Harnessing Ramp Capability of Spinning Reserve Services for Enhanced Power Grid Flexibility

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***Abstract*—Flexible ramping product (FRP) has been recently launched in a number of electricity markets to enhance the power grid flexibility and accommodate additional deals of uncertainty introduced by renewable energy resources. The FRP procures additional ramp capacities provided by the dispatchable generating units and consumers in the real-time market (RTM) with the aim to enhance the ability of supply to closely follow the net-load at the next immediate time-interval. An important challenge in widespread adoption of this technology is a key question: *Does the available energy capacity of the RTM participants contain sufficient ramp capacity to tackle the net-load uncertainties?* Indeed, shortage of the systems ramp capacity may not only jeopardize its flexibility, but also may cause drastic fluctuations in the RTM energy prices. To address this challenge, this paper proposes a novel optimization framework to harness the procured spinning reserve services in the day-ahead market (DAM) for FRP provision in the RTM while meeting the system reliability requirements. On this basis, the FRP will be simultaneously procured from the RTM energy and DAM spinning reserve capacities. Furthermore, a new payment mechanism is proposed to compensate the portion of spinning reserve utilized for FRP procurement in the RTM. The proposed framework is simulated on the IEEE 118-bus test system and the results verify its effectiveness in modern electricity markets.**

***Index Terms*—Electricity market, flexibility, flexible ramping product (FRP), ramp capability, spinning reserve, wind.**

NOMENCLATURE

A. Sets

t	Index of the RTM time-intervals $(1,\ldots,T)$.
n	The alias defined on index t.
k	Index of thermal generating units $(1,\ldots,K)$.
f	The alias defined on index k reflecting the fast-start generating units.
w	Index of wind generating units $(1,\ldots,W)$.
l	Index on the number of lines $(1,\ldots,L)$.

B. Parameters

voll	The value of lost load.
ND_t	The net-load at time interval *t*.
D_t	The total load at time interval *t*.
e_t^{up}, e_t^{dn}	The upper and lower forecast errors of the net-load at time interval *t*.
$pw_{w,t}$	The output power of wind generator w at time interval *t*.
psr	The percentage of the total load that should be covered by spinning reserve at time interval *t*.
C_k^u, C_k^d	The startup and shutdown costs of thermal generating unit *k*.
$C_{k,t}^r$	The spinning reserve bid of thermal generating unit *k* at time interval *t*.
rr_k	The ramp limit of thermal generating unit *k*.
su_k, sd_k	The startup and shutdown ramp limits of thermal generating unit *k*.
$\underline{P}_k$, $\bar{P}_k$	The minimum and maximum power output limits of thermal generating unit *k*.
a_k	The minimum output power cost of thermal generating unit *k*.
m_k^l	The slope of line l in the power-operating cost function of thermal generating unit *k*.
$\bar{\delta}_k^l$	The maximum power of part l in the linearized cost function of thermal generating unit *k*.
UT_f, DT_f	The minimum up and down times of the fast-start thermal generating unit *f*.
G_f, L_f	The minimum time-intervals the fast-start thermal generating unit *f* must stay online and offline, respectively, due to the corresponding minimum up and down times.

C. Variables

ll_t	The load curtailment at time interval *t*.
$cp_{k,t}$	The operating cost of thermal generating unit *k* at time interval *t*.
$cr_{k,t}$	The spinning reserve cost of thermal generating unit *k* at time interval *t*.
$cu_{k,t}$, $cd_{k,t}$	The startup and shutdown costs of thermal generating unit *k* at time interval *t*.
$p_{k,t}$	The power output of thermal generating unit *k* at time interval *t*.

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$\bar{p}_{k,t}$	The maximum accessible power output of thermal generating unit *k* at time interval *t*.
$sr_{k,t}$	The spinning reserve of thermal generating unit *k* at time interval *t*.
$sr_{k,t}^{\text{dam}}$	The spinning reserve awarded by thermal generating unit *k* in the DAM at time interval *t*.
$sr_{k,t}^{rtm}$	The spinning reserve awarded by thermal generating *k* in the RTM at time interval *t*.
$x_{k,t}$	The binary indicating the operating state of thermal generating unit *k* at time interval *t*.
$\delta_{k,t}^{l}$	The power of part l in linearized cost function of generating unit *k* at time interval *t*.
$\text{fru}_{k,t}$	The total FRU awarded by thermal generating unit *k* at time interval *t*.
$\text{frd}_{k,t}$	The total FRD awarded by thermal generating unit *k* at time interval *t*.
$ru_{k,t}^{e}$, $ru_{k,t}^{r}$	The FRU of generating unit *k* at time interval *t* provided from real-time energy and day-ahead spinning reserve capacities, respectively.

I. Introduction

A. Problem Description

RENEWABLE energy resources (RES), namely wind and solar, are increasingly penetrated in modern power systems, primarily as they bring about significant advantages such as massive reductions in greenhouse gas emission and environmental pollution. RESs, however, carry inherent uncertainties and generation variability, which potentially introduces new challenges to the successful operation and control of power grids. Seamless integration of RESs in the electric industry is primarily driven by the grid operational flexibility, i.e., the capability of supply to meet the uncertainty and variability of load and intermittent RESs [1]–[3]. In fact, if the inherent uncertainty associated with the RES, and wind in particular, is not well responded, large load curtailments and/or RES spillage will be foreseeable [4]–[7].

