



Leveraging Conservation Voltage Reduction for Energy Efficiency, Demand Side Control and Voltage Stability Enhancement in Integrated Transmission and Distribution Systems

Final Project Report

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Power Systems Engineering Research Center
*Empowering Minds to Engineer
the Future Electric Energy System*



Leveraging Conservation Voltage Reduction for Energy Efficiency, Demand Side Control and Voltage Stability Enhancement in Integrated Transmission and Distribution Systems

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Executive Summary

The project team has developed a comprehensive framework for the implementation and assessment of conservation voltage reduction (CVR). For CVR assessment, we have (i) designed a robust load modeling algorithm to evaluate real-time real/reactive load-reduction effects of CVR; (ii) developed a co-simulation framework for integrated transmission and distribution systems to investigate the impacts of CVR on voltage stability margins of transmission systems; and (iii) studied the mutual impacts between voltage reduction and distributed generator (DG) control. For CVR implementation, we have (i) designed a decentralized optimization algorithm to coordinate smart inverters and conventional voltage/var control (VVC) devices to facilitate voltage reduction; and (ii) studied the impact of loss of communication on decentralized VVC. The combination of these approaches can assist utilities to select feeders to implement voltage reduction, perform cost/benefit analysis, and improve the operation of integrated transmission and distribution systems.

The main observations and conclusions are listed as follows:

- The load-reduction effects of CVR are time-variant due to the continuous change of load compositions. Thus, online methods are needed to assess real-time CVR effects.
- The proposed hybrid VVC design noticeably improves the voltage regulation performance even after the communication links fail.
- The voltage reduction in a distribution grid will affect the upstream transmission grid, thus, requiring an integrated transmission and distribution simulation platform to study its effects. Our results have shown that CVR has negative effects on the long-term voltage stability margin (VSM) of transmission systems.
- The influence of DG penetration is not significant on the impact of CVR on VSM.
- There exists a trade-off between voltage-led demand reduction and power loss reduction, which depends on the load-to-voltage sensitivities. For a distribution system with a dominant fraction of voltage-dependent loads, maximizing voltage reduction will reduce more load demands than maximizing loss reduction.

Part I: Implementation and Assessment of CVR

Robust Time-Varying Load Modeling for Conservation Voltage Reduction Assessment

With the increasing integration of renewable energy, load characteristics become highly stochastic, thus posing a great challenge for CVR assessment in power distribution systems. This part will propose a robust time-varying load modeling technique based on robust recursive least squares (RLS) for CVR assessment, where the aggregate load at a substation is represented by a ZIP model with time-varying parameters. To effectively capture the variations of these parameters under different conditions, such as steady and sudden step changes of parameters, a strategically designed variable forgetting factor for RLS is proposed. To enhance the robustness of the RLS for bounding the influences of bad or missing measurements, a Huber M-estimator with a convex cost function is advocated and effectively solved by an iteratively reweighted technique. To this end, CVR factors can be assessed appropriately using the identified time-varying load models. The

effectiveness and robustness of the proposed method are compared with existing methods using both simulation and field tests.

Distributed CVR in Unbalanced Systems with PV Penetration

We will firstly study how DGs under different operating conditions affect the CVR effects. We have observed that when CVR is deployed on the distribution system with DG penetration, it not only reduces the real power which is the goal of CVR but it also reduces the reactive power demand at the substation. Under unity power factor operation mode, it is observed that the amount of real or reactive power reduction due to CVR is not influenced by the presence of DG, however, the presence of DG itself largely reduces the demand at the substation.

To understand the impact of Volt/VAr controlled DG to deploy CVR, we developed a distributed multi-objective optimization model to coordinate the fast-dispatch of photovoltaic (PV) inverters with the slow-dispatch of on-load tap changer (OLTC) and capacitor banks (CBs) in unbalanced three-phase distribution systems. In existing studies, PV inverters and voltage regulation devices are generally dispatched by a fully centralized or a multi-level optimization method. However, centralized optimization methods require significant communications and suffer large computational burden. On the other hand, multi-level optimization methods cannot ensure the optimality. To tackle these challenges, a distributed dispatch method is developed to coordinate PV inverters and conventional voltage regulation devices in distribution systems. The proposed method is based on an alternating direction method of multipliers (ADMM) algorithm. The main contributions of this part are: (1) An optimization model is developed to coordinate the fast-dispatch of PV inverters with the slow-dispatch of OLTC and CBs, in order to facilitate voltage reduction in unbalanced three-phase distribution systems. (2) In order to solve the communication concerns and ensure the solution optimality, a distributed optimization method is proposed to dispatch all the above-mentioned devices in one optimization problem. (3) A modified ADMM is designed to handle the non-convex problem with discrete variables of CBs and OLTC. (4) The trade-off between voltage reductions and real power loss reductions is analyzed using the newly developed multi-objective VVO formulation.

