t)$ for $t = 1, \ldots, T,\ m \in \mathcal{M}$; (iii) Include the following additional linear constraints in the constraint set: $p_m^a \geq p_m$ and $p_m^a \geq -p_m$, $t = 1, \ldots, T,\ m \in \mathcal{M}$. Any solution for the resulting constrained cost minimization problem will then require $p_m^a(t) = |p_m(t)|$ for $t = 1, \ldots, T$ and $m \in \mathcal{M}$. Also, although power levels for all market participants nominally appear in the objective function (2), it will be seen below that the constraints for the SC DAM optimization formulation restrict the power amounts for market participants with non-cleared SCs to be zero.

		SCUC	SCED	SC Contract Clearing
Similarities		• Both SCUC & SC contract clearing are solved as mixed integer linear programming (MILP) problems subject to physical constraints		
Differences	• Objective	Min {Start-Up /Shut-Down Costs + No-Load Costs + Dispatch Costs + Reserve Costs}	Min {Dispatch Costs + Reserve Costs}	Min {Availability Cost + Expected Performance Cost}
	• Start-up & shut-down constraints	Yes	No	Start-up/shut-down constraints are implicit in submitted contracts
	• Primary decision variables	Unit Commitment vector	Energy dispatch & reserves	Cleared contracts
	• Settlement		LMPs calculated as SCED dual variables	Availability prices paid for cleared contracts

Fig. 3. Comparison of the SC DAM optimization formulation with SCUC/SCED optimization formulations for current DAMs

- *Market participant power dispatch levels:*

$$p_m(t), \quad \forall m \in \mathcal{M}, \ t \in T$$

The constraints for this SC DAM optimization formulation include: unit-commitment constraints; a voltage angle constraint at the angle reference bus 1; line power constraints; transmission constraints; power-balance constraints; capacity constraints; ramping constraints; and system-wide reserve-requirement constraints. These constraints will now be expressed in analytic form.

Unit commitment constraints:

$$v_m(t) = c_m \cdot A_m(t), \qquad \forall \ m \in \mathcal{M}, \ t \in T \qquad (3)$$

The unit commitment $v_m(t) \in \{0,1\}$ for each market participant $m \in \mathcal{M}$ in each period t is determined by two factors:

(a) Is m's SC offer cleared by the ISO?
(b) Does m's SC offer include service for hour t?

The generator contract clearing indicator $c_m \in \{0,1\}$ represents condition (a), and the offer service indicator $A_m(t) \in \{0,1\}$ represents condition (b). If conditions (a) and (b) are both met, then m is synchronized to the grid in period t and can provide service. Otherwise, if at most one of these conditions is met, m is offline in period t and is not able to provide service.

Voltage angle specification at angle reference bus 1:

$$\theta_1(t) = 0, \qquad \forall t \in T \qquad (4)$$

Line power constraints:

$$w_\ell(t) = S_0 B(\ell) \left[\theta_{O(\ell)}(t) - \theta_{E(\ell)}(t)\right], \qquad (5)$$

$$-\pi \leq \theta_b(t) \leq \pi, \ \forall b \in \mathcal{B}, \ell \in \mathcal{L}, \ t \in T \qquad (6)$$

Transmission constraints:

$$-F_\ell^{max} \leq w_\ell(t) \leq F_\ell^{max}, \qquad \forall \ell \in \mathcal{L}, \ t \in T \qquad (7)$$

Power balance constraint at each bus:

$$\sum_{m \in \mathcal{M}_b} p_m(t) + \sum_{\ell \in \mathcal{L}_{E(b)}} w_\ell(t) = NL_b(t) + \sum_{\ell \in \mathcal{L}_{O(b)}} w_\ell(t), \quad \forall b \in \mathcal{B}, \ t \in T \qquad (8)$$