The available options in response are effective coordination of flexible energy resources, advanced operational decisions, and market products, among others. A number of resources exist, which can be harnessed to enhance the flexibility of power systems, ranging from the energy storage systems, hydroelectric generators, power to heat and power to gas facilities, electric vehicles, and fast-start generating units [1], [8]–[10]. Even though effective in significantly enhancing the grid flexibility, deployment and utilization of such resources are very costly and time lengthy. Furthermore, there are a number of tools the operators and decision makers may benefit from to enhance the grid flexibility in a much shorter time span. Amongst, the demand response, innovative power system operation designs, and new market products are worth mentioning [11]–[13]. In addition to the mentioned options, new market products are constantly under development and the existing products are being modified to leverage the grid flexibility in the electric operation sector. One market product, which is particularly launched in practice by a few modern independent system operators (ISOs), e.g., California ISO (CAISO) and mid-continental ISO (MISO) concerned to the grid flexibility requirements is called the flexible ramping product (FRP) [14]–[15]. As a real-time market (RTM) product, FRP aims to enhance the ability of supply to closely follow the net-load—the load minus intermittent supply—at the next immediate time-interval by procuring additional ramp-up and ramp-down capacities provided by dispatchable generating units and consumers in the RTM [14]–[16]. Should the FRP implemented properly, it can play a superb role on the enhancement of power system operational flexibility.

The FRP performance mainly depends on the available ramping capacity in the RTM, which is not already scheduled in other products, episodically energy and spinning reserve. Hence, procuring sufficient ramping capacity in the RTM turns out to be a new challenge for electricity market operators. This paper attempts to propose a novel mechanism to free up a portion of the day-ahead procured spinning reserve in the RTM to increase the available ramping flexibility for FRP procurement.

B. Literature Review

There exists a rich literature on optimization of reserve products in the DAM and RTM to deal with the intermittent supply uncertainty [17]–[21]. An operational strategy is proposed in [17], which attempts, based on the available data on renewable generation uncertainty, to optimize the energy and reserve dispatch problem. This data-driven method implements the Kernel density estimation (instead of theoretical probability functions) to build ambiguous probability distributions for renewable generation. In [18], a distributionally robust optimization framework is proposed that optimally schedules the energy and reserve based on the partial data available on wind generation. To overcome the computational complexity of the stochastic optimization in large-scale systems, Hedayati-Mehdiabadi *et al.* [19] suggested offline stochastic algorithms to construct appropriate operational policies and more efficient deterministic optimization formulations to stochastically determine the reserve. A distributed stochastic method for multi-area reserve procurement is proposed in [20] considering high levels of wind penetration.

These studies typically attempt to optimize the system required operational reserve based on the available renewable generation uncertainty information and acceptable risk levels. However, a crucial point is that at each time-interval of the market operation, the reserve is procured to cover the uncertainty and contingencies occurring in that particular time-interval. Conversely, at each time-interval, the FRP is procured to cover the net-load uncertainties in the next time-interval. Furthermore, employing additional ramp capacity to procure more reserve product is not cost-efficient since, first, reserve service itself is extremely costly, and second, it reduces the available energy capacity of generating units, which may lead to higher energy prices [14], [22]. However, the FRP procured from available energy capacity of the market participants is much more cost efficient to handle the renewable uncertainties [22]. Hence, we propose the idea of utilizing a portion of the unused spinning reserve in the RTM for FRP procurement while maintaining the system reliability requirements.

There are a number of remarkable studies that can be found in the literature concerning different aspects of the FRP structure, its provision and allocation processes in modern electricity markets [23]–[41]. Wang and Hudge [23] provided a comprehensive review on the main features of FRP and its operational aspects. C. Wu *et al.* comprehensively discussed the effects of the FRP on the optimal generation dispatch and proposed a risk-limiting scheme to procure optimal FRP [24]. Chen *et al.* [25] and Cui *et al.* [26] attempted to provide an opportunity for wind generators to participate in the FRP market, where the simulation results indicated the benefits to both wind generators profitability and the system flexibility. B. Wang *et al.* [27] compared the stochastic and deterministic real-time unit commitment (RTUC) considering FRP requirements, where it was concluded that the solutions to the former is more cost effective. A stochastic model for FRP markets is also proposed in [27] in order to leverage the system flexibility. H. Ye and Z. Li presented a modified version of the FRP, which addresses the limited deliverability of the traditional FRP due to transmission line constraints [28]. Contrary to the previous models where FRP was procured for the entire system ignoring the transmission line constraints, this model separately procures the FRP for each node by the available generating units. Several studies attempted to modify the conventional day-ahead market (DAM) process, e.g., by adding intra-hourly constraints in stochastic optimization methods, in order to host the FRP requirements to tackle the real-time uncertainty of wind realizations [29]–[34]. Wang [35] investigated the characterization of wind generators ramping in different forecast scenarios and proposed an adjustable chance-constrained framework to optimally procure FRP while taking into account the operational risks. An optimal bidding strategy for energy storages with the goal of maximizing their profit in the day-ahead energy, reserve and FRP markets is proposed in [36]. Gharibpour and Aminifar [37] attempted to achieve a multi-stage stochastic equilibrium based on the principle concepts of game theory to overcome the inter-temporal nature of the FRP.

