RCSTF Supplement: Product Nesting and Resource-Level Constraints

Contents

1. Purpose

The goals of this document are to provide details of the following:

- System-level constraints for the different reserve services
- The nesting of the different reserve products in the system-level constraints, and the implications to the system marginal prices of the reserve products
- The resource-level constraints for the different reserve products

Disclaimer: Some of the constraints have been simplified for expositional purposes. Moreover, the constraints may be modified in the final implementation based on computational limitations. In case the exposition in this document contradicts the tariff language, the tariff has precedence.

2. Preliminaries

This section provides the notation used throughout this appendix.

$\mathcal{T} := \{\text{SR}, \text{10-RUR-U(p)}, \text{10-RUR-D(own)}, \text{30-RUR}, \text{30-SecR}, \text{60-Spin}, \text{60-NonSpin}\}$ denotes the set of reserve products

$\mathcal{S} := \{\text{SR}, \text{10-RUR-U(p)}, \text{10-RUR-D(own)}, \text{30-RUR}, \text{30-Min-Reserves}, \text{EG}, \text{DASR}\}$ denotes the set of reserve services

$\mathcal{G}^{\text{ON}}$ denotes the set of resources that are online

$\mathcal{G}^{\text{OFF}}$ denotes the set of all offline resources

$g_i(t) \in \mathfrak{R}_+$ is the energy dispatch of unit i at time t

$r_i^{\text{type}}(t) \in \mathfrak{R}_+$ is the reserve assignment (in MW) of unit i of a given reserve product $\text{type} \in \mathcal{T}$ at time t; e.g., $r_i^{\text{10-RUR-U}}(t)$ is the 10-min RUR (Up) assignment for unit i at time t

$E_i^{\text{MAX}}(t), E_i^{\text{MIN}}(t)$ denote the ECOMAX and ECOMIN (in MW) of the unit i at time t, respectively

$\text{RR}_i(t)$ is the ramp rate in MW/min of unit i at time t (up and down ramp rates assumed symmetric in this document for expositional simplicity)

TTS_i indicates the time to start (in minutes) — inclusive of startup and notification times — for an offline resource $i \in \mathcal{G}^{\text{OFF}}$

$Q^{\text{type}}(t) \in \mathfrak{R}_+$ denotes the total systemwide MWs cleared on the demand curve for reserve service $\text{type} \in \mathcal{S}$ at time t

3. System-level Constraints

This section discusses the system-level constraints to ensure that the supply from all the reserve products that can provide a specific reserve service is sufficient to meet the quantity cleared on the demand curve for that service.

We begin with reserve services that are carried in both real-time and day-ahead markets.

SR. Since only the SR products can provide the SR service, the system-level constraint to ensure that the cleared SR products are sufficient to meet the quantity cleared on the SR demand curve at time t is as follows:

$$\sum_i r_i^{\text{SR}}(t) \geq Q^{\text{SR}}(t) \tag{1}$$

Let $\lambda^{\text{SR}}(t)$ be the shadow price corresponding to the constraint (1).

10-Min RUR. Since only 10-Min RUR products can provide 10-Min RUR services, the system-level constraints for the up and down 10-Min RUR services at time t are given by, respectively:

$$\sum_i r_i^{\text{10-RUR-U}}(t) \geq Q^{\text{10-RUR-U}}(t) \tag{2.1}$$

$$\sum_i r_i^{\text{10-RUR-D}}(t) \geq Q^{\text{10-RUR-D}}(t) \tag{2.2}$$

Let $\lambda^{\text{10-RUR-U}}(t)$ and $\lambda^{\text{10-RUR-D}}(t)$ be the shadow prices corresponding to (2.1) and (2.2), respectively.

30-Min RUR. Since only 30-Min RUR products can provide the 30-Min RUR service, the corresponding system-level constraint at time t is given by:

$$\sum_i r_i^{\text{30-RUR}}(t) \geq Q^{\text{30-RUR}}(t) \tag{3}$$

Let $\lambda^{\text{30-RUR}}(t)$ be the shadow price corresponding to the constraint (3).

