Reliability Assessment of Regulating Reserve Product Bifurcation in PJM

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***Abstract*—This paper examines the reliability impacts of bifurcating a single bidirectional regulating reserve product into distinct regulation up and down signals in the PJM market. PJM is currently implementing a two-phase redesign of its regulation market. Phase 1, completed in October 2025, consolidated RegA and RegD bidirectional signals into a single bidirectional signal. Phase 2, planned for implementation in October 2026, will introduce separate regulation up and down products. Because regulation is a crucial ancillary service for maintaining system reliability, we analyze the reliability implications of this bifurcation utilizing appropriate PJM system and historical data. The study employs simulation of day-ahead and real-time markets, together with deployment of regulating reserve through Automatic Generation Control (AGC) to assess the performance of regulating reserve products in mitigating Area Control Error (ACE). Simulation results indicate that the bifurcated design performs well on several reliability metrics compared to the single regulation product. We further examine the differences of generator types that provide regulation service in each case and derive insights into the performance improvement.**

***Index Terms*— Ancillary Service, Area Control Error, Electricity Markets, Regulating Reserve, Power System Reliability.**

I. Introduction

Regulating reserve, also known as regulation or load frequency control, is an essential grid service provided by generators and other controllable resources to balance the generation and load of a Balancing Area (BA). These balancing services help to maintain the Area Control Error (ACE) within the bounds required by NERC reliability standards [1]. ACE is largely composed of a BA's interchange and frequency error, where the interchange error is a direct measure of supply and demand deviation from a scheduled interchange target. Regulation operates at a fast timescale from a few seconds to few minutes to mitigate short-term energy imbalances and maintain interconnection frequency. This ancillary service is deployed through Automatic Generation Control (AGC) depending on ACE and system frequency. PJM procures regulating reserves using a real-time ancillary service market mechanism that co-optimizes regulation with energy and synchronized reserve on an hourly basis with intra-hour adjustments made as required.

Four of the US Independent System Operators (ISOs) and Regional Transmission Organizations (RTOs), and the two Canadian ISOs procure a combined upward and downward regulating reserve service. Three US ISOs/RTOs procure regulating reserve up and regulating reserve down as two

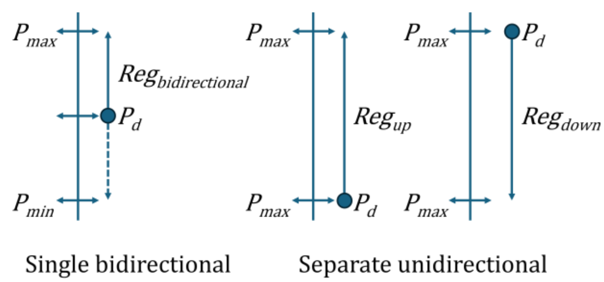

Figure 1. Comparison of regulating reserve products.

distinct products [2]. PJM, the largest RTO in the United States, is one of the four US ISOs/RTOs that currently procures a single bidirectional regulating reserve product, which implies resources providing the service shall have equal head room and leg room to move upward or downward depending on the requirement to correct ACE. In comparison, resources providing separate regulation up and down service must have either headroom or legroom to provide regulation up or down service, respectively. Figure 1 shows a comparison of the regulating reserve products where P_d, P_{max} and P_{min} represent the dispatch point, maximum and minimum capacity of a unit.

Following eighteen months of effort by PJM's Regulation Market Design Senior Task Force, FERC approved the new regulation market changes and the two-phase design proposals in 2024 [3]. The changes included consolidation of RegA and RegD into a single bidirectional signal this year. In October 2026, the signal will be split into distinct regulation up and down signals. This change has potential reliability implications, as the separate products can better capture the asymmetric flexibility of resources in providing up or down regulation. PJM is the first US ISO/RTO making this transition to the best of the authors' knowledge and it is essential to investigate reliability impacts corresponding to the change. Therefore, we study the

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reliability performance of the proposed market design under a simulation setup and evaluate different reliability metrics. We do not focus on reliability performance of the AGC controller.