C. Our Contributions

Unlike the other market products, e.g., energy, operational reserve and regulation services, market participants cannot submit direct economic bids for the FRP. The payment method of this product is based on the lost energy opportunity cost of the generating units whose energy capacity is reserved for FRP requirements [14]–[16]. A serious concern, which is not addressed properly in the literature, is "*does the available energy capacity of the RTM participants contain sufficient ramp capacity to tackle both the FRP and power balance requirements?*" Indeed, shortage of the systems ramp capacity may not only jeopardize its flexibility, but also may cause drastic fluctuations in the RTM energy prices. In such scenarios, the FRP procurement disadvantages surpass its advantages, and hence, provision of sufficient ramp capacity in the RTM process is requisite. To effectively address the aforementioned challenge, the authors suggest a revolutionary approach to utilize the day-ahead-provided spinning reserve services as an auxiliary source of ramp capacity in the RTM. Building on this hypothesis, this paper proposes an FRP co-provision mechanism simultaneously from the real-time energy capacity and day-ahead spinning reserve services. Different from the traditional practice, the provided spinning reserve in the DAM is no longer to be locked-up during the RTM processes, but plays an active role in the spinning reserve-energy procured FRP (SEFRP). A point worth emphasizing is that utilizing a portion of the day-ahead procured spinning reserve in the RTM to handle the system uncertainties is still insufficient, since spinning reserve is procured for the current time-interval (T) and cannot be used to cover the next immediate time-interval (T + 1) net-load forecast uncertainty. Conversely, if implementation of the proposed method requires a portion of this spinning reserve to be utilized for FRP procurement—which deals with the uncertainties in the next time-interval (T + 1)—the spinning reserve can significantly heighten the performance of FRP and consequently enhance the system operational flexibility. In summary, the main contributions of this paper are threefold.

1) A novel optimization framework for provision of a modified FRP (e.g., SEFRP) from the submitted energy capacity of the RTM participants and the allocated spinning reserve to DAM participants is proposed and linearized. This framework brings about significant ramp capacities that, first, can continuously cover the net-load variability, and second, lowers both the FRP marginal prices, energy price spikes, and the system total operating cost.
2) A new payment mechanism for the awarded SEFRP is proposed such that the generating units will be only compensated for the withheld energy capacity in the RTM based on the SEFRP marginal cost.
3) The proposed framework is applied to the IEEE 118-bus test system and the simulation results demonstrate the impressive efficacy of the SEFRP on load curtailments and RTM price spikes realized due to the intermittency of the net-load. Furthermore, a sensitivity analysis on the uncertainty increments impacting the performance of SEFRP is conducted, where the simulation results implicate the higher effectiveness of the SEFRP in systems with massive proliferation of RESs.

D. Paper Organization

The rest of the paper is organized as follows. The conventional FRP model is described in Section II. Section III discusses the suggested SEFRP features, justifications, and payment mechanism, followed by the proposed mathematical formulations in Section IV. Numerical case study is detailed in Section V and finally come the conclusions in Section VI.

II. Conventional Flexible Ramping Product

The FRP assures that the supply can closely follow the load at the next immediate time-interval with a high confidence level. This is accomplished by reserving sufficient ramp-up and ramp-down capacities, respectively, called flexible ramp-up (FRU) and flexible ramp-down (FRD), from the energy capacity of generating units participating in the RTM. The participating generating units are compensated according to their lost energy opportunity cost, where its marginal values determine the FRU and FRD marginal prices. The FRP is procured in multi time-interval RTUC and the real-time dispatch (RTD) processes [14].

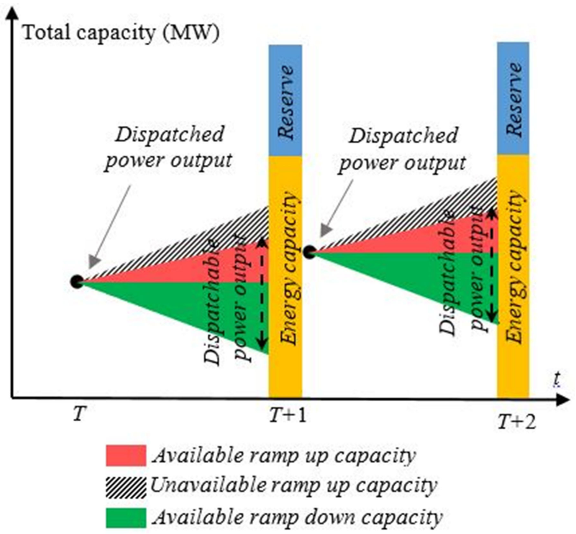

Fig. 1. Conventional FRP model and performance.

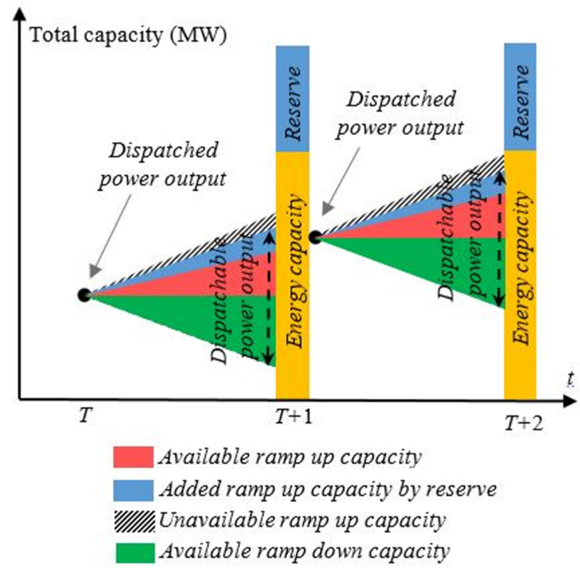

Fig. 2. Proposed SEFRP model and the increased ramp-up capacity.

Note that the RTUC typically runs every 15 min and during every RTUC, three five-minute RTDs are simulated [42]. Therefore, the FRP is first procured to handle the 15-min net-load forecast error in the RTUC process. Then, in order to cover the five-minute net-load forecast errors, incremental amounts of FRP will be procured in every RTD process [14], [16].

III. Proposed SEFRP

A. SEFRP Features

In the proposed SEFRP model, the FRD provision process remains the same as the conventional FRP. However, FRU provision is achieved where additional ramp-up capacity is provided by the allocated spinning reserve to the generating unit in the DAM. As can be seen in Fig. 1 on the conventional FRP models, a large portion of a generating unit's ramp-up capacity may be locked up for other ancillary services, e.g., spinning reserve and regulation, which consequently reduces the unit's capability to reach higher power outputs. It also affects the FRP performance and hinders the system flexibility. According to Fig. 2 on the proposed SEFRP model, the generating unit's awarded spinning reserve in the DAM is freed up in the RTM process in order to be actively available for FRP procurement. Thus, a portion of the spinning reserve of a generating unit may be used for FRP requirements. Regarding the grid reliability considerations, the following three points worth mentioning.