Market participant capacity constraints:

$$\underline{p}_m(t) \leq p_m(t) \leq \bar{p}_m(t), \qquad \forall m \in \mathcal{M}, \ t \in T \qquad (9)$$

$$\bar{p}_m(t) \leq P_m^{max} v_m(t), \qquad \forall m \in \mathcal{M}, \ t \in T \qquad (10)$$

$$\underline{p}_m(t) \geq P_m^{min} v_m(t), \qquad \forall m \in \mathcal{M}, \ t \in T \qquad (11)$$

Market participant ramp-up and ramp-down constraints:

$$\bar{p}_m(t) - p_m(t-1) \leq R_m^U \Delta t v_m(t-1) + P_m^{max}[1 - v_m(t-1)] \quad \forall m \in \mathcal{M}, \ \forall t = 2, \cdots, |T| \qquad (12)$$

$$p_m(t-1) - \underline{p}_m(t) \leq R_m^D \Delta t \cdot v_m(t) + P_m^{max}[1 - v_m(t)] \quad \forall m \in \mathcal{M}, \ \forall t = 2, \cdots, |T| \qquad (13)$$

System-wide reserve requirement constraints:

$$\sum_{m \in \mathcal{M}} \bar{p}_m(t) \geq \sum_{b \in \mathcal{B}} NL_b(t) + RR^U(t), \quad \forall t \in T \qquad (14)$$

$$\sum_{m \in \mathcal{M}} \underline{p}_m(t) \leq \sum_{b \in \mathcal{B}} NL_b(t) - RR^D(t), \quad \forall t \in T \qquad (15)$$

An "inherent reserve range" can be calculated for the system in each period t as follows. Define

$$RR^{max}(t) = \sum_{m \in \mathcal{M}} \bar{p}_m(t) \qquad \forall t \in T \qquad (16)$$

$$RR^{min}(t) = \sum_{m \in \mathcal{M}} \underline{p}_m(t) \qquad \forall t \in T \qquad (17)$$

The terms $RR^{max}(t)$ and $RR^{min}(t)$ are the maximum and minimum power levels available for the system in period t. The *inherent reserve range* for period t can then be calculated as the interval $RR(t) = [RR^{min}(t), RR^{max}(t)]$.

TABLE I
SCs SUBMITTED BY THE THREE GENCOS IN THE ILLUSTRATIVE EXAMPLE

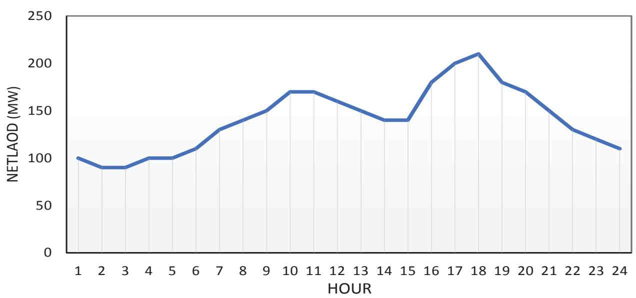
GenCo	Service Period $[t_s, t_e]$	Power Range $[P^{min}, P^{max}]$ (MW)	Ramp Rate Range $[-R^D, R^U]$ (MW/h)	Performance Price ϕ ($/MWh)	Availability Price α ($)
1	[1, 24]	[0, 80]	[-60, 60]	25	1500
2	[1, 24]	[0, 200]	[-30, 30]	10	2000
3	[8, 24]	[0, 120]	[-50, 50]	20	1000

TABLE II
UNIT COMMITMENT (0/1) DETERMINED BY THE SC DAM OPTIMIZATION FOR THE ILLUSTRATIVE EXAMPLE

GenCo	Periods																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
3	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

TABLE III
OPTIMAL DISPATCH SCHEDULING (MWs) DETERMINED BY THE SC DAM OPTIMIZATION FOR THE ILLUSTRATIVE EXAMPLE

GenCo	Periods																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	100	90	90	100	100	110	130	140	150	170	170	160	150	140	130	160	190	200	180	170	150	130	120	110
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20	10	10	0	0	0	0	0	0