The rest of the paper is organized as follows. Section II describes the market design changes related to the PJM regulation market. Section III details the simulation framework and methodology used to study the reliability impact of separate unidirectional regulation products compared to a single bidirectional regulation signal. In Section IV, we discuss the simulation results and Section V states some conclusions.

II. BACKGROUND AND MARKET DESIGN CHANGES

Before October 2025, PJM utilized two regulation signals (RegA and RegD) to correct the ACE imbalance within PJM's balancing area. The AGC utilized a modified proportional-integral (PI) controller design to create an ACE-correcting signal. RegA was a low-pass filter of the signal suitable for traditional slower resources, while RegD was a high-pass filtered signal designed for fast and flexible resources. The market clearing engine cleared regulation against a single requirement which meant an accurate marginal benefits factor or marginal rate of technical substitution was necessary to optimize two signals. There were existing regulatory issues with how the benefits factor was applied to the optimization and how it was utilized in pricing and settlements.

In April 2024, PJM filed regulation market reforms with FERC and proposed a phased implementation approach. Phase I, completed on Oct 1st, 2025, consolidated RegA and RegD into a single bidirectional signal, updated performance scoring to focus on precision, and revised the requirements calculation to better capture future system needs. Phase II, scheduled for October 2026, will separate the single bidirectional regulation signal into distinct up- and down-regulation signals. The design will allow PJM to differentiate system needs in terms of different up and down requirements, promote new market entry, enhance supply flexibility and potentially improve overall reliability performance of the regulation product.

In the next section, we describe the simulation framework and methodology used in our study to evaluate reliability implication of moving from a single bidirectional regulation product to separate regulation up and down products.

III. SIMULATION FRAMEWORK AND METHODOLOGY

The Flexible Energy Scheduling Tool for Integrating Variable Generation (FESTIV), developed by researchers at the National Renewable Energy Laboratory (NREL) and Electric Power Research Institute (EPRI) is a steady-state- power-systems simulation software [4]. We utilize FESTIV to perform the reliability analysis of the regulation product. FESTIV consists of several sub-models including the Day-Ahead Security-Constrained Unit Commitment (DASCUC), Real-Time SCUC (RTSCUC) and Real-Time Security-Constrained Economic Dispatch (RTSCED) that can be configured to approximate market operations in PJM. Additionally, the AGC sub-model uses a rule-based algorithm and can simulate regulating reserve deployment. More details on FESTIV sub-models can be found in [5].

In our study, the input to the FESTIV software is configured to emulate the PJM market by incorporating appropriate generator parameters, transmission constraints, and demand profiles. We developed a zonal PJM system model to reflect its 22 load zones. All applicable generator parameters are modeled such as capacity, no-load and startup cost, ramp rates, minimum run and minimum down times, and startup time among others. The incremental energy values of the generators are derived from their corresponding heat rate as opposed to bid-in values. We model inter-zonal transmission lines 230kV and above to capture key network constraints. Energy, regulation, synchronized, primary and 30-minute reserves are co-optimized where the reserve requirements and demand curve values reflect current PJM market values. We conducted simulations for one representative week per season in 2024 to reflect different load and renewable generation profiles during Spring, Summer, Fall and Winter periods. The demand and renewable forecasts are derived by averaging 15-sec Energy