1) Based on the proposed formulation, the SEFRP ensures sufficient spinning reserve in the RTM to be procured in order to maintain the system reliability. This spinning reserve should be at least equal to the portion of the DAM spinning reserve utilized for FRP provision.
2) The system conditions must comply with all the reliability requirements.
3) In line with the conventional FRP model [14], the SEFRP is only procured during the system normal operating condition. Once a contingency occurs, the SEFRP provision process will be stopped until the contingency is cleared. Hence, utilizing spinning reserve for SEFRP procurement does not impact the system reliability.

Note that as long as the ramp-up capacity of the energy sector in the system is sufficient to cover the net-load uncertainty, i.e., system's ramp requirements do not distort the optimal dispatch, no SEFRP is procured from spinning reserve capacity. In other words, the spinning reserve capacity will be mainly utilized for SEFRP provision in the case of severe net-load increments.

B. Payment Mechanism

Two different variables are defined for the SEFRP provision through energy and spinning reserve capacities of every generating unit in the system. In line with the conventional FRP model, every participating generating unit will be compensated for the SEFRP provided from its energy capacity based on the FRU and FRD marginal prices. However, the generating units are not paid for the part of SEFRP provided from their spinning reserve capacity. The justification comes from the fact that the generating units are paid for the spinning reserve in the DAM according to the spinning reserve marginal price. Therefore, if they are also paid for utilizing that reserve for FRP procurement, double payment will occur. In fact, the generating units encounter a loss of energy opportunity cost when their real-time energy capacity is withheld for FRP constraints. However, they do not encounter any loss for their DAM reserve capacity, which otherwise must be locked-up during the RTM process. Furthermore, if any portion of the provided SEFRP, either from energy or spinning reserve capacities, is utilized for energy generation at the next immediate time-interval, the corresponding generating units will be paid based on the RTM energy marginal price.

IV. Mathematical Formulations

Since the core portion of the FRP is procured during the RTUC process, the RTUC formulation is proposed below. The proposed formulation is generic and can be simply converted to model the 5-min RTD process. The thermal generating units based on their minimum up and down times are divided to fast-start (with minimum up/down times lower than the RTUC time-span) and long-start (minimum up/down times greater than the RTUC time-span) categories. The unit commitment decisions for the former can be made in the RTM, while only dispatch decisions may be made in the latter. The objective function that the ISO attempts to minimize is

$$C = \min \left[\sum_{t=1}^{T} \left(\sum_{k=1}^{K} (cp_{k,t} + cr_{k,t}) + \sum_{f=1}^{F} (cu_{k,t} + cd_{k,t}) + voll * ll_t \right) \right]. \quad (1)$$

A. System Security Constraints

The power balance constraint is formulated as follows:

$$ND_t = \sum_{k=1}^{K} p_{k,t} \quad \forall t \quad (2)$$

where

$$ND_t = D_t + \sum_{w=1}^{W} pw_{w,t} \quad \forall t. \quad (3)$$

The provided reserve by the generating units must meet the system reliability requirements. Without loss of generality, the reliability constraint is enforced here such that the spinning reserve must be greater than a percentage of the total load in the system. Indeed, the model is generic enough to accommodate any type of reliability requirements the system should comply with

$$psr * D_t \le \sum_{k=1}^{K} sr_{k,t} \quad \forall t. \quad (4)$$

The system FRU and FRD requirements are set in the following equations:

$$e_t^{up} + ND_{t+1} - ND_t \le \sum_{k=1}^{K} \mathrm{fru}_{k,t} \;\; \forall t = 1 \ldots T-1 \quad (5)$$

$$e_t^{dn} + ND_t - ND_{t+1} \le \sum_{k=1}^{K} \mathrm{frd}_{k,t} \;\; \forall t = 1 \ldots T-1. \quad (6)$$

B. Thermal Generating Units Constraints

The startup and shutdown costs of the thermal generating units are enforced as follows:

$$cu_{k,t} \ge C_k^u (x_{k,t} - x_{k,t-1})\,; \;\; cu_{k,t} \ge 0 \quad \forall k\, \forall t \quad (7)$$

$$cd_{k,t} \ge C_k^d (x_{k,t-1} - x_{k,t})\,; \;\; cd_{k,t} \ge 0 \quad \forall k\, \forall t. \quad (8)$$

The thermal generating units' spinning reserve costs are evalauted as follows:

$$cr_{k,t} = C_{k,t}^r sr_{k,t} \quad \forall k\, \forall t \quad (9)$$

where

$$sr_{k,t} \le rr_k \quad \forall k\, \forall t. \quad (10)$$

The linearized power output cost function for thermal generating units is formulated as follows [43]:

$$cp_{k,t} = a_k x_{k,t} + \sum_{l=1}^{L} \left(m_k^l \delta_{k,t}^l \right) \quad \forall k\, \forall t \quad (11)$$

$$p_{k,t} = \underline{P}_k x_{k,t} + \sum_{l=1}^{L} \delta_{k,t}^l \quad \forall k\, \forall t \quad (12)$$

$$0 \le \delta_{k,t}^l \le \bar{\delta}_k^l \quad \forall k\, \forall t. \quad (13)$$