30-Min Reserves. Both 30-Min RUR products and the offline 30-Min secondary reserve products can provide the 30-Min Reserve service. In other words, the 30-Min RUR products are nested with the 30-Min secondary reserve products to satisfy the cleared quantity on the 30-Min reserve demand curve. Consequently, the system-level constraint at time t is given by:

$$\sum_{i \in \mathcal{G}^{\text{ON}}} r_i^{\text{30-RUR}}(t) + \sum_{j \in \mathcal{G}^{\text{OFF}}} r_j^{\text{30-SecR}}(t) \geq Q^{\text{30-Min-Reserves}}(t) \tag{4}$$

The 30-Min reserve demand curve accounts for both the contingency requirement based on the most severe single contingency and the 30-Min RUR requirement.

Let $\lambda^{\text{30-SecR}}(t)$ be the shadow price corresponding to the constraint (4).

Next, we introduce the system-level constraints for the day-ahead-market only services.

Energy Gap (EG). 10-Min RUR (Up), 30-Min RUR, and 60-Min spin products can all provide the EG service. Consequently, the system-level constraint for EG at time t is given by:

$$\sum_i r_i^{\text{10-RUR-U}}(t) + r_i^{\text{30-RUR}}(t) + r_i^{\text{60-Spin}}(t) \geq Q^{\text{EG}}(t) \tag{5}$$

Let $\lambda^{\text{EG}}(t)$ be the shadow price corresponding to (5).

DASR. All products in $\mathcal{T} \setminus \{\text{SR}, \text{10-RUR-D(own)}\}$ can provide the DASR service. Consequently, the system-level constraint at time t is given by:

$$\begin{aligned}\sum_{i \in \mathcal{G}^{\text{ON}}} & r_i^{\text{10-RUR-U}}(t) + r_i^{\text{30-RUR}}(t) + r_i^{\text{60-Spin}}(t) \\ & + \sum_{j \in \mathcal{G}^{\text{OFF}}} r_j^{\text{30-SecR}}(t) + r_j^{\text{60-NonSpin}}(t) \geq Q^{\text{EG}}(t) + Q^{\text{DASR}}(t)\end{aligned} \tag{6}$$

The right hand side of (6) includes the sum of the cleared quantities on the EG and DASR demand curves, since the DASR demand curve does not automatically incorporate the energy gap requirement. All the products providing the energy gap service are nested with the offline products to satisfy the cumulative quantities cleared on the EG and DASR demand curves.

Let $\lambda^{\text{DASR}}(t)$ be the shadow price corresponding to (6).

4. System Marginal Prices of Reserve Products

In this section, we discuss the system marginal prices of the different reserve products based on the constraints provided in Section 3. The final clearing price of the reserve products are the sum of the two components: (i) system marginal price and (ii) reserve congestion price. In this appendix, we focus on the first component. The second component is detailed in the appendix discussing the locational constraints for reserves.

We begin with the products that are only cleared in the day-ahead market.

60-Min Spin. The 60-Min Spin reserve product can provide both energy gap and DASR services as shown in (5) and (6). Consequently, the system marginal price of the 60-Min Spin reserve product at time t is $\lambda^{\mathrm{EG}}(t) + \lambda^{\mathrm{DASR}}(t)$.

60-Min NonSpin. The 60-Min Non-Spin reserve product can only provide the DASR service. Consequently, the system marginal price of the 60-Min Non-Spin reserve product at time t is $\lambda^{\mathrm{DASR}}(t)$.

Next, we discuss products that are cleared in both day-ahead and real-time markets.

SR. In both day-ahead and real-time markets, the SR products can only provide SR services. Consequently, the system marginal price of the SR product at time t is $\lambda^{\mathrm{SR}}(t)$ in both markets.

10-Min RUR Up. In the real-time market, the 10-Min RUR Up product can only provide the 10-Min RUR Up service. Consequently, in the real-time market, the system marginal price of the 10-Min RUR Up product at time t is $\lambda^{\text{10-RUR-U}}(t)$.