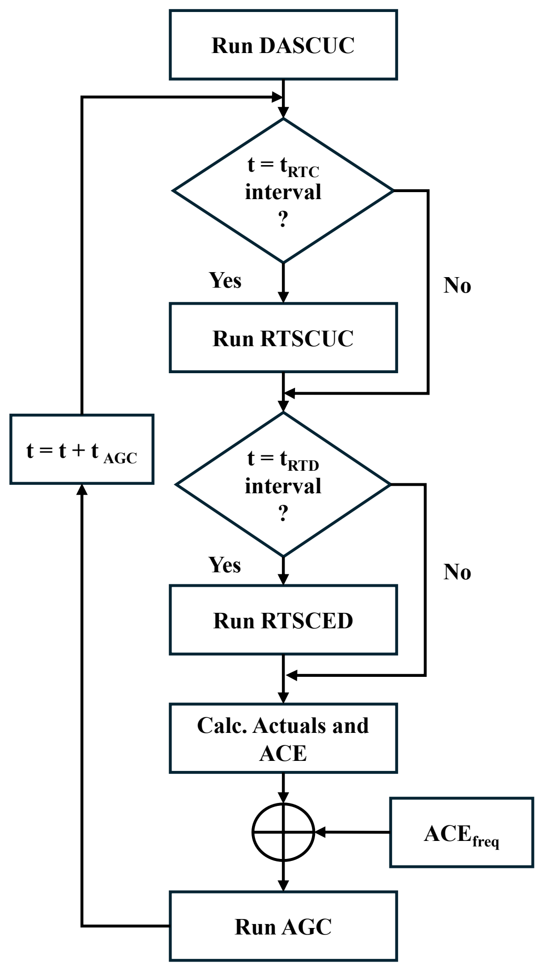

Figure 2. FESTIV Simulation Process Flow.

Management System (EMS) load into hourly resolution for DASCUC, 15-minute resolution for RTSCUC and 5-min resolution for RTSCED. We perform our simulations under a perfect forecast scenario to focus on the impacts of different regulation products on system reliability.

TABLE I. AREA CONTROL ERROR AND CPS2 STATISTICS

	Spring		Summer		Fall		Winter	
Metrics	1 Reg	2 Reg	1 Reg	2 Reg	1 Reg	2 Reg	1 Reg	2 Reg
Mean-Absolute ACE	175.09	139.87	239.65	217.22	172.94	136.67	166.17	133.63
ACE-Standard Deviation	235.71	181.13	308.38	268.68	240.04	184.30	218.62	175.18
CPS2 Violations	16	0	203	202	11	0	11	4
CPS2	98.41%	100%	79.86%	79.96%	98.91%	100%	98.91%	99.60%

The zonal model is benchmarked using the load-weighted Locational Marginal Price (LMP) across all zones derived from FESTIV against the actual PJM RTO load-weighted LMP. The generation by fuel type was also compared to ensure reasonable alignment with PJM market outcomes for the simulated periods. Figure 2 shows the process flow diagram of the simulation setup used in our study. DASCUC is run for the whole day, and RTSCUC and RTSCED are run at t_{RTC} and t_{RTD} intervals, which in our simulations are 15 and 5 minutes respectively. The realized output of all resources and ACE is calculated before AGC in run at t_{AGC} intervals which is 15 seconds. The reliability metrics we evaluate in this study are related to mitigating ACE. ACE is defined in equation (1) below [6].

$$ACE = (NI_A - NI_S) - 10B(F_A - F_S) - I_{ME} \tag{1}$$

$$(NI_A - NI_S) = \sum_{i=1}^{NG} p_{g,i} - \left(\sum_{j=1}^{ND} p_{d,i} + Losses\right) \tag{2}$$

Ignoring interchange meter error I_{ME}, ACE consists of the difference between actual and scheduled interchange (NI_A–NI_S) which is the total imbalance between generation and load plus losses within the BA. The second term represents the frequency component of ACE (F_A, F_S are actual and scheduled frequency) to ensure each BA helps restore interconnection frequency where B represents the frequency bias setting and determines an individual area's contribution to frequency correction.

