Enhancing electricity market flexibility by deploying ancillary services for flexible ramping product procurement

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A R T I C L E I N F O

Keywords:
Energy storage systems (ESSs)
Flexible ramping product (FRP)
Flexibility
Ramp capability
Real-time market (RTM)
Renewable integration

A B S T R A C T

The escalated penetration of wind energy in the electric industry has by large contributed to an intensified uncertainty and variability of the net-load, i.e., the difference between stochastic demand and intermittent supply. In response, some Independent System Operators (ISOs) have recently introduced the Flexible Ramping Product (FRP) to heighten the grid flexibility via effective hosting of the uncertain renewables. This paper suggests a novel framework for optimal FRP provision in real-time markets (RTM) in which the shortage in the RTM ramp capacity is compensated by optimal deployment of day-ahead procured spinning reserve. In the envisioned mechanism, the ISO can deploy specific portions of the spinning reserve capacity as the FRP price increases. On this basis, a new optimization algorithm is formulated that can best capture the joint ability of ESSs and thermal generating units in providing FRP in the RTM. The proposed model is numerically investigated on the IEEE 118-bus test system, where it reveals its efficacy and applicability in load curtailment reduction.

1. Introduction

Massive penetration of renewable energy resources have transformed the electricity grid planning and operation paradigms which are no longer reliant on the expensive fossil fuels with significant greenhouse gas emissions. These eco-friendly energy resources have, however, engendered new technical and financial challenges to a secure operation of the grid. Such challenges are primarily driven by the inherent uncertainty and variability of these resources and will be aggravated by the augmented hosting of renewables in forthcoming years. According to the US government’s reports, renewables will account for 33% and 50% of the total electricity generation by 2020 and 2030, respectively [1]. With such a remarkable share of renewable resources in power grid generation portfolio, system operators and decision makers have to be equipped with advanced tools and efficient mechanisms to accommodate a high level of variability and intermittency. Otherwise, widespread load curtailments and drastic price spikes in real-time operations will be expected. This can be translated to a degraded reliability of the grid and a decline in profitability of renewable investments, further highlighting the urgent need to accommodate a higher flexibility in power grid operation [2].

Power system flexibility is defined as its ability to effectively respond to variations in supply and demand and maintain a secure balance. With the intensified penetration of renewables, the limited ramping capability of the conventional generating units may fail to compensate the rushing arrival of uncertainties [2]. To put a figure on this, the importance of sufficient system flexibility and ramp requirements in CAISO is illustrated in Fig. 1 (accessed 02/02/2020). It can be observed, in Fig. 1, that significant ramp-up flexibility between hours 5–7 and 16–19 and ramp down flexibility between hours 7–9 are required to manage the variations associated with the net-load (load minus intermittent supply). Indeed, additional ramp capability is needed to account for the load and renewable forecast errors as well [3, 4].

Several works attempted to quantify the flexibility of the power grid in different time-frames and leverage the grid resources for enhanced flexibility [5–9]. The authors in [5] integrated the concept of flexibility into the generation planning procedures. They defined a new metric named insufficient ramping resource expectation (IRRE) to evaluate the long-term flexibility in the generation sector. The operational flexibility
of the power system is modelled via dynamical flexibility envelope in [6]. The authors in [7] assert that the transmission grid has more effects on the availability of flexibility and propose two metrics to quantify it. The availability of flexibility through tie-lines in multi-area power systems is assessed in [8]. Another flexibility metric is defined in [9] attempting to consider system operation constraints in the flexibility evaluation.

In order to enhance the power grid flexibility in facing the net-load uncertainties, several Independent System Operators (ISOs) have introduced new flexibility products in their markets. This product in California ISO (CAISO) is named Flexible Ramping Product and in introduced new flexibility products in their markets. This product in

### Nomenclature

**Parameters**

- \( \rho \) Penalty cost
- \( \theta^k \) Cost of step \( k \) in SR relaxation for FRP
- \( nl \) Value of net-load
- \( d \) Value of total demand
- \( pw \) Forecasted wind power
- \( \psi^U, \psi^D \) Upward and downward net-load forecast error to be covered by FRP
- \( SR \) Total Spinning reserve procured in DAM
- \( sr \) SR awarded by the market participant in DAM
- \( \alpha \) Maximum portion of DAM SR to be deployed for FRP procurement
- \( K \) Number of steps the DAM SR may be deployed for FRP procurement
- \( C_{P_{da}, \text{th}} \) The operation cost of the thermal generating unit in DAM
- \( A \) Minimum operating cost of thermal generating units
- \( m^l \) The slope of block \( l \) in piecewise linear power-cost function
- \( \hat{P}_j, \hat{P}_j^l \) Minimum and maximum power levels
- \( \delta_j \) Maximum power of block \( l \) in piecewise linear power-cost function
- \( r_r \) Maximum operating ramp rate
- \( s_u, s_d \) Start-up and shut down ramp rates
- \( C \) Start-up cost of the market participant
- \( G_j, L_j \) Minimum initial times the thermal generating unit \( f \) needs to be online and offline, respectively.
- \( U_{T_f, \text{DT}_f} \) Minimum up and down time for thermal generating unit \( f \)
- \( \Delta t \) Time-intervals
- \( \nu^l, \nu^l_{j} \) Minimum and maximum storable water behind the dam
- \( \xi, \xi^q \) Minimum and maximum water flow
- \( \xi_{q^p, r}^{b}, \xi_{q^p, r}^{b} \) Maximum water flow of block \( r \) in piecewise linear ESS water-power relationship in generating and pumping modes
- \( \zeta \) ESS round-trip efficiency
- \( \ln_{b, r}^{b} \) The slope of block \( r \) in ESS water-power piecewise linear relationship in generating and pumping modes
- \( d_s^{sr^k}, d_s^P \) Portion of DAM-awarded SR which is summoned for energy generation
- \( p_{j, b}^a, p_{j, b}^P \) Maximum power in level \( b \) of the energy bid of ESS \( s \) in generating and pumping states
- \( n_{j, b}^a, n_{j, b}^P \) Price of level \( b \) in the energy bid submitted by ESS \( s \) in generating and pumping states.