The output power of a thermal generating unit should meet the minimum and maximum accessible limits enforced in (14)

$$\underline{P}_k x_{k,t} \le p_{k,t} \le \bar{p}_{k,t} \le \bar{P}_k x_{k,t} - sr_{k,t} \quad \forall k\, \forall t \quad (14)$$

where $\bar{p}_{k,t}$ stands for the maximum accessible power output at time interval *t*, which is bounded with the following equations:

$$\bar{p}_{k,t} \le p_{k,t-1} + rr_k x_{k,t-1} + su_k (x_{k,t} - x_{k,t-1}) + \bar{P}_k (1 - x_{k,t}) \quad \forall k\, \forall t \quad (15)$$

$$\bar{p}_{k,t} \le sd_k (x_{k,t} - x_{k,t+1}) + \bar{P}_k x_{k,t+1} \; \forall k \quad \forall t = 1 \ldots T-1 \quad (16)$$

$$p_{k,t-1} - p_{k,t} \le rr_k x_{k,t} + sd_k (x_{k,t-1} - x_{k,t}) + \bar{P}_k (1 - x_{k,t-1}) \forall k \quad \forall t = 1 \ldots T-1. \quad (17)$$

The constraints corresponding to the minimum up and down times of fast-start generating units are presented as follows:

$$\sum_{t=1}^{G_f} [1 - x_{f,t}] = 0 \quad \forall f \quad (18)$$

$$\sum_{n=1}^{t+UT_f-1} x_{f,n} \ge UT_f [x_{f,t} - x_{f,t-1}] \quad \forall f\, \forall t = G_f + 1 \ldots T - UT_f + 1 \quad (19)$$

$$\sum_{n=t}^{T} [x_{f,n} - (x_{f,t} - x_{f,t-1})] \quad \forall f\, \forall t = T - UT_f + 2 \ldots T \quad (20)$$

$$\sum_{t=1}^{L_f} x_{f,t} = 0 \quad \forall f \quad (21)$$

$$\sum_{n=1}^{t+DT_f-1} [1 - x_{f,n}] \ge DT_f [x_{f,t-1} - x_{f,t}] \quad \forall f\, \forall t = D_f + 1 \ldots T - DT_f + 1 \quad (22)$$

$$\sum_{n=t}^{T} [1 - x_{f,n} - (x_{f,t-1} - x_{f,t})] \quad \forall f\, \forall t = T - DT_f + 2 \ldots T. \quad (23)$$

The SEFRP constraints and interactions with the real-time energy and reserve services are proposed as follows:

$$\mathrm{fru}_{k,t} = ru^{e}_{k,t} + ru^{r}_{k,t} \qquad \forall k \forall t = 1 \ldots T-1 \tag{24}$$

$$\bar{p}_{k,t+1} \geq p_{k,t} + \mathrm{fru}_{k,t} + sr_{k,t} \qquad \forall k \forall t = 1 \ldots T-1 \tag{25}$$

$$0 \leq ru^{r}_{k,t} \leq sr^{\mathrm{dam}}_{k,t} \qquad \forall k \forall t = 1 \ldots T-1 \tag{26}$$

$$sr_{k,t} = sr^{rtm}_{k,t} + \left(sr^{\mathrm{dam}}_{k,t} - ru^{r}_{k,t}\right) \qquad \forall k, \forall t \tag{27}$$

$$p_{k,t} - \mathrm{frd}_{k,t} \geq \underline{P}_k x_{k,t+1} \qquad \forall k \forall t = 1 \ldots T-1 \tag{28}$$

$$\mathrm{frd}_{k,t} \leq sd_k(x_{k,t} - x_{k,t+1}) + rr_k x_{k,t+1} \qquad \forall k \forall t = 1 \ldots T-1. \tag{29}$$

The total FRU of a generating unit is formulated in (24), which consists the contributions from both energy and spinning reserve capacities. The total ramp-up-related products of a thermal generating unit—including the FRU and spinning reserve services—is enforced in (25) not to exceed the maximum accessible power output at the next immediate time-interval. Constrained in (26), the maximum FRU a generating unit is able to provide must be lower than its awarded spinning reserve in the DAM. It should be mentioned that unlike $ru^{e}_{k,t}$, variable $ru^{r}_{k,t}$ cannot be negative. The rationale is that $ru^{r}_{k,t}$ is an auxiliary ramp-up capacity utilized when the system faces ramp shortages, while $ru^{e}_{k,t}$ stands for the unused ramp-up capacity of the generating unit. Hence, $ru^{e}_{k,t}$ may get negative, reflecting that the available energy capacity at the next immediate time-interval is lower than the current power output, e.g., when a generating unit receives a shutdown command for the next time-interval. Wang and Hobbs (27) assured that sufficient spinning reserve is procured in the RTM to satisfy the system reliability requirements—see (4). Note that no FRU from the DAM spinning reserve capacity is procured as long as the system reliability constraints are not met. The FRD constraints of the generating units are set in (28) and (29), where (28) assures that the FRD of the online generating units does not exceed $p_{k,t} - \underline{P}_k$ and (29) assures that the FRD is limited to the maximum ramp-down rate.

Note that compared to the traditional FRP model—where the FRU is only provided by the available energy capacity of RTM participant—the proposed SEFRP is able to benefit from the day-ahead provided spinning reserve which consequently enhances its capability to boost the RTM flexibility—see (24)–(27). The proposed formulation can be converted to the traditional FRP by setting $ru^{r}_{k,t}$ equal to 0. In order to satisfy the system reliability requirements, the procured spinning reserve is ensured to be greater than a certain percentage of the system load—see (4) and (27).

