



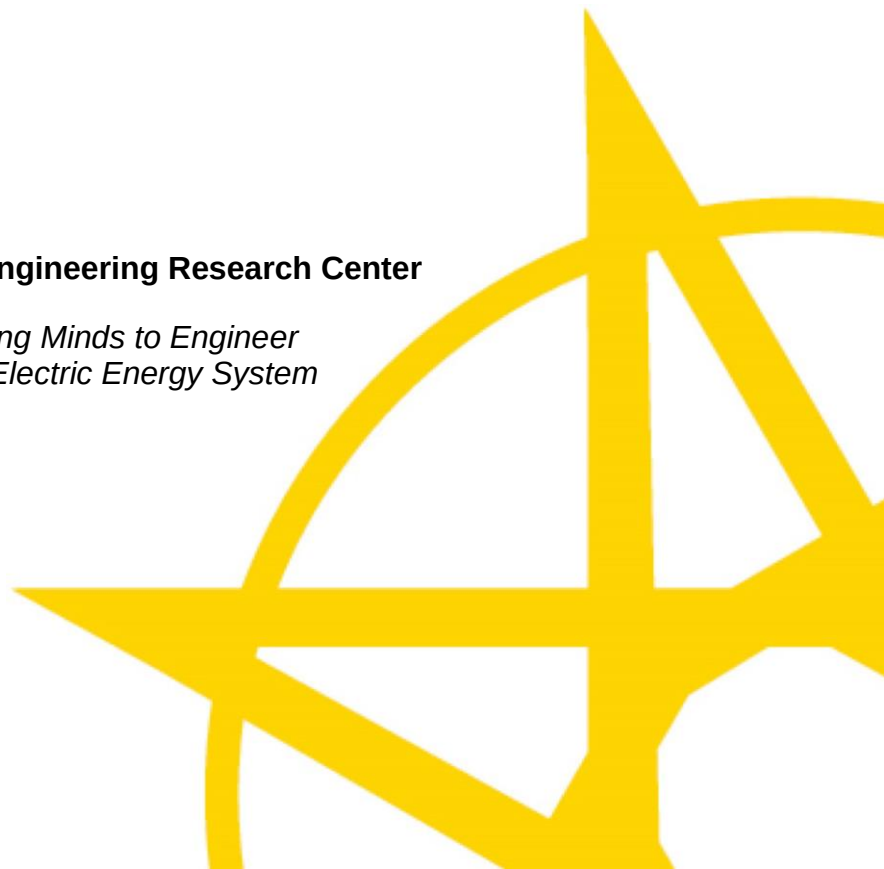
Newly Implemented and Proposed Market Products and Reformulations: Pricing Implications, Analysis, and Enhancements

Final Project Report

M-39

Power Systems Engineering Research Center

*Empowering Minds to Engineer
the Future Electric Energy System*



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Final Project Report

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Power Systems Engineering Research Center

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Executive Summary

Energy markets are ever evolving due to operational complexities as well as complications due to a changing resource mix (e.g., renewables). Independent system operators are introducing new market products and reformulations to accommodate the inherent complexity of the electricity production, transmission, and consumption. This research focuses on three core areas: (1) flexible ramping products and multi-period pricing policies, (2) enhanced generator contingency modeling, and (3) management of stochastic resources. This research evaluates these essential structural changes to energy markets and provide a comprehensive evaluation of the impacts on settlements. This research also provides suggestions on market reformulations to enhance market efficiency, pricing, and transparency. The report is presented in two parts.

Part I: Analyzing the Market Impacts of Ramping and Multi-Period Pricing Approaches, Contingency Modeling Enhancements, and Management of Stochastic Resources

Part I of this report focuses on: (1) day-ahead resource scheduling with enhanced flexible ramp product (FRP) design, (2) pricing implications and objective function evaluation for markets with stochastic formulations, (3) the conditions for inter-temporal ramp rate constraints causing uplift payments, and (4) the market implications of the explicit representation of generator contingencies. The research shows that:

- Accounting for 15-min net load changes in day-ahead flexible ramping product procurement enhances the quantity allocation of ramping capabilities by making relatively small changes in market models compared to the existing FRP design. This approach leads to less expected final operating cost in the fifteen-minute market, higher reliability as the power system gets close to real-time operation, and less discrepancy between day-ahead and real-time unit commitment decisions.
- With more accurate representation of contingencies in the extensive-form two-stage security-constrained unit commitment, $N-1$ security constraints are better satisfied with less need for out-of-market corrections while the value of services (contingency-based reserve) provided by generators is reflected in the locational marginal prices.
- The stochastic market design with expected objective function does not give solutions that ensure minimum realized operating costs at $N-1$ contingency states. Instead, the stochastic market design with base-case objective function had better performance compared to the market model with expected objective function in terms of the base-case costs (i.e., normal operating costs) and realized $N-1$ costs.
- Possible inaccuracies in scenario probability estimations significantly affect results of stochastic market models with expected cost minimization as the objective function. Thus, it defeats the purpose of such expected cost minimization models.
- Constant ramp rate constraints do not cause uplift payments if dispatch decisions and prices in all scheduled time intervals are financially binding. In contrast, dispatch-dependent ramp rates introduce nonconvexity into the market, which may cause uplift payments. Uplifts may occur when using a multi-period model for scheduling while using a single-period pricing run.