**Sets**

- \( t \) Market time-steps \( t = 1...T \)
- \( j \) Thermal generating units \( j = 1...J \)
- \( f \) Fast-start thermal generating units \( f = 1...F \)
- \( s \) Energy storage systems \( s = 1...S \)
- \( k \) Steps of SR used for FRP \( k = 1...K \)
- \( l \) Number of blocks in piecewise linear power-cost function of thermal generating units \( l = 1...L \)
- \( r \) Number of blocks in ESS piecewise linear water-power relationship \( r = 1...R \)
- \( b \) Levels of the offered energy bids of ESSs in the RTM \( b = 1...B \)

**Superscripts**

- \( th \) Thermal generating unit
- \( fr \) Fast-response thermal generating unit
- \( ess \) Energy storage system
- \( g \) Generation mode
- \( p \) Pumping mode
- \( e \) Energy
- \( sr \) Spinning reserve
- \( rt \) Real-time market
- \( da \) Day-ahead market.

**Abreviations**

- AS Ancillary Service
- CAISO California Independent System Operator
- DAM Day-Ahead Market
- MCP Market Clearing Price
- ESS Energy Storage System
- FM Forecasted Movement
- FRD Flexible Ramp Down
- FRP Flexible Ramping Product
- FRU Flexible Ramp Up
- MISO Mid-continent Independent System Operator
- PHS Pumped-Hydro Storage
- RTD Real-Time Dispatch
- RTM Real-Time Market
- RTUC Real-Time Unit Commitment
- SR Spinning Reserve
- UA Uncertainty Award
- VOLL Value of Lost Load
Flexible Ramping Product (FRP) is defined as the total ramping capability of generating units to respond to the net-load variability at the next immediate time-interval in the electricity market. The FRP procurement offers the ability to reserve both upward and downward ramp capabilities, namely flexible ramp up (FRU) and flexible ramp down (FRD), respectively. Providing the FRP in the market changes the generation dispatch, which in turn calls for new payment mechanisms to the players. In contrast to energy and ancillary services, the FRP cannot be implemented solely through the traditional energy market rules since the participants do not submit economic bids for FRP. The associated cost of FRP is determined according to the energy opportunity cost of participants, amounted as the difference between the market clearing price (MCP) and the submitted bid [9–12].

The FRP could be implemented in any market structure. In [13] and [14], a framework is presented which utilizes the FRP in day-ahead market (DAM) mechanisms. Since the forecast errors are much higher in DAM than in near real-time procedures, this market product may lead to excessive amounts of FRU and FRD, which may overshadow the main advantages of the FRP. Hence, FRP procurement is preferred in real-time market (RTM) as the forecast errors are proportionally lower in RTM—about one-tenth of that in DAM [15]. Several ISOs have included the FRP product into the real-time unit commitment (RTUC) and real-time dispatch (RTD) procedures [9, 10]. The FRP model applied in the California ISO (CAISO) is introduced in [16] and the ramping capability product model for the Midcontinent ISO (MISO) is presented and discussed in [17].

Only a few research efforts can be found in the literature on the FRP definition and market analysis with FRP. The research in [18] was toward comparing the main differences between deterministic and stochastic RTM optimization models considering FRP, where it was demonstrated that the stochastic optimization results in a more reliable and economic solution. Currently, FRP is determined and allocated to participants according to the entire system's requirements without taking into account transmission line constraints. A locational FRP model is developed in [19] to assure its deliverability to each bus considering the line congestion constraints. The authors in [20] aim to minimize the risk in real-time dispatch and attempt to provide optimal amounts of FRP. They define the extended loss of load probability as a risk index. In the previous work of the authors [21], the optimal provision of FRP by thermal generating units considering FRU and FRD as algebraic values is developed. They discuss how a market participant may provide negative amounts of FRU or FRD and how they will be penalized. Furthermore, the authors previously proposed mathematical formulations to implement FRP from ancillary services (ASs) in the RTM. They assumed that if the AS price in the RTM is lower than the FRP price minus the price of those ASs in DAM, additional FRP may be procured from the DAM AS [22]. In this case, additional ASs must be procured in the RTM to secure reliable operation of the system. The optimal allocation of FRP through chance-constrained and Nash-Cournot approaches are discussed in [23] and [24], respectively. An algorithm is proposed in [25] and [26] to involve wind farms in FRP market mechanisms. Likewise, the provision of FRP by solar generation is investigated in [27] and a surrogate-based optimization problem is developed to determine optimal amount of FRP procurement. The authors in [28], proposed the bidding strategy of battery energy storage systems (BESSs) in DAM energy and FRP market. However, FRP is an RTM market product and based on that, the authors in [29] developed an optimal framework for the participation of BESSs in the RTM market considering FRP provision. A scenario-based stochastic optimization approach is developed in [30] for the bidding strategy of electric vehicles in the FRP market aiming at maximizing the charging station profitability and enhancing the grid reliability and flexibility. A review on FRP is presented in [31] in which the current FRP provision mechanism and future challenges are investigated. Another review on the FRP products and the electricity markets, current research on the topic, and the potential research gaps is provided in [32].

In order to further differentiate the proposed model in this paper against the state-of-the-art models, a summary of the literature review and the aspects of the FRP each work has focused on is provided in Table 1.

Complementary to the past research on FRP, this paper proposes an advanced mechanism and a new optimization algorithm for FRP procurement through a multi-interval RTUC problem in the energy markets, where the FRP shortage is compensated by a gradual release of day-ahead procured reserve services. The main contributions of this paper are highlighted as follows.

- A novel framework for optimal procurement of FRP in RTM is introduced, offering opportunities to effectively handle the net-load variability in real-time. In this framework, in the case the FRP provision jeopardizes the cost-efficiency of the RTUC, a portion of the spinning reserve (SR) procured in DAM is deployed in multiple steps for additional FRP provision. At each time-step, a deterministic optimization is run over multiple time-intervals and only the results of the first interval are implemented.
- A precise mathematical model formulated as a mixed-integer linear programming (MILP) optimization problem is proposed for FRP procurement by ESSs in both generation and consumption operating states. This, in turn, impressively increases the ESSs efficiency when participating in the RTM.
- The framework is implemented on IEEE 118-bus test system and the simulation results demonstrate its effectiveness on load curtailment and energy price spike occurred due to the lack of ramp capacity. Furthermore, a sensitivity analysis is conducted on the net-load uncertainty increment due to renewable energy penetration, wind in particular. Based on the simulation results, the higher the renewable generation, the higher efficacy of the framework in load curtailment and energy price spike mitigation.

The rest of the paper is organized as follows: The FRP model is introduced in Section 2, followed by the suggested mathematical formulations in Section 3. The case studies and numerical results are presented in Section 4 and finally come the conclusions in Section 5.