V. Numerical Case Study

A. Assumptions

The proposed SEFRP model is implemented on the IEEE 118-bus test system [44], for which Fig. 3 depicts the day-ahead load and wind profiles. Driven by the MISO forecast error model, the wind and load forecast errors are assumed to follow Gaussian probability distribution functions. Standard deviations of the wind and load forecast errors are, respectively, 10% and 1% in the day ahead, and 1% and 0.15% in the real-time scenarios [45]. Hence, Fig. 3 also demonstrates the upper and lower limits for the wind and net-load forecast errors (the load errors are not depicted as they were proportionally trivial). In order to more clearly assess the performance of the suggested approach, the day-ahead forecasted wind and load profiles are intentionally adjusted to expose the system in a designated scenario of net-load fluctuations. A simulation on the DAM process is run and the unit commitment decisions are utilized as the initial conditions for the RTUC process. To comply with the system reliability requirements, it is assumed that the required spinning reserve is 10% of the net-load. It should be mentioned that in real cases of the FRP implementation around the world, CAISO and MISO in particular, the FRP is implemented for the entire balancing authority area without considering transmission constraints [14]. Following this practice and without loss of generality, the transmission lines constraints are ignored in this paper and it is assumed that all the system generating units and loads are virtually connected to a single bus.

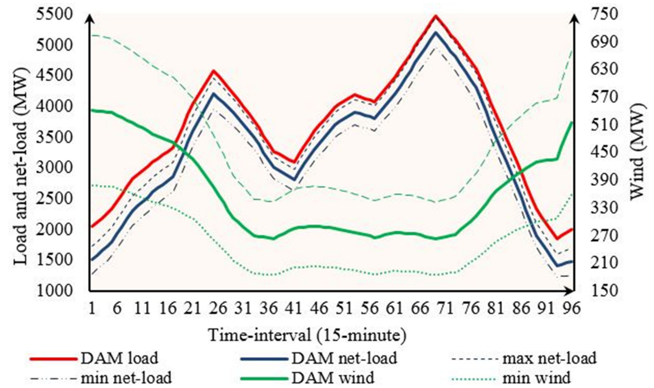

Fig. 3. DAM load, wind and net-load profiles with the associated maximum and minimum forecast errors.

The following three test cases (TC) are simulated and the results are compared and extensively analyzed.

1) TCI: Without FRP procurement.
2) TCII: With the traditional FRP procurement.
3) TCIII: With the proposed SEFRP procurement.

Note that (5), (6) and (24)–(29) must be ignored in TCI. Similarly, $ru^{r}_{k,t}$ must be set to 0 in TCII. The VOLL is set to \$3500/MWh, and the spinning reserve, FRU and FRD shortage caps are, respectively, set to \$1000/MW, \$240/MW, and \$240/MW. The forecast error coverage level is 95% [14]. The proposed model is simulated in the GAMS 25.0.3 optimization platform. The CPLEX solver is applied to solve the proposed mixed-integer linear programming optimization model.

B. Simulation Results

In order to model the load and wind generation forecast uncertainties, the Monte Carlo simulation is applied where 100 scenarios are generated each of which is comprised of 96 number of 15-min net-load values (for the entire day). The total load curtailed due to the load and wind forecast uncertainties

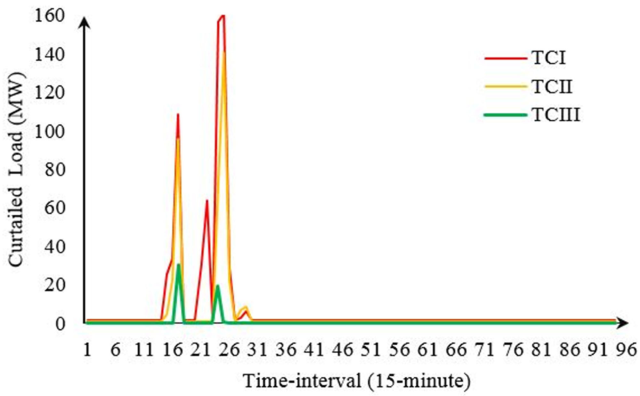

Fig. 4. TLoad curtailment due to the wind and load forecast errors in TCI, TCII, and TCIII.

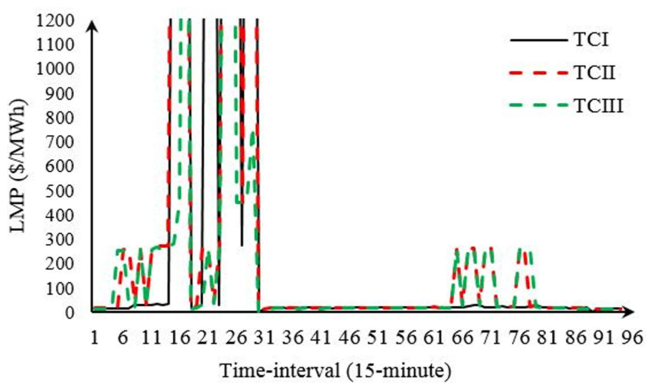

Fig. 5. RTM LMPs in TCI, TCII, and TCIII. The vertical axis is capped at $1200/MWh. All prices over $1200/MWh are equal to the voll value of $3500/MWh.

at each time-interval is demonstrated in Fig. 4. Comparing the results in Figs. 3 and 4, the load curtailment due to the forecast uncertainty is observed to mainly occur when the net-load increment is drastic and the system encounters an intense shortage of ramp-up capacity—which consequently affects the FRP performance. The traditional FRP model (TCII) is unable to significantly mitigate the load curtailment. Conversely, the proposed SEFRP model has provided an opportunity to harness additional ramp-up capacity from the DAM spinning reserve, as a result of which the load curtailment in TCIII has impressively decreased. Note that such benefits are realized while the system reliability requirements are met by procuring additional spinning reserve in the RTM, at least equal to the portion of DAM spinning reserve used in SEFRP. According to Fig. 4, the total curtailed load in TCI, TCII, and TCIII are, respectively, evaluated as 148 MWh, 91 MWh, 12.8 MWh.