Hour	1	2	3	4	5	6	7	8	9	10	11	12
NL	100	90	90	100	100	110	130	140	150	170	170	160
Hour	13	14	15	16	17	18	19	20	21	22	23	24
NL	150	140	140	180	200	210	180	170	150	130	120	110

Fig. 4. 24-hour net load profile for the illustrative example

IV. ILLUSTRATIVE EXAMPLE

This section reports illustrative SC DAM optimization findings for a simple power system with three dispatchable GenCos and no transmission congestion. Each GenCo submits one SC to the ISO-managed SC DAM, as depicted in Table I. Time periods t are measured in hours, and the net load for each hour t of the following day is depicted in Fig. 4. The system-wide reserve requirement is set at 10MW above/below net load for each hour t, i.e., $RR^U(t)$ = $RR^D(t)$ = 10MW for each hour t.

The ISO applies an MILP solver to determine an SC DAM optimization solution for the following day, conditional on the three submitted SCs. Simulation results show that the SCs submitted by GenCo2 and GenCo3 are cleared: i.e., c_{g1} = 0, c_{g2} = 1, and c_{g3} = 1. The optimal unit commitment $v_g(t)$ and dispatch schedule $p_g(t)$ for each GenCo g in each hour t are shown in Tables II and III, respectively.

The DAM prices for the cleared SCs are their submitted availability prices, and the payments to be received for any actual services performed under these SCs the following day are based on the energy prices specified by the cleared SC performance payment methods: that is, ϕ_{g2} = $10/MWh and ϕ_{g3} = $20/MWh.

The results show that GenCo2 serves as base load due to its relatively low performance price, similar to a coal or nuclear plant. The reasons why GenCo3's submitted SC is also cleared are as follows. First, there is a big ramp-up in net load from hour 15 to hour 16. Due to GenCo2's limited ramp capability, the maximum available power output for GenCo2 at hour 16 is 160MW. Thus, GenCo3 is cleared although it is relatively more expensive. Second, the net load for hour 18 is 210MW, which exceeds GenCo2's upper output limit 200MW. Thus, GenCo3 is needed to provide additional power.

Although GenCo3's available power is not used until hour 16, the unit commitment for GenCo3 in fact spans from hour 8 to hour 24. The reason for this is that GenCo3's SC commits this GenCo to be available to provide power from hour 8 through hour 24. Thus, if the ISO clears the contract, GenCo3 must be synchronized to the grid during each of these hours.

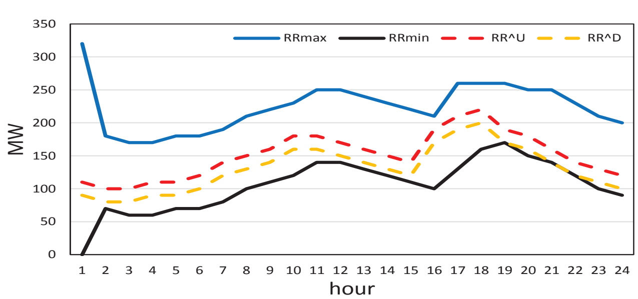


Fig. 5. Comparison of the inherent reserve range RR with the down/up reserve requirements RR^D and RR^U

Fig. 5 depicts the inherent reserve range resulting from the cleared SCs for GenCo2 and GenCo3, together with the down/up reserve requirements. The reserve range is represented by solid lines and the down/up reserve requirements are represented by dashed lines. Note that the reserve range satisfies the down/up reserve requirements while at the same time providing valuable flexibility to the ISO for use in real-time balancing operations.

V. Conclusion

A new MILP optimization formulation has been proposed and demonstrated for an ISO-managed DAM based on swing contracts for the combined flexible provision of energy and reserve services. Future work will extend this formulation to encompass combined DAM/RTM operations and will undertake systematic feasibility and cost comparisons with existing DAM/RTM operations.

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