2. Flexible ramping product

FRP is the energy capacity of RTM participants which is reserved to cover the net-load uncertainty and variability at the next immediate time-interval. The FRU and FRD, the main FRP products, are modeled by inserting the ramp-up and ramp-down constraints into the RTUC and RTD formulations [3, 12]. According to Fig. 2, the ISO dispatches the system generating units at time $T$ considering the net-load forecast at $T + 1$ and in such a way that assures the system sufficient ramping capability in response to the uncertainties. The required ramp-up and ramp-down capacities are equal to the FRU and FRD, respectively.

The RTM process includes an RTUC and RTD. RTUC is a multi-interval process that runs every 15 min resulting in real-time unit

![Fig. 1. Net-load variability resulted by high penetration of renewables in CAISO market on 02/03/2020.](image-url)
and UA are the marginal prices between the forecasted net-load at (FM) and the uncertainty award (UA). FM is defined as the difference FRU and FRD of these units as algebraic values.

The FRP model is comprised of two parts: the forecasted movement (FM) and the uncertainty award (UA). FM is defined as the difference between the forecasted net-load at $T + 1$ and its realized value at $T$ ($T$ is the binding time-interval in RTUC or RTD) [16]. This part of the FRP indicates the expected change (variation) in the net-load that the system must be able to follow. All market players, i.e., conventional generating units, renewable units and ESSs, can contribute to the net-load. UA is the FRP needed to account for the uncertainties in the forecasted net-load at $T + 1$. In fact, forecasts of the renewable generation and load include certain upward and downward errors (uncertainty) for which the system must reserve ramp capacities through the UA part of the FRP. Only those players with certain ramping capabilities that participate in the RTM are eligible to procure UA. The system total FRU requirement is then the sum of upward FM and UA [3]. Separate assessment of the FM and UA offers the following advantages:

- It makes it possible to distinguish the required FRP in the face of net-load variability and uncertainty.
- Intermittent supplies such as wind turbines will be able to participate in the FM resulting in higher profitability.
- Every market participant may be penalized or awarded according to its FM. If a player’s FM is positive and the system calls for a ramp-up capacity, the player helps to provide it and thus, it will gain profit. On the contrary, if the player’s FM is negative, this can be translated into a higher ramp-up requirement and thus, the player will be penalized.

The FM and UA assessments and related payments are elaborated in the following:

### 2.1. Forecasted movement (FM)

A player’s FM in a multi-interval RTM is defined as the difference between its output power at the binding time-interval $T$ and the advisory time-interval $T + 1$ [3, 16]. Indeed, the player’s FM reflects its ability in accommodating the net-load variability—the difference between the forecasted net-load at time $T + 1$ and that at time $T$ (see Fig. 2). The player may be rewarded when the net-load variation follows its FM, while it may be penalized when its FM and the net-load variation are in the opposite directions (i.e., intensified system ramping requirements). Accordingly, the FM payment for each market participant can be determined as follows:

$$c_i^{fm} = f_m \times (\lambda_i^{u} - \lambda_i^{d})$$

Where $f_m$ represents the award or penalty of the market player, $f_m$ is the forecasted movement of player, $\lambda_i^{u}$ and $\lambda_i^{d}$ are the marginal prices for FRU and FRD. Note that if the output power of a generating participant is expected to increase, it reflects a positive FM and vice versa. On the other hand, the FM for a consuming player is the opposite of that for generating participants. Indeed, as customer demand increases, the correspond FM would be negative. The rationale behind (1) comes primarily from the fact that if the output power of a generating unit increases (or power consumption decrease), it procures FRU in the system and consequently, the system FRD capacity increases. Therefore, the player will be paid or penalized according to the FRU or FRD marginal prices, respectively. Provided that the FM of a generating unit (customer) is negative (positive), the system FRD will increase while the FRU decreases.

### 2.2. Uncertainty award (UA)

The net-load uncertainty is originated from the forecast errors in the stochastic demand and intermittent supply. The UA is procured to manage this uncertainty [3, 16]. Both the load and intermittent supply contribute to this FRP product. Thus, their payments are assessed according to their contribution to the total upward and downward uncertainty and settled on the FRU and FRD marginal prices. Charges are paid to those market participants whose energy capacity is partially reserved to cope with the net-load uncertainties.

### 2.3. Additional FRP by deploying reserve services

In the traditional practice, the FRP will be procured up to its associated price cap. Hence, in the cases where net-load ramp is high, the system may encounter insufficiency in the FRP and consequently inability to maintain the balance between supply and demand. Also, a
large portion of the DAM-procured SR usually remains unused in the RTM while it can provide more flexibility to the system. In this research, it is proposed to utilize a portion of DAM SR for FRP procurement, when the ramp up capacity of the market is insufficient or the FRU price is high. On this basis, the portion of the DAM SR, which is being utilized for flexibility improvement in RTM, will be divided into multiple steps with different associated prices set by the ISO. Then, as the FRU price increases, these steps of SR are gradually released for FRP procurement. By this approach, the final FRP price will be lower and more capacity for FRP procurement will be available. The market participant whose DAM-awarded SR is used for FRU procurement in the RTM will be compensated based on the FRU marginal price.

3. Mathematical formulation

The RTUC problem that an ISO runs is a multi-interval optimization, the first-interval results of which are binding and of the other intervals are advisory. Fig. 3 demonstrates the binding and advisory intervals in real-time procedures. All the market participants are obliged to follow the binding-interval decisions, violations on which will result in certain penalties. Advisory data are also provided to the market participants to help them modify their market participation strategies if needed [33]. Since the RTUC time-horizon is about two hours, UC instructions (start-up/shut-down) can barely be made for those generating units whose minimum up or down-time is higher than two hours. Therefore, the ISO only has the authority to provide the UC commands to fast-start generating units including ESSs. The RTUC optimization problem is presented here in three main sub-sections: system requirements, thermal generating units, and ESSs, where the corresponding formulations are introduced in the following.