FESTIV calculates ACE as interchange error without accounting for the frequency component. Therefore, we extract the actual ACE frequency component for the simulated days and add them at t_{AGC} intervals after ACE is calculated by FESTIV as shown in Figure 2. It is worth noting that in addition to several other AGC modes, FESTIV also simulates a smooth mode of AGC where units with a regulation award from RTSCED follow a proportional integral signal called Smoothed ACE (SACE). Our simulation deploys the regulating reserve against the SACE signal. SACE is calculated in FESTIV as follows [5].

$$SACE(t) = K1 * ACE(t) + \frac{K2}{Tn}\int_{t-Tn}^{t} ACE(\tau)d\tau \tag{3}$$

where,

$$K1 = \frac{CPS2interval - mod(t_{AGC}, CPS2interval)}{CPS2interval} \tag{4}$$

$$K2 = 1 - K1 \tag{5}$$

$$Tn = mod(t, CPS2interval) \tag{6}$$

Equation (3) shows that SACE is a combination of a proportional term and an integral term where K1 and K2 determine the weight of the ACE value at the current interval and the average value of ACE over previous intervals bounded by the integral length. K1 and K2 are set to 1 to apply equal weights to current and previous averaged ACE values. We set the integral length Tn to 180 seconds or 12 AGC timesteps. The Control Performance Standard 2 (CPS2) interval is set to 10 minutes in line with NERC standards. The units providing regulation through AGC follow the SACE and provide regulation MW proportional to their regulation schedule. We simulate two market design choices for one representative week per season in 2024. The cases are as follows:

- Combined Regulation (1 Reg): A single bidirectional regulation product is co-optimized with energy and other reserve products. The regulation requirements are set to the current requirements used in the PJM market.
- Separate Regulation (2 Reg): This case simulates separate regulation up and down products. The hourly regulation requirements are kept the same as current requirements in the PJM market except they are assigned to regulation up and down products separately.

While synchronized, primary and 30-minute reserves are nested, regulation in both cases are treated as separate products like in the PJM market. It is worth mentioning that PJM uses a separate co-optimization platform called Ancillary Service Optimizer (ASO) that commits resources to provide regulation service whereas FESTIV co-optimizes regulation with energy and other reserves in DACUC, RTSCUC and RTSCED sub-models. However, under a perfect forecast scenario, the commitment of units for providing regulation in DASCUC and RTSCUC are not different. Hence, FESTIV's framework can replicate PJM's market construct. We introduce the reliability metrics that are compared in our study as well as the simulation results in the next section.

IV. RESULTS AND DISCUSSION

We illustrate the reliability performance of both regulation market design choices in this section and shed some lights on the resource mix that provides regulation service in both cases. Table I shows the comparison of ACE related metrics and CPS2 violations in both cases for the representative weeks in the four seasons considered in the simulations.

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TABLE II. AGC CONTROLLER SATURATION-UP AND -DOWN EVENT RESULTS

	Spring		Summer		Fall		Winter	
Metrics	1 Reg	2 Reg	1 Reg	2 Reg	1 Reg	2 Reg	1 Reg	2 Reg
Total Saturation-Up Events	218	11	104	6	157	15	220	24
Total Saturation-Down Events	183	177	406	423	138	127	178	143
Average Saturation-Up Event Duration	4.92	1.45	6.66	2.17	5.57	1.53	4.39	1.46
Average Saturation-Down Event Duration	3.10	2.65	17.06	16.92	2.97	2.29	3.60	3.24

The mean-absolute ACE represents the typical magnitude deviation of ACE for the study period in either direction independent of whether the BA is over generating or under generating. Across all seasons, 2 Reg consistently achieves lower mean-absolute ACE compared to 1 Reg highlighting its ability to more effectively track the ACE signal. The standard deviation of ACE indicates the distribution or the spread of ACE deviations. Similar to mean-absolute ACE, 2 Reg consistently reduces the variability of ACE across all seasons. The seasonal pattern shows summer has the highest ACE variability. The reduction is ACE variability further confirms the efficacy of the two-product regulation design.