However, in the day-ahead market, as (2.1), (5), and (6) show, the 10-Min RUR Up products can provide three services: (i) 10-Min RUR Up, (ii) EG, and (iii) DASR. Consequently, in the day-ahead-market, the system marginal price of the 10-Min RUR Up product at time t is $\lambda^{\text{10-RUR-U}}(t) + \lambda^{\mathrm{EG}}(t) + \lambda^{\mathrm{DASR}}(t)$.

10-Min RUR Down. In both day-ahead and real-time markets, the 10-Min RUR Down products can only provide 10-Min RUR Down services. Consequently, the system marginal price of the 10-Min RUR Down product at time t is $\lambda^{\text{10-RUR-D}}(t)$ in both markets.

30-Min RUR. In real-time, as shown in (3) and (4), the 30-Min RUR products can provide both the 30-Min RUR and the 30-Min Reserve services. Consequently, in the real-time market, the system marginal price of the 30-Min RUR product at time t is $\lambda^{\text{30-RUR}}(t) + \lambda^{\text{30-SecR}}(t)$.

On the other hand, as shown in (3), (4), (5), and (6), in the day-ahead-market, the 30-Min RUR products can provide four services: (i) 30-Min RUR, (ii) 30-Min Reserves, (iii) EG, and (iv) DASR. Consequently, in the day-ahead-market, the system marginal price of the 30-Min RUR product at time t is $\lambda^{\text{30-RUR}}(t) + \lambda^{\text{30-SecR}}(t) + \lambda^{\mathrm{EG}}(t) + \lambda^{\mathrm{DASR}}(t)$.

30-Min Secondary Reserve. In the real-time market, the 30-Min SecR product can only provide the 30-Min Reserve service. Consequently, in the real-time market, the system marginal price of the 30-Min SecR product is $\lambda^{\text{30-SecR}}(t)$.

In the day-ahead-market, the 30-Min SecR product can provide the 30-Min Reserve service as well as the DASR service. Consequently, the day-ahead system marginal price of the 30-Min SecR product at time t is $\lambda^{\text{30-SecR}}(t) + \lambda^{\text{DASR}}(t)$.

5. Resource-Level Reserve Constraints

In this section, we provide the resource-level constraints for the different reserve products. Broadly, there are two types of constraints: (i) on headroom, i.e., ECOMAX and ECOMIN; and (ii) on ramp capability (ramp rate).

5.1. Online Reserve Constraints

We begin with the resource-level constraints on online resources.

5.1.1. Headroom Constraints

The headroom constraints are imposed with respect to the ECOMAX and ECOMIN of an online resource.

Constraint on ECOMAX. The sum of energy dispatch and all cleared up-ramping reserve products on an online resource should not exceed its ECOMAX. In the real-time market, this constraint is given by,

$$g_i(t) + r_i^{\text{10-RUR-U}}(t) + r_i^{\text{30-RUR}}(t) \leq E_i^{\text{MAX}}(t), \qquad \forall i \in \mathcal{G}^{\text{ON}} \tag{7}$$

In the day-ahead market, the constraint needs to account for the additional 60-Min Spin reserve product, which gives,

$$g_i(t) + r_i^{\text{10-RUR-U}}(t) + r_i^{\text{30-RUR}}(t) + r_i^{\text{60-Spin}}(t) \leq E_i^{\text{MAX}}(t), \qquad \forall i \in \mathcal{G}^{\text{ON}} \tag{8}$$

Constraint on ECOMIN. The energy dispatch and the headroom reserved for the down ramp product cleared on an online resource should not be below the ECOMIN of the resource. In both real-time and day-ahead markets, this leads to the following constraint:

$$g_i(t) - r_i^{\text{10-RUR-D}}(t) \geq E_i^{\text{MIN}}(t), \qquad \forall i \in \mathcal{G}^{\text{ON}} \tag{9}$$

5.1.2. Ramp-Capability Constraints

The ramp-capability constraints are imposed on the cleared reserve products of an online resource with respect to the 10-Min, 30-Min, and 60-Min ramp rates of the resource. The 10-Min and 30-Min ramp rate constraints are applicable in both day-ahead and real-time markets, while the 60-Min ramp rate constraints only apply in the day-ahead market.