3.1. System requirements

The proposed objective function (C) for the RTUC optimization problem is as given in (2):

\[
C = \min \left[ \sum_{k=1}^{K} k \left( \sum_{j=1}^{J} \left( \sum_{l=1}^{L} \left( c_{p}^{j,sl} + c_{u}^{j,s} + \sum_{i=1}^{S} \left( c_{p}^{j,si} + c_{u}^{j,si} \right) \right) + \theta^{k} \sum_{l=1}^{L} \left( \sum_{s=1}^{S} \sum_{i=1}^{S} \left( p_{srj,sl} + \rho^{s,\psi} \bar{p}_{srj,sl} + \rho^{s,\phi} \mu_{srj,sl} + \rho^{s,\phi} \frac{\partial \mu_{srj,sl}}{\partial \psi} \right) \right) \right) \right]\right]
\]

In which, \( \bar{\psi} \) stands for the demand not supplied and \( \bar{\mu} \) the oversupply which is curtailed, \( \mu_{srj,sl} \) and \( \bar{\mu}_{srj,sl} \) are the portions of FRU and FRD requirements which are not procured. The first 4 terms in the proposed objective function attempt to minimize the units’ operation and startup costs, while term 5 accounts for the value of the DAM SR used for FRP procurement. Associating \( psr_{kr} \), with \( \theta^{k} \) causes the system to deploy the SR for FRP provision in multiple steps as the FRU price increases. Terms 5 and 6 show the costs of load loss and wind curtailment. Lastly, terms 7 and 8 stand for costs of the portions of FRU and FRD that are not covered due to lack of ramp rate or FRP price cap.

The proposed optimization aims to maintain the balance between demand and supply:

\[
nl_{t} = (d_{t} + \bar{d}_{t}) - (p_{s} + \bar{p}_{s}); \quad \bar{d}_{t}, \bar{p}_{s} \geq 0 \quad \forall \ t
\]

(3)

\[
ln_{t} = \sum_{j=1}^{J} p_{j,sl}^{h} + \sum_{i=1}^{S} (p_{j,si}^{g} - p_{j,si}^{h}) \quad \forall \ t \in T
\]

(4)

Where variable \( p^{h} \) is the output power of thermal units and \( p^{g}, p^{h} \) are the power output of ESS in discharging (generating) and charging (pumping) modes, respectively. Based on (3), the net-load equals the supplied demand minus the delivered wind generation. The thermal units along with ESSs are responsible to supply the net-load enforced in

The FRP is procured to tackle the net-load uncertainty at the next immediate time-interval; therefore we have:

\[
nl_{t+1} - nl_{t} + \psi_{t+1}^{\psi} + \mu_{srj,sl}^{\psi} \leq fru_{t+1}^{\psi} + fru_{t+1}^{\psi} \quad \forall \ t = 1 \ldots T - 1
\]

(5)

\[
nl_{t} - nl_{t+1} + \psi_{t}^{\psi} + \mu_{srj,sl}^{\psi} \leq frd_{t+1}^{\psi} \quad \forall \ t = 1 \ldots T - 1
\]

(6)

\[
fru_{t+1}^{\psi} = \sum_{j=1}^{J} \sum_{l=1}^{L} \left( r_{j,sl}^{p} + \sum_{s=1}^{S} r_{j,sl}^{g,s} \right) \quad \forall \ t = 1 \ldots T - 1
\]

(7)

\[
frd_{t+1}^{\psi} = \sum_{j=1}^{J} \sum_{l=1}^{L} \left( r_{j,sl}^{d} + \sum_{s=1}^{S} r_{j,sl}^{d,s} \right) \quad \forall \ t = 1 \ldots T - 1
\]

(8)

\[
fru_{t+1}^{\psi} = \sum_{k=1}^{K} \sum_{i=1}^{S} psr_{k,sl+1} \quad \forall \ t = 1 \ldots T - 1
\]

(9)

\[
\sum_{k=1}^{K} psr_{k,sl} \leq \alpha \cdot sr_{t} \quad \forall \ t = 2 \ldots T
\]

(10)

\[
0 \leq psr_{k,sl} \leq \frac{sr_{t}}{K} \quad \forall \ k, \ t = 2 \ldots T
\]

(11)

\[
fru_{t+1}^{\psi} = \sum_{j=1}^{J} \sum_{l=1}^{L} \left( r_{j,sl}^{g,psr} + \sum_{s=1}^{S} r_{j,sl}^{d,psr,s} \right) \quad \forall \ t = 1 \ldots T - 1
\]

(12)

The system FRU and FRD requirements are determined through the two constraints (5), (6). In (7), (8), the energy part of FRU and FRD is provided from the energy capacity of participants. Based on (9), (10), the total SR available for FRU provision is set to \( \alpha \% \) of the total SR. Note that the FRP is procured to cover the uncertainties at the next time-step whereas the SR is procured to deal with the contingencies at the same time-step. On this basis, the SR part of FRU is provided in (9) from the SR at \( t + 1 \). In (11), the available SR in each step of SR to be deployed for FRU provision is determined which per (12) is procured from SR capacity of the market participants. Note that the relevant Lagrange multipliers of (5) and (6) determine the FRU and FRD marginal prices, respectively.

3.2. Thermal generating units

Participation of thermal generating units in the RTUC is similar to the algorithmic model presented in [34]. The power production and the corresponding costs are given below:

\[
cp_{j,sl}^{\psi} = \psi_{j,sl}^{\psi} \sum_{i=1}^{S} \left( p_{j,si}^{g} + p_{j,si}^{h} \right) \quad \forall \ j, \ t
\]

(13)

\[
cp_{j,sl}^{\psi} \geq cp_{j,sl}^{\psi} - C_{p} \cdot \psi_{j,sl}^{\psi} \quad \forall \ j, \ t
\]

(14)

\[
\psi_{j,sl}^{\psi} = \psi_{j,sl}^{\psi} \sum_{i=1}^{S} \sum_{r=1}^{R} \beta_{j,sl}^{g} \quad \forall \ j, \ t
\]

(15)

\[
0 \leq \beta_{j,sl}^{g} \leq \beta_{j,sl}^{g} \quad \forall \ j, \ t
\]

(16)

![Fig. 3. Binding and advisory time-intervals in an RTUC or RTD process.](image-url)
In which, the binary variable \( x_{ij,t} \) declares the state of operation of the thermal generating unit (1: on, 0: off). The piecewise linear operating cost of the thermal unit \( j \) per the output power is reflected in (13). According to (14), the operating cost of the thermal unit considered in the objective function of RTM optimization equals the difference in the total RTM cost and the DAM cost, if the RTM power output is higher. If the RTM power is lower, it will be 0 since the traded energy in the DAM is binding. The power output of the thermal units is divided to block in (15) and the maximum power of each block is set in (16).