The remaining two metrics in Table I are related to the CPS2 metric. CPS2 violations represent the number of 10-minute intervals absolute average ACE exceeds a threshold called L10 defined for each BA. The CPS2 score represents the percentage of intervals without violations reflecting how often the system avoids significant imbalances. The number of CPS2 violations is lower under the 2 Reg market design across all seasons. For instance, CPS2 violations are reduced to zero in spring and fall (achieving 100% CPS2 compliance) under the 2 Reg design, while 1 Reg shows 16 and 11 violations, respectively. Summer shows high-stress system conditions where 2 Reg does not perform as well as other seasons in reducing system violations. Overall, the CPS2 metrics demonstrate 2 Reg market design enhances compliance and reduces risk of CPS2 penalties, especially outside of the high-load summer period.

Table II shows the AGC controller saturation event count and duration results. Saturation-up and -down events are defined as AGC intervals where the SACE exceeds the regulating reserve requirements in positive or negative directions causing controller saturation. Saturation-up events represent intervals where the regulation-down requirement is insufficient to mitigate SACE, while saturation-down events represent intervals where the regulation-up requirement is exceeded by SACE. It can be seen from Table II that for the 2 Reg case the number of saturation-up events is reduced significantly compared to the saturation-down events. The reason is evident in the resource mix providing regulation-down service in the 2 Reg case that we will discuss later. The number of saturation-down events also reduces in the 2 Reg case compared to the 1 Reg case due to the added flexibility of resources providing separate regulation services.

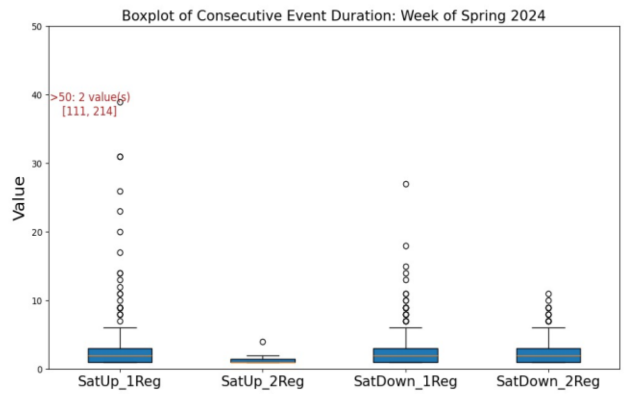

Figure 3. Controller saturation event duration distribution for Spring.

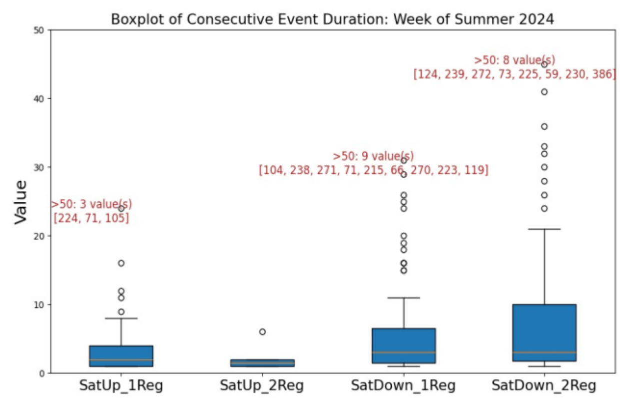

Figure 4. Controller saturation event duration distribution for Summer.

The average duration of the saturation-up and -down events are also important metrics to consider, especially for duration-limited resources. The durations listed in Table II are in AGC timesteps. It can be observed from Table II that the 2 Reg design is effective in reducing both the average saturation-up and -down event durations. The saturation-down event duration is more prominent in summer due to the lack of regulation-up capability in the presence of high load and the least-cost solution implies higher ACE variability for certain intervals. Even then the average saturation-down event duration reduces under the 2 Reg design.