Constraint on 10-Min Ramp Rate. The total 10-Min reserve products cleared on an online resource should not exceed the 10-Min ramp rate of the resource. This leads to two separate constraints on up-ramping reserves and down-ramping reserves, respectively:

$$r_i^{\text{SR}}(t) + r_i^{\text{10-RUR-U}}(t) \leq 10\,\text{RR}_i(t) \tag{10.1}$$

$$r_i^{\text{10-RUR-D}}(t) \leq 10\,\text{RR}_i(t), \qquad \forall i \in \mathcal{G}^{\text{ON}} \tag{10.2}$$

Constraint on 30-Min Ramp Rate. The total up ramp from the 30-Min ramp capable reserve products should not exceed the 30-Min ramp rate of the resource, which gives the following constraint:

$$r_i^{\text{SR}}(t) + r_i^{\text{10-RUR-U}}(t) + r_i^{\text{30-RUR}}(t) \leq 30\,\text{RR}_i(t), \qquad \forall i \in \mathcal{G}^{\text{ON}} \tag{11}$$

Constraint on 60-Min Ramp Rate. We have an additional ramp rate constraint in the day-ahead market because of the 60-Min Spin product, which is given by:

$$r_i^{\text{SR}}(t) + r_i^{\text{10-RUR-U}}(t) + r_i^{\text{30-RUR}}(t) + r_i^{\text{60-Spin}}(t) \leq 60\,\text{RR}_i(t), \qquad \forall i \in \mathcal{G}^{\text{ON}} \tag{12}$$

5.2. Offline Reserve Constraints

An offline resource can clear 30-Min secondary reserve product (in both markets) and 60-Min Non-Spin reserve product (day-ahead market only). Consequently, we need headroom and ramp rate constraints on these products for offline resources.

5.2.1. Headroom Constraints

In the real-time market, the 30-Min secondary reserve product should be within the ECOMIN and ECOMAX limits of an offline resource:

$$E_i^{\text{MIN}}(t) \leq r_i^{\text{30-SecR}}(t) \leq E_i^{\text{MAX}}(t), \qquad \forall i \in \mathcal{G}^{\text{OFF}} \tag{13}$$

In the day-ahead market, the sum of the 30-Min secondary reserve and the 60-Min Non-Spin reserve products cleared on an offline resource should be within the ECOMIN and ECOMAX limits:

$$E_i^{\text{MIN}}(t) \leq r_i^{\text{30-SecR}}(t) + r_i^{\text{60-NonSpin}}(t) \leq E_i^{\text{MAX}}(t), \qquad \forall i \in \mathcal{G}^{\text{OFF}} \tag{14}$$

Note: For offline resources, imposing the left-hand side constraints in (13) and (14) for non-zero ECOMIN necessitates the introduction of an integer-valued commitment variable. Consequently, depending on computational needs, we may relax the left-hand side constraints in (13) and (14).

5.2.2. Ramp-Capability Constraints

The ramp-capability of an offline resource is influenced by its time to start (minutes from notification time till the resource can operate at ECOMIN) and its ramp rate following the time

to start. The 30-Min secondary reserve product cleared on the resource cannot exceed its ramp capability; in both markets, this is imposed by the following constraint:

$$r_i^{\text{30-SecR}}(t) \leq E_i^{\text{MIN}} + \text{RR}_i \times (30 - \text{TTS}_i), \qquad \forall i \in \mathcal{G}^{\text{OFF}} \tag{15}$$

In the day-ahead market, we have an additional constraint on the 60-Min ramp-capability of an offline resource:

$$r_i^{\text{30-SecR}}(t) + r_i^{\text{60-NonSpin}}(t) \leq E_i^{\text{MIN}} + \text{RR}_i \times (60 - \text{TTS}_i), \qquad \forall i \in \mathcal{G}^{\text{OFF}} \tag{16}$$