The output power of thermal generating units is limited to their ramp as well as maximum and minimum output limits:

\[
P_{f,t}^{\min} \leq p_{f,t}^n \leq P_{f,t}^{\max} \quad \forall j \in J, \; \forall t \in T
\]  

(17)

\[
p_{f,t}^n + sr_{f,t} \leq P_{f,t}^{\max} \quad \forall j \in J, \; \forall t \in T
\]  

(18)

Where, \( P_{f,t}^{\min} \) is an auxiliary variable indicating the maximum output power that the generating unit is able to increase at time \( t \). As shown in (17), if the thermal unit is online, the power output is greater than the minimum limit, and per (18), the summation of energy and awarded SR is lower than the maximum accessible power (\( P_{f,t}^{\max} \)) which in turn is limited to maximum power limit. Note that variable \( P_{f,t}^{\max} \) depends on the operating state, the ramp-up and ramp-down limits, minimum and maximum output power limits, the power output at the last time-interval, and the allocated spinning reserve in DAM. Thus, the following constraints should be enforced:

\[
p_{f,t} + sr_{f,t} - P_{f,t}^{\max} \leq 0 \quad \forall j \in J, \; \forall t \in T
\]  

(19)

\[
p_{f,t}^{\min} \leq P_{f,t}^{\max} \quad \forall j \in J, \; \forall t \in T
\]  

(20)

As the set of equations above suggests, if the thermal unit is starting up \( (x_{ij,t} = 1, \; x_{ij,t+1} = 0) \), the maximum accessible power is set to startup ramp in (19), while (20) and (21) are relaxed. If the unit is operating \( (x_{ij,t} = 1, \; x_{ij,t+1} = 1) \), the maximum change in power is set to the maximum operating ramp rate in (19) and (21), while (20) is relaxed. If the unit is being shut down \( (x_{ij,t} = 0, \; x_{ij,t+1} = 1) \), the ramp-down rate is set to the shut-down ramp rate and in (21), the power output at \( t-1 \) is set to the shut-down ramp rate, as well. Lastly, if the unit is offline \( (x_{ij,t} = 0, \; x_{ij,t+1} = 0) \), (19) and (21) are relaxed and (20) sets the maximum accessible power to 0.

The start-up cost of the fast-start generating units in the RTM is modeled in (22) and (23):

\[
c_{ij,t}^{\text{start-up}} = c_{ij,t}^{f,i} - c_{ij,t}^{f,a} \quad \forall j \in J, \; \forall t
\]  

(22)

\[
c_{ij,t}^{f,i} = C_f (x_{ij,t} - x_{ij,t-1}) \quad \forall j \in J, \; \forall t
\]  

(23)

Where \( c_{ij,t}^{f,a} \) is the auxiliary variable standing for RTM imposed start-up cost and \( C_f \) denotes the start-up cost. Parameter \( c_{ij,t}^{f,i} \) is the corresponding start-up cost in DAM. Note that the only time at which the start-up cost of the generating unit needs to be considered in RTM optimization objective function is when the unit is not started in the DAM and is called for start-up in the RTM, i.e. \( (x_{ij,t} = 1, \; x_{ij,t+1} = 0) \). In this case, in (23): \( c_{ij,t}^{f,i} = C_f \) and consequently in (22): \( c_{ij,t}^{f,a} = C_f \). Otherwise, we have \( c_{ij,t}^{f,a} = 0 \).

The corresponding minimum up and down times for the fast-start generating units are enforced below:

\[
\sum_{t=1}^{T-1} (1 - x_{ij,t}) = 0 \quad \forall f
\]  

(24)

\[
\sum_{n=t}^{T-D_{f,t-1}} x_{ij,t} \geq D_{f,t} (x_{ij,t} - x_{ij,t-1},) \quad \forall f, \forall t = G_f + 1, \ldots, T - D_{f,t} + 1
\]  

(25)

\[
\sum_{n=t}^{T-D_{f,t-1}} x_{ij,t} = 0 \quad \forall f
\]  

(26)

\[
\sum_{n=t}^{T-D_{f,t-1}} x_{ij,t} = 0 \quad \forall f
\]  

(27)

\[
\sum_{n=t}^{T-D_{f,t-1}} (1 - x_{ij,t}) \geq D_{f,t} (x_{ij,t} - x_{ij,t-1}) \quad \forall f, \forall t = D_f + 1, \ldots, T - D_{f,t} + 1
\]  

(28)

\[
\sum_{n=t}^{T-D_{f,t-1}} (1 - x_{ij,t}) = 0 \quad \forall f, \forall t = T - D_{f,t} + 2, \ldots, T
\]  

(29)

The minimum up time due to the initial conditions is set in (24), and the minimum up time for the remaining intervals is secured in (25) and (26). Similar equations for the minimum down time are given in (27)–(29). Note that the UC decisions for slow-start generating units are not made in the RTUC, and therefore, their minimum up and down times are not included in the optimization model.

The FRP associated with the thermal generating units are included in the constraints below:

\[
0 \leq \sum_{j=1}^{J} r_{f,t}^{\text{start-up}} - sr_{f,t} \leq \sum_{j=1}^{J} r_{f,t}^{\text{shutdown}} \quad \forall j, \forall t = 1, \ldots, T - 1
\]  

(30)

\[
0 \leq \sum_{j=1}^{J} r_{f,t}^{\text{shutdown}} - sr_{f,t} \leq \sum_{j=1}^{J} r_{f,t}^{\text{start-up}} \quad \forall j, \forall t = 1, \ldots, T - 1
\]  

(31)

\[
P_{f,t}^{\min} \leq P_{f,t}^{\max} - r_{f,t}^{\text{shutdown}} \quad \forall j, \forall t = 1, \ldots, T - 1
\]  

(32)

\[
r_{f,t}^{\text{shutdown}} \leq s_d (1 - x_{ij,t+1}) + s_r x_{ij,t+1} \quad \forall j, \forall t = 1, \ldots, T - 1
\]  

(33)

As can be seen in (30), the energy part of the FRU from the thermal generating units is limited by summation of the maximum accessible power and the allocated SR at \( t + 1 \). Note that this FRU could be negative depending on the maximum power output level at \( t + 1 \) (e.g., when the unit receives a shut-down command). The FRU from SR is limited to the maximum awarded SR at \( t + 1 \) in (31). According to (32), (33), the awarded FRD when the generating unit is off at \( t + 1 \) would be 0. If the generating unit is on at \( t + 1 \), the FRD is limited by the ramp rate constraint (\( P_{f,t}^{\min} - P_{f,t}^{\max} \)). When the unit is decided to be off at \( t + 1 \), the FRD is limited by the relevant shut-down ramp-rate. Eventually, when the unit receives a start-up command, the FRD is limited to \( P_{f,t}^{\min} \); this primarily comes from the fact that when a generating unit starts, its FM is positive. Thus, the system FRD requirement will increase by \( E_F \).