Figures 3 and 4 show the saturation-up and -down event duration distributions for both market design choices. In both

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TABLE III. REGULATION CONTRIBUTION BY GENERATOR TYPE

Season	Product	Steam (%)	Combined Cycle (%)	Hydro (%)	Pumped Storage (%)	Storage (%)
Spring	1 Reg	18.19	72.14	0.00	4.64	5.03
Spring	2 Reg Up	20.60	68.79	0.00	2.31	8.31
	2 Reg Down	51.36	34.75	7.26	3.62	3.02
Summer	1 Reg	25.35	67.35	0.00	2.96	4.33
Summer	2 Reg Up	26.44	63.87	0.00	1.93	7.75
	2 Reg Down	55.98	33.69	5.97	1.66	2.70
Fall	1 Reg	15.14	74.43	0.00	5.74	4.68
Fall	2 Reg Up	17.15	71.41	0.00	2.50	8.93
	2 Reg Down	47.85	34.70	8.18	5.60	3.67
Winter	1 Reg	23.42	64.66	0.00	4.16	7.76
Winter	2 Reg Up	28.27	60.88	0.00	3.08	7.77
	2 Reg Down	54.27	34.12	6.02	2.70	2.88

the figures, event durations that are more than 50 AGC timesteps are annotated for legibility. In Figure 3, most saturation-up and -down events during the Spring period cluster below 10 AGC timesteps with 2 Reg case displaying lower variability in event duration distribution. The outliers above 50 AGC timesteps can only be seen in the saturation-up direction in 1 Reg case. The event duration distributions show similar trends during the Fall and Winter seasons; therefore, we don't include them to avoid repetition. The Summer period shown in Figure 4 shows a similar trend in the saturation-up case where the 2 Reg case reduces the event duration variability. However, the saturation-down case is an outlier where the variability increases in the 2 Reg case. This is because Summer is a high-load period in the PJM system and the ACE variability increases after adding the frequency component of ACE, which in turn increases event variability in both cases. Otherwise, 2 Reg performs better in reducing both saturation-up and -down event frequency and duration.

Table III shows the resource mix providing regulation services in both the 1 Reg and 2 Reg cases by generator type. The resource mix in the 1 Reg and 2 Reg Up cases are similar. The 2 Reg Down service, however, is assigned more to the cheaper units with lower incremental energy cost such as steam and hydro. In the case of hydro units, the ramp rates are high, making them suitable for providing effective regulation down service. As a result, we see the saturation-up event frequency reduces in the 2 Reg case since fast ramping units provide more effective regulation-down service. On the other hand, the saturation-down event frequency reduces in the 2 Reg case due to the unit flexibility providing the service.

Overall, the separation of regulation up and down into distinct products provides opportunities for flexible resource selection in providing the services. Whereas a combined bidirectional regulation signal requires the same units to provide both regulation up and down service, separate regulation up and down services can be provided by different resources. Therefore, it is possible to optimally track ACE and improve reliability performance of the regulation product using the 2 Reg case compared to the 1 Reg case as evident from the simulation results.

V. CONCLUSION

In this paper, we evaluate the reliability implications of bifurcating the regulating reserve product in the PJM market. The simulations performed using the FESTIV tool demonstrate that separating the regulation product enhances ACE tracking, reduces CPS2 violations, and decreases the frequency and durations of controller saturation events across all the simulated periods. The variability of saturation events also reduces under the separate regulation product market design in general.

The analysis also reveals that the resource participation pattern in providing regulation shifts under the bifurcated design, especially for the regulation down service. The participation of cheaper and faster ramping units, like hydro, can enhance the effectiveness of regulation down service and improve reliability performance. Overall, the transition from a single bidirectional regulation product to separate unidirectional regulation products may offer tangible reliability benefits such as reducing ACE imbalance errors, variability, and improving CPS2 performance scores. Our simulation is based on cost-based generator offers and actual bids may impact the outcome. Future work may extend this analysis to evaluate economic metrics and resource mix.

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