The energy locational marginal prices (LMPs) in the studied test cases are presented in Fig. 5. As can be observed, the traditional FRP is not very effective to mitigate the price spikes at the time intervals where the net-load increment is drastic. Between time intervals 16–31, the traditional FRP in TCII could only slightly decrease the number of price spikes observed in TCI, implicating its inefficiency in tackling the high ramp-up

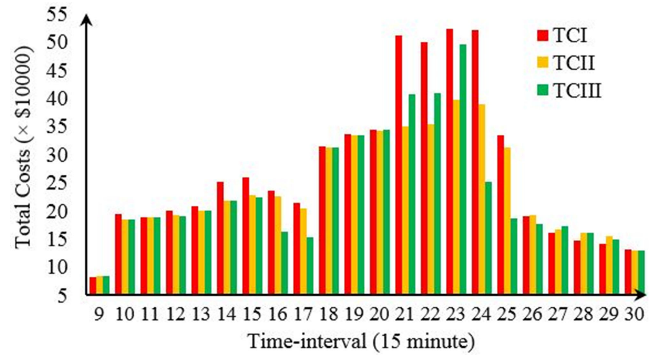

Fig. 6. System total operation costs in TCI, TCII, and TCIII.

requirements. On the other hand, as can be observed by comparing TCII and TCIII in Fig. 5, the number of real-time energy price spikes in TCIII is fewer than that in the other cases—see time intervals 14, 15, and 27–30. In fact, TCIII benefits from the additional ramp capacity of the DAM spinning reserve, and the proposed SEFRP is observed to be able to reduce the number of price spikes remarkably, reflecting a significant improvement over the traditional FRP mechanisms. It should be mentioned that in a few time intervals, e.g., 6–11 and 63–80 (see Fig. 5), both the traditional FRP (TCII) and SEFRP (TCIII) provision mechanisms have resulted unfavorable price spikes, while no price spikes were observed in TCI with no FRP procurement. The main reason lies in the fact that even though the system was able to follow the realized net-load without FRP procurement (TCI), it was facing a ramp-up capacity shortage to be prepared to meet the net-load forecast errors. Nonetheless, additional ramp capacity provided in TCIII has resulted in relatively much lower price caps in the system as opposed to TCI and TCII.

The total system operation cost—which reflects the objective function (1)—is evaluated in each test case as depicted in Fig. 6. One can observe, in Fig. 6, that both the traditional FRP and the proposed SEFRP models could magnificently reduce the system operation costs. However, except in three time-intervals, the proposed SEFRP model (TCIII) outperforms the traditional FRP mechanism (TCII). The system total operation costs in all 96 time-intervals of the day is $13 049 255 in TCI, $12 419 808 in TCII, and $12 250 185 in TCIII. The system enjoys a 4.8% and 6.4% total cost saving in TCII and TCIII, respectively. Indeed, from an economic perspective, the SEFRP has brought about a great cost saving opportunity system wide.

Unlike the system operation costs which is mainly affected by the load outage cost, the sold results or the "*total payment*" may better reflect the economic influence of the SEFRP. The payments to the generating units including the energy, spinning reserve, and the FRP/SEFRP procurement in the RTM and DAM are presented in Table I. The proposed SEFRP model applied in TCIII has resulted in about more than 50% saving in the RTM energy payments, mainly by preventing the RTM energy price spikes. Besides, the generating units compensation for SEFRP provision is found lower than that in the traditional FRP model. It is mainly due to the fact that by freeing-up the

TABLE I
TOTAL RTM AND DAM PAYMENTS ($)

	DAM	RTM		
		TCI	TCII	TCIII
Energy	5,276,500	156,900	179,700	73,500
Reserve	394,700	37,800	52,900	75,700
FRP/SEFRP	–	–	80,300	70,300
Total	5,671,000	194,700	312,900	219,500

day-ahead procured spinning reserve, relatively higher ramp capacity is available for SEFRP provision, leading to lower FRU marginal prices. However, the real-time spinning reserve payment has increased since providing a portion of the SEFRP from the DAM reserve capacity requires more spinning reserve procurement in the RTM. Finally, the total energy, spinning reserve and FRP/SEFRP sold to the generating units in TCI, TCII, and TCIII, respectively, are given in the last row in Table I. The total RTM payments in TCIII (SEFRP provision) compared to TCII (FRP provision) is very low, which is resulted by the relatively lower prices of energy and SEFRP. It should be mentioned that the total payment to the generating units in the RTM and in TCI (without FRP) is the lowest. By comparing the total payments in DAM, which is $5 671 000, one may conclude that since the RTM payments are relatively trivial, a slight payment increment definitely costs a significant reduction in load curtailments. Altogether, the total payment (including RTM and DAM payments) in TCIII is 1.5% less than that in TCII, which justifies the SEFRP's advantage over the traditional FRP, and 0.4% higher than that in TCI.

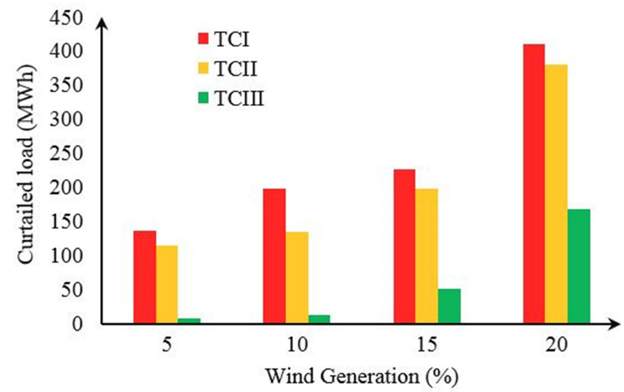

Fig. 7. Sensitivity analysis on the load curtailment under different wind penetration levels in TCI, TCII, and TCIII.