3.3. Pumped-Hydro storage

The ESSs can operate either as a generating unit or load with a higher ramping capability, and thus, their profitability in the FRP market can be much higher than other participants [35]. In this paper, the participation of pumped hydro storage (PHS) units are considered in the proposed FRP model. The suggested model is, however, generic enough to accommodate any other ESS technologies. The main operating conditions for a PHS can be categorized into generation, pumping, and the idle states. Therefore, the ESS only can function in one particular operating state at each time-interval [36, 37]. This is modeled in (34) using two binary variables \( i_{f,t}^b, i_{f,t}^p \) for generating and pumping modes:

\[
i_{f,t}^b + i_{f,t}^p \leq 1 \quad \forall s \in S, \forall t \in T
\]  

(34)

\[
c_{f,t}^{\text{start-up}} \geq c_{f,t}^{\text{start-up}} - c_{f,t}^{\text{transit}} \quad \forall s \in S, \forall t \in T
\]  

(35)

\[
c_{f,t}^{\text{shutdown}} = C_s (i_{f,t}^p - i_{f,t}^g) \quad \forall s \in S, \forall t \in T
\]  

(36)
The start-up cost is only paid when the ESS functions in the generation operating mode. The water volume stored behind the PH dam, water, and the ESS output power are modeled in the following set of constraints:

\[ v_{i,t} - v_{i,t-1} = (q_{i,t}^P - q_{i,t-1}^P)\Delta t \quad \forall s \in S, \forall t \in T \]  
(37)

\[ v_{i,t} \leq v_{i,t} \leq 0 \quad \forall s \in S, \forall t \in T \]  
(38)

\[ q_{i,t}^P \leq q_{i,t}^P \leq q_{i,t}^{P,N} \quad \forall s \in S, \forall t \in T \]  
(39)

\[ q_{i,t}^P = q_{i,t}^{P,N} + \sum_{r=1}^{R} \delta q_{i,t}^{P,r} \quad \forall s \in S, \forall t \in T \]  
(40)

\[ 0 \leq \delta q_{i,t}^{P,r} \leq \delta q_{i,t}^{P,N,r} \quad \forall s \in S, \forall t \in T, \forall r \in R \]  
(41)

\[ p_{i,t}^P = P_{i,t}^{P,N} + \sqrt{\sum_{r=1}^{R} \delta q_{i,t}^{P,r}} \cdot I^P \quad \forall s \in S, \forall t \in T \]  
(42)

\[ q_{i,t}^P \leq q_{i,t}^P \leq q_{i,t}^{P,N} \quad \forall s \in S, \forall t \in T \]  
(43)

\[ q_{i,t}^P = q_{i,t}^{P,N} + \sum_{r=1}^{R} \delta q_{i,t}^{P,r} \quad \forall s \in S, \forall t \in T \]  
(44)

\[ 0 \leq \delta q_{i,t}^{P,r} \leq \delta q_{i,t}^{P,N,r} \quad \forall s \in S, \forall t \in T, \forall r \in R \]  
(45)

\[ p_{i,t}^P = P_{i,t}^{P,N} + \frac{1}{\sqrt{\sum_{r=1}^{R} \delta q_{i,t}^{P,r}}} \cdot I^P \quad \forall s \in S, \forall t \in T \]  
(46)

As can be observed in (39)-(46), the nonlinear relationships between the water flow and the ESS output power in both generating and pumping operating modes are linearized through piecewise linear equations. Furthermore, the ESS output power is the sum of the corresponding amounts in DAM and the change in RTM:

\[ p_{i,t}^P = P_{i,t}^{P,N} + d\sigma_{i,t}^P + P_{i,t}^{P,da} \quad \forall s \in S, \forall t \in T \]  
(47)

\[ p_{i,t}^P = P_{i,t}^{P,N} - d\sigma_{i,t}^P + P_{i,t}^{P,da} \quad \forall s \in S, \forall t \in T \]  
(48)

In which, \( p_{i,t}^{P,N} \) and \( p_{i,t}^{P,da} \) are the respective traded power in the RTM and DAM. In the RTM optimization, the day-ahead output powers are considered as the initial values. The ESSs are able to submit energy bids with different power levels and prices, modeled in the following set of constraints:

\[ p_{i,t}^{P,N} = \sum_{b=1}^{B} p_{i,t}^{P,N,b} \quad \forall s \in S, \forall t \in T \]  
(49)

\[ \frac{p_{i,t}^{P,N,b}}{\mu_{i,t}^{P,b}} \leq \frac{p_{i,t}^{P,N,b}}{\mu_{i,t}^{P,b}} \leq \frac{p_{i,t}^{P,N,b}}{\mu_{i,t}^{P,b}} \quad \forall s \in S, \forall t \in T, \forall b \in B \]  
(50)

\[ p_{i,t}^{P,N} = \sum_{b=1}^{B} p_{i,t}^{P,N,b} \quad \forall s \in S, \forall t \in T \]  
(51)

\[ \frac{p_{i,t}^{P,N,b}}{\mu_{i,t}^{P,b}} \leq \frac{p_{i,t}^{P,N,b}}{\mu_{i,t}^{P,b}} \leq \frac{p_{i,t}^{P,N,b}}{\mu_{i,t}^{P,b}} \quad \forall s \in S, \forall t \in T, \forall b \in B \]  
(52)

\[ c_{i,t}^{ESS} = \sum_{b=1}^{B} (p_{i,t}^{P,N,b} \cdot \mu_{i,t}^{P,b} - p_{i,t}^{P,N,b} \cdot \mu_{i,t}^{P,b}) \quad \forall s \in S, \forall t \in T \]  
(53)

According to (51)-(53), ESSs may submit the minimum and maximum energy levels, prices, and the number of bids. The ESS awarded energy in the RTM are reflected via \( p_{i,t}^{P,N} \) and \( p_{i,t}^{P,da} \) in (49), (50). The FRP provision by ESSs are modeled as follows:

\[ p_{i,t}^P - ru_{i,t}^P \geq P_{i,t}^{P,N,1} \quad \forall s \in S, \forall t = 1, ..., T - 1 \]  
(54)

\[ ru_{i,t}^{da} = ru_{i,t}^P \quad \forall s \in S, \forall t = 1, ..., T - 1 \]  
(58)

\[ rd_{i,t}^{da} = rd_{i,t}^P \quad \forall s \in S, \forall t = 1, ..., T - 1 \]  
(59)

\[ 0 \leq \sum_{i=1}^{K} ru_{i,t}^{ESS} \leq sr_{i,t+1}^P \quad \forall j \in J, \forall t = 1, ..., T - 1 \]  
(60)