- The explicit representation of generator contingencies adds a new congestion component within the traditional locational marginal price, which reflects the influence of congestion during the post-contingency states for the modeled critical generator contingencies.

Part II: Pricing Multi-interval Dispatch Under Uncertainty

Part II of this report focuses on pricing multi-interval dispatch under operational uncertainty. In particular, we consider rolling-window look-ahead dispatch in the real-time market where inaccurate forecasts of future demand are used. This project aims to gain insights into the issue of lack of dispatch-following incentives that result in discriminative out-of-the-market settlements. It is known that all existing uniform pricing schemes, including the standard locational marginal pricing (LMP), require out-of-the-market uplifts when forecasts of demand and renewable generation are not accurate.

Main results of this paper include the following:

- We show that no uniform pricing exists that guarantees dispatch-following incentives. Therefore, discriminative out-of-the-market settlements are necessary for uniform pricing schemes. In other words, price discrimination is unavoidable for multi-interval look-ahead dispatch.
- We propose a non-uniform pricing scheme, referred to as temporal locational marginal pricing (TLMP), that eliminates out-of-the-market settlements under arbitrary forecasting uncertainties. In other words, TLMP provides full dispatch-following incentives by prepaying the opportunity costs of ramp-limited generators and, at the same time, penalizes generators with limited ramping capabilities. To this end, TLMP discriminates in-side-the market to guarantee dispatch following incentives, whereas all uniform pricing schemes discriminate through out-of-the-market settlements.
- We establish several attractive features of TLMP. In particular, TLMP has a natural decomposition as the sum of LMP and the ramping prices. In other words, TLMP is the sum of energy price, congestion price, and ramping prices.
- We conducted detailed empirical studies (with and without network constraints) to evaluate TLMP and existing pricing benchmarks for multi-interval look-ahead dispatches. Among the performance measures evaluated are the dispatch following and ramping revelation incentives, the revenue adequacy of the operator, generator profits, and demand payments.
- Empirical studies show no single pricing scheme dominates all others. In general, TLMP performed well in both dispatch-following and ramping revelation incentives, operator revenue adequacy, and consumer payments while resulted in lower generator payments. TLMP, however, tends to have lower generator profits for generators with limited ramping constraints.

Project Publications:

- [1] M. Ghaljehei and M. Khorsand, “Representation of Uncertainty in Electric Energy Market Models: Pricing Implication and Formulation,” *IEEE System Journal*, under review, available on-line at <https://arxiv.org/abs/2004.14369>.

- [2] M. Ghaljehei and M. Khorsand, “Day-ahead Resource Scheduling with Enhanced Flexible Ramp Product: Design and Analysis,” *to be submitted to IEEE Transactions on Power Systems*.
- [3] Y. Guo, C. Chen, and L. Tong, “Pricing Multi-Interval Dispatch under Uncertainty---Part I: Dispatch-Following Incentives,” *to be submitted to IEEE Transactions on Power Systems*, available on-line at <https://arxiv.org/abs/1911.05784>.
- [4] C. Chen, Y. Guo, and L. Tong, “Pricing Multi-Interval Dispatch under Uncertainty---Part II: Extensions and Performance Evaluation,” *to be submitted to IEEE Transactions on Power Systems*.
- [5] L. Tong, “Pricing multi-period dispatch under uncertainty,” *Presented at 2019 IEEE PESGM*, August, 2019.
- [6] M. Saleh, K. Saikumar and K. W. Hedman, “Pricing Implications of Transmission Security Modeling In Electric Energy Markets,” *2019 North American Power Symposium (NAPS)*, Wichita, KS, 2019.
- [7] S. Zhang and K. Hedman, “Conditions for Ramp Rates Causing Uplift,” *North American Power Symposium (NAPS)*, Wichita, KS, 2019.
- [8] N. Singhal, J. Kwon, and K. W. Hedman, “Generator Contingency Modeling in Electric Energy Markets: Derivation of Prices via Duality Theory,” *Energy Policy*, under review.