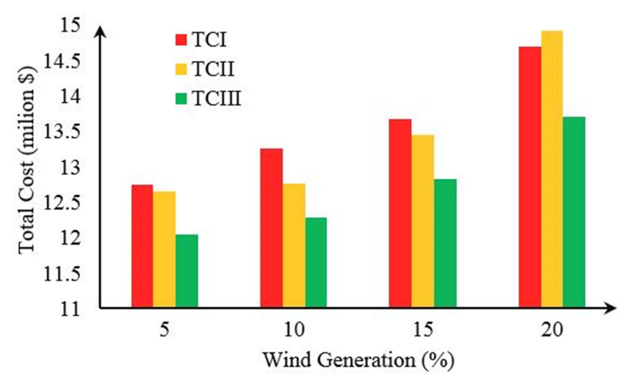

Fig. 8. Sensitivity analysis on the system total operation costs under different wind penetration levels in TCI, TCII, and TCIII.

C. Sensitivity Analysis

The current wind capacity installed in the United States is around 8% of the total demand and the goal is to achieve 20% by 2030 [46]. Accordingly, the power grid flexibility should be heightened in order to make this transition smoother. In order to assess the SEFRP performance in modern power grids with massive penetration of intermittent supply, i.e., with higher net-load forecast errors, a sensitivity analysis is conducted on the SEFRP performance against the net-load forecast error increments as the wind penetration level increases. It is assumed that the load and wind are growing with the same rate and, hence, the net-load has remained constant while its forecast errors are subject to intense fluctuations. The total wind penetration level is enhanced from 5% to 20%. The three case studies—without FRP, with conventional FRP, and SEFRP—are simulated under four different wind penetration levels, which are 5%, 10%, 15%, and 20% of the total load. For each Case, 100 scenarios are generated each of which is comprised of 96 number of 15-min net-load values (for entire day).

The simulation results on the load curtailments and the system total operation costs are presented in Figs. 7 and 8, respectively. The load curtailments demonstrated in Fig. 7 represent the average load curtailments over 100 scenarios for the entire day (96 real-time market time-intervals) at each wind penetration level. Likewise, the total costs illustrated in Fig. 8 represent the average system total operational cost over 100 scenarios at each specific wind penetration level. It should be noted that the system total cost is comprised of the energy generation and spinning reserve procurement costs of generating units as well as that associated with load curtailments. As can be observed in Fig. 7, the conventional FRP (TCII) is not able to mitigate the load curtailments significantly, which is mainly due to the low ramping capacity available in the RTM. On the other hand, the proposed SEFRP model could significantly mitigate the load curtailments by effectively utilizing a portion of the ramp capacity in the day-ahead procured spinning reserve. As the wind uncertainty increases, the efficiency of the conventional FRP drastically decreases (due to lack of ramping capacity). Conversely, the efficiency of the proposed SEFRP model increases in higher wind penetrations as it harnesses additional ramping capacity. Note that, in scenarios with higher penetration of wind, other flexibility products should be also employed to more effectively tackle the growing uncertainties. According to Fig. 8, the proposed SEFRP model has played a superior role in reducing the system total operation cost: the higher the uncertainty level, the more promising the SEFRP performance becomes. This observation is further highlighted considering the fact that the effectiveness of the conventional FRP model on the system total operation costs has decreased as the uncertainty level increased. The system total operation costs when the wind penetration level is 20% is observed higher in TCII compared to TCI, reflecting that the traditional FRP model may even impose additional costs to the system operation, while also not effectively mitigating the load curtailment scenarios.

VI. Conclusion

Massive penetration of intermittent RESs in modern power systems, if not responded properly, may jeopardize the grid operational flexibility. FRP, as a new market product, has been recently launched in order to handle this challenge and enhance the RTM flexibility by providing additional ramping capacity from the participating generating units in the market. However, the available ramp capacity in the RTM for FRP procurement, particularly at instances when the net-load changes radically, can impact the FRP performance. This paper proposes a modified FRP model, named SEFRP, that further enhances the RTM flexibility by procuring additional ramp-up capacity from the DAM spinning reserve services. According to this hypothesis, in case where the system existing ramp-up capacity is not sufficient to cover the net-load forecast errors, the system utilizes a portion of the DAM spinning reserve for SEFRP provision, while ensuring that sufficient spinning reserve is procured in the RTM. Additionally, a new payment rationale is proposed suggesting the generating unit participants to be compensated only when the provided SEFRP from their DAM spinning reserve capacity is deployed for energy production and not for the ramp capacity provided from their DAM-awarded spinning reserve.

The proposed SEFRP model is implemented on the IEEE 118-bus test system and the simulation results could verify its efficacy and advantages over the traditional FRP models as well as system operation without FRP. The proposed SEFRP could, first, significantly reduce the load curtailments occurred due to the load and wind forecast errors, and second, effectively reduce the LMP price spikes and the system total operating costs. Although the SEFRP procurement has resulted in a 0.4% increment in the total payments to the system generating units compared to the case without FRP procurement, this payment has decreased by 1.5% compared to the traditional FRP mechanism, which further infers its advantages over the state-of-the-art FRP models.

A sensitivity analysis on the grid-scale penetration of intermittent supply is eventually conducted, demonstrating a promising performance of the proposed SEFRP model—significant reductions in both load curtailments and the system total operation cost—under massive presence of uncertainties. Future work could potentially investigate the cooperation of multiple ramp products (e.g., regulation services) in the RTM operations so as to achieve both ramp-up and ramp-down flexibility facilitating both FRU and FRD procurement.

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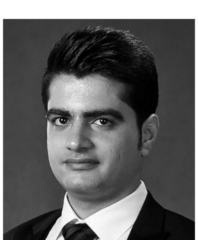

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