According to (47), sum of the ESS output power, FRU from energy and SR, when operating in the generating state, is limited by its maximum output power and the state of ESS at the next immediate time-interval. If a shut-down command or a change in the consumption mode is received at \( t + 1 \), the FRU from energy would be negative. The reason lies in the fact that the FRM is negative and it will consequently increase the system required FRU. According to (55), the awarded FRD, when the ESS operates in its generating state, is limited by its minimum power level and the state of ESS at \( t + 1 \). Similarly, the FRD could be negative, when a shut-down command or a change in the generation mode is received at \( t + 1 \), and this is because the FRM is equal to \( P_{i,t}^F \) resulting in an increase in the system FRD. According to (56)-(57) when the ESS is in a pumping state, the model is analogous to that when operating in its generating state, except for that the FRD and FRU in the pumping mode is modeled similar to the FRU and FRD in the generating mode, respectively. This is justified as the ESS consumes power in the pumping mode and is modeled as a load. Thus, an increase (decrease) in its power consumption is translated to providing FRD (FRU). According to (58)-(59), the total FRU and FRD that the ESS can procure is assessed by the sum of the relevant amounts in generating and pumping modes. Lastly, (60) assures that the FRU from SR does not exceed the awarded SR in the next time-step.

4. Case study and numerical results

4.1. Test system and critical assumptions

The studied system is the modified IEEE 118-bus test system, which contains 54 thermal generating units, 19 of which are fast-start (with minimum up and down times less than 2 h) and the rest 35 are slow-start ones; there is one PHS located in the network, and the system and equipment data are acquired from [38]. The grid-scale wind penetration is considered 20%, resulting in a 100 MW power generation. Variations in load, wind power, and the net-load forecast in a 24-hour time-interval are depicted in Fig. 4. It is assumed that the day-ahead forecast errors in both load and wind power follow the normal probability distribution function with the mean values (\( \mu \)) equal to the DA forecasts and standard deviations (\( \sigma \)) equal to 1% and 10%, respectively [15]. The RT forecast errors of load and wind power are assumed to follow the normal probability distribution functions with \( \mu \) equal to the RT forecasts and \( \sigma \) equal to 0.15% and 1%, respectively. Therefore, the net-load forecast error is assigned the normal probability distribution function as follows:

![Fig. 4. Day-Ahead forecasts of load, net-load, and wind.](image-url)
\[ N(\mu_{w^2}, \sigma^2_{w^2}) = N(\mu_{w^2} - \mu_w, \sigma^2_{w^2} + \sigma^2_w) \]  

(61)

In line with the CAISO practices, the accepted confidence level of the net-load forecast error coverage is considered 95% [3], meaning that the net-load uncertainty should be covered 97.5% upward and 2.5% downward. Hence, \( \sigma_{nl} \) of the net-load forecast error in both upward and downward directions should be handled. Accordingly, \( \Psi^{pu}_{nl} \) and \( \Psi^{pw}_{nl} \) in (5) and (6) are considered equal to 1.96 \( \sigma_{nl} \) of \( n|\sigma_{nl} \). The penalty share of wind and load uncertainties can be separately determined as follows:

\[
p^\text{wind} = \frac{\sigma^2_{w^2}}{\sigma^2_w} \times 1.96\sigma_{nl} \times (\lambda^w + \lambda^2) \\
\]

(61)

\[
p^\text{load} = \frac{\sigma^2_{d^2}}{\sigma^2_d} \times 1.96\sigma_{nl} \times (\lambda^d + \lambda^2) \\
\]

(62)

These penalties will be paid to the market participants that procure FRP to accommodate the network uncertainties. Note that the DAM runs before the RTM process starts, and the UC signals for all participating generating units are determined. The Monte-Carlo Simulation is implemented on the forecast errors distribution functions in DAM and 20 scenarios are generated, each containing a different net-load level in RTM during 96 fifteen-minute time-intervals. The Value of Lost Load (VOLL) is considered 1000$/MWh and the price cap of the FRU and FRD shortages are set to 60$/MWh [3]. The SR in DAM is set to 7% of the total load. The proposed model is a Mixed-Integer Linear Programming (MILP) formulation solved via the CPLEX solver.

4.2. Simulation results and discussions

Four test cases are considered:

- Case 1: No FRP procurement
- Case 2: FRP procurement from the RTM energy capacity
- Case 3: FRP procurement from the joint RTM energy capacity and 10% of DAM SR. The SR portion of FRP is dispatched when the FRU price reaches its cap, i.e., \( \delta^3 = 60 \$/MWh \forall k \).
- Case 4: FRP procurement from the joint RTM energy capacity and 10% of DAM SR. The SR portion of FRP is divided to 10 steps \( (K = 10) \) and the price of each step is set to \( \delta^3 = \frac{1}{K}60 \$/MWh \forall k \).

The formulation for Case 1 can be achieved by removing (5), (6) from the optimization and setting \( fru^u = fru^w = frd^u = frd^w = \alpha = 0 \). For Case 2, we only need to set \( fru^w = \alpha = 0 \). For Case 3, \( \alpha = 0.1, K = 1 \) and \( \delta^3 = 60 \$/MWh \forall k \). Lastly, for Case 4, \( \alpha = 0.1, K = 10 \) and \( \delta^3 = \frac{1}{K}60 \$/MWh \forall k \).

The simulation is conducted on the test system in an RTM time-frame and the results are numerically compared for the four test cases. The grid-scale FRP effectiveness in the system with high penetration of intermittent supply is analyzed next.

The energy prices in each of the four test cases are recorded at each scenario and the mean values at each time-interval is depicted in Fig. 5. Comparing Fig. 4 and Fig. 5, it can be traced that the energy price spikes mainly occur when the net-load sees a drastic increase and the system is facing ramp up shortage—time-intervals 16–26, 65–70. In Case 1, where no FRP is procured, more energy price spikes with higher intensity is observed. This situation occurs due to the limited ramping capability of the available generating units to cope with the net-load forecast errors. In Case 2, both the number of price spikes and their intensity is reduced since FRP procurement assists the market to better respond to the net-load forecast errors by providing ramping capacity. In Case 3, whenever the FRU price hits its associated cap, the FRU from SR capacity is dispatched. Hence, the energy price spikes are lower compared to Case 2 in intervals 20, 67 and 68. As seen in Fig. 6, these three intervals are the ones at which the FRU price reached its cap. In other intervals, the market in Case 3 is run similar to Case 2 since no FRU from SR is procured. Lastly, the FRP performance in mitigating the price spikes is significantly improved in Case 4. The reason lies in the fact that, as the FRU price increases, additional FRU from SR is dispatched. Therefore, the FRU is procured in a lower price and accordingly, energy price spikes will be less intense.

The FRU marginal prices in Cases 2–4 are depicted in Fig. 6. The FRD marginal price in these three cases is depicted in Fig. 6 as well. Note that the difference between the three cases is in the FRU procurement, thus, they result in similar FRD price. Comparing Figs. 6 and 4, one can observe that as the net-load considerably increases, the system ramp-up capability will not suffice and the FRU marginal price increases, i.e., procuring extra ramp-up capacity with higher cost to manage the net-load uncertainty. Similarly, at times when the net-load significantly declines and lack of the ramp-down capacity is experienced, the FRD marginal price increases. The FRU price in Case 2 and Case 3 is the same since the FRU from SR is only dispatched when the FRU price hits its cap. On the other hand, in Case 4, since the FRU from SR is deployed in multiple steps as the FRU price increases, the final FRU marginal price is lower than that in Case 2 and Case 3.

The dispatched FRU from SR in Case 3 and Case 4 is given in Fig. 7—only the time-intervals with non-zero dispatch are shown. The FRU from SR in Case 4 is more frequently deployed whereas in Case 3, the FRU from SR is only deployed in 3 time-intervals where FRU price hits its cap.

The total payment in the RTM as well as the load and supply curtailments are given in Table 2. In addition, in order to investigate the FRP effects on the global welfare, the VOLL factor is modeled in the cost function, and therefore, a summation on the objective terms at \( t = 1 \) for all the 96 time-intervals (i.e., the entire day) represents a comparative total cost index (IC):

\[ IC = \sum_{n=1}^{96} C_n(t = 1) \]  

(63)

The total RTM payment to system generating units that have produced energy and FRP services is the lowest in Case 1 where no FRP is procured. In Cases 2–4 in which FRP is procured, the least payment is in Case 4 that frequent FRU dispatch from SR capacity kept the FRU and energy prices relatively low. In the conducted studies, the cost function index defined in (63) is assessed to be the highest in Case 1 and the lowest in Case 4. This highlights the fact that firstly, the FRP constraints can relatively reduce the total costs, and secondly, the proposed FRU procurement model can further reduce the total costs and increase the global welfare.

Moreover, FRP procurement results in a load loss decrease from 7.3 MWh in Case 1 to 5.0 MWh in Case 2, 2.1 MWh in Case 3, and 1.9 MWh in Case 4. It demonstrates the higher effectiveness of the proposed FRU procurement method compared to the traditional practice. The supply curtailment declines from 3.1 MWh in Case 1 to 1.2 MWh in Cases 2–4. The reason in realizing the same values in Cases.
2–4 is that our proposed method only affects the available FRU capacity and not the available FRD capacity which is procured to deal with downward net-load forecast errors. All in all, implementing this approach would result in a significant financial saving by avoiding the load loss and supply curtailment.

To investigate the effects of FRP services on wind farms, we here analyze the suggested reward and penalty mechanism. The FM-centered reward and penalty for wind farms are $627 and $2851, respectively. The uncertainty-driven penalty of the wind farms is $1121. The proposed FRP model provides an opportunity for intermittent supply sources to gain profit according to their FM. However, Fig. 4 reveals that the penalty is higher than the reward since the variations in wind and the net-load are almost counter-directed. In other words, when the system requires ramp-up flexibility, the wind generation declines in this case, imposing additional ramping requirements to be met. In order to gain a higher profit in the FRP market, wind farms should have a precise forecast of the net-load variations, so as to be able to modify their generation output accordingly.

### 4.3. Sensitivity analysis on wind penetration

In order to investigate the FRP performance in scenarios with higher contribution of intermittent supply, network wind penetration level is increased from 10% to 40%. It is assumed that the load increases proportionally, and therefore, the forecasted net-load remains constant, while the forecast errors would increase.

Simulation results are illustrated in Fig. 8 and Fig. 9 where it can be clearly observed that as the wind penetration increases, the load loss and the number of price spikes would proportionally increase. It can be also observed that the FRP performance in avoiding the load loss and price spikes would be more impressive as the wind penetration grows.

As observed in Fig. 8, the increase in wind penetration leads to an increase in load loss. Per Case 2, FRU procurement from energy only, is not sufficient in load loss mitigation. On the other hand, assigning a portion of SR for FRU deployment in Case 3 and Case 4 has reduced the load loss drastically. The performance of Case 3 and Case 4 in load loss reduction is similar due to the fact that the total dispatchable FRU from SR capacity is equal in both cases. As demonstrated in Fig. 9, the number of energy price spikes tends to increase per wind penetration increment. The performance of Case 2 and Case 3 are similar in price spike reduction because the FRU from SR in Case 3 is only dispatched when the FRU price hits its cap and as a consequence, the energy price spikes. However, the performance of FRU in Case 4 is improved and the number of price spikes has reduced compared to other Cases.

### 5. Conclusion

This paper suggested a novel optimization framework for modeling and analyzing the FRP procurement in energy markets. The deployment of a portion of DAM-procured SR for FRU procurement in RTM was proposed. On this basis, as the FRU price increases, a portion of SR capacity in multiple steps is released for FRU procurement. It was assumed that the portion of FRU from SR can either be dispatched when the FRU price hits its cap or be dispatched in multiple steps as the FRU price increases. The Mathematical formulations for joint participation of thermal generating units and ESSs in the proposed FRP markets were presented. The effectiveness of the proposed FRP model was numerically tested and the results verified its applicability in real-world scenarios; expressly, the FRP procurement was observed to reduce the load curtailments to less than one-third of the case without FRP procurement (Case 1) and half of that in FRP from energy only (Case 2). Also, the FRP procurement can reduce the number of energy price spikes in RTM to half. Besides, the results revealed that FRP services could positively affect the global welfare in the market optimizations. Eventually, a sensitivity analysis on the grid-scale wind proliferation demonstrated that the proposed FRP model can more efficiently assist handling the net-load uncertainties as the renewable penetration increases.

One can conclude, based on the numerical investigations, that the reduction in the number of price spikes and load loss can lend the system operators a hand to ensure that the real-time market optimization solutions are highly reliable and precise. Furthermore, it indicates that the FRP cost-effectiveness will be more significant in systems (and time-intervals) with higher share of renewables. This study, as well, shed lights on the effective deployment and utilization of FRP services in energy market optimization which will be more on demand as we move toward 100%-renewable power grids of the future.
Acknowledgements

This work was supported by Iran National Science Foundation.

References