Impact of CVR on Voltage Stability Margin through T&D Co-Simulation

From all the previous work we see that the net real and reactive power demand at the substation level decreases, which implies that CVR may have impacts on long-term voltage stability margin (VSM). Since CVR is implemented in distribution systems, considering a detailed model of the distribution system along with the transmission system is important to accurately assess the impact of CVR on VSM. Therefore, it is imperative to co-simulate transmission and distribution systems. Transmission and distribution systems have different characteristics in terms of the network parameters (R , X) and operations (e.g., balanced vs unbalanced operations). Although there are separate solvers, such as PSSE for transmission systems and GridLAB-D for distribution systems, the lack of a co-simulation platform still inhibits integrated transmission and distribution studies. Hence, we have developed an interface in Python to integrate the two solvers for steady-state system co-simulations. The interface is compatible with parallel computing, thus can be extended to handle multiple distribution grids modeled in GridLAB-D. The simulation results indicate that the unbalance in distribution systems affects the VSM of the system. In a system with unbalance, the VSM is less than that of a balanced system for the same power demand at the substation. We also use this framework to simulate CVR by varying the taps of the secondary substation

transformer. Then we have assessed the long-term VSM with different ZIP load models. Our results show that CVR has a negative impact on the long-term VSM of the overall system. This study was extended to systems with distributed generation (DG) and we have observed the same impact of CVR on VSM.

Part II: Distribution System Management and Voltage Control

This part of work focuses on the performance limit and algorithm design for distribution voltage control as a major component of distribution system management (DSM). In particular, we consider this problems facilitated by distributed energy resources (DERs) under the realistic time varying operating conditions with unreliable or under-deployed communication networks. Our goal is to model the DSM problem and characterize its performance for these settings, as well as to develop algorithms that can achieve the performance limit in an online fashion. To this end, we first study the dynamic voltage regulation problem under limited communication rates. Thanks to advancement in power electronics, DERs can be leveraged to regulate the distribution grid voltage by quickly changing their reactive power outputs. We develop a hybrid voltage control (HVC) strategy that can seamlessly integrate both local and distributed designs to effectively coordinate the network-wide DERs. By minimizing a special voltage mismatch objective, we achieve the proposed HVC design by adopting partial primal-dual (PPD) gradient updates that can allow for an online implementation. The proposed HVC design improves over existing distributed approaches by reliably integrating local voltage feedback. As a result, it can dynamically adapt to varying system operating conditions while being fully cognizant of the instantaneous availability of communication links. Under the worst-case scenario of total link outages, the proposed design naturally boils down to a surrogate local control implementation. Furthermore, we consider a more general DSM framework with a locally connected communication network. In particular, the objective of general DSM can be viewed as to coordinate the power injection at the DERs to maintain certain quantities across the network, e.g., voltage magnitude, line flows, and line losses, to be close to a desired profile. We investigate the modeling and algorithm design and analysis considering non strongly connected communication network and time-varying system operating condition. In particular, a game-theoretic characterization is first proposed to account for a locally connected communication network over DERs, along with the analysis of the existence and uniqueness of the Nash equilibrium (NE) therein. To achieve the equilibrium in a distributed fashion, a projected-gradient-based asynchronous DSM algorithm is then advocated. The algorithm performance, including the convergence speed and the tracking error, is analytically guaranteed under the dynamic setting.

Project Publications:

- [1] Z. Wang, B. Cui, and J. Wang, "A Necessary Condition for Power Flow Insolvability in Power Distribution Systems with Distributed Generators," *IEEE Transactions on Power Systems*, vol. 32, no. 2, pp. 1578-1579, March 2017.
- [2] J. Zhao, Z. Wang, and J. Wang, "Robust Time-Varying Load Modeling for Conservation Voltage Reduction Assessment," *IEEE Transactions on Smart Grid*, vol. 9, no. 4, pp. 3304-3312, July 2018.
- [3] C. Wang, Z. Wang, J. Wang, and D. Zhao, "Robust Time-Varying Parameter Identification for Composite Load Modeling," *IEEE Transactions on Smart Grid*, accepted for publication.

- [4] C. Wang, B. Cui, and Z. Wang, "Analysis of Solvability Boundary for Droop-Controlled Microgrids," IEEE Transactions on Power Systems, accepted for publication.
- [5] C. Wang, B. Cui, Z. Wang, and C. Gu, "SDP-based Optimal Power Flow with Steady-State Voltage Stability Constraints," IEEE Transactions on Smart Grid, accepted for publication.
- [6] H.-J. Liu, W. Shi, and H. Zhu, "Distributed voltage control in distribution networks: online and robust implementations," IEEE Transactions on Smart Grid, accepted for publication.
- [7] H. J. Liu, W. Shi, and H. Zhu, "Hybrid Voltage Control in Distribution Networks Under Limited Communication Rates," IEEE Transactions on Smart Grid, accepted for publication.
- [8] Z. Wang, "Assessment of Conservation Voltage Reduction by Unscented Kalman Filter based Load Modeling," 2016 IEEE PES General Meeting, Boston, July 17-21, 2016.
- [9] Z. Wang, "Decentralized Voltage/VAR Control based on PV Inverters," 2016 IEEE PES Innovative Smart Grid Technologies Conference, Minneapolis, September 6-9, 2016.
- [10] A.K. Bharati, A. Singhal, V. Ajjarapu, and Z. Wang, "Comparison of CVR Impact on Transmission System Load Margin with Aggregated and De-Aggregated Distribution System," The 49th North American Power Symposium, Morgantown, WV, September 17-19, 2017.
- [11] S. Madani, Z. Wang, and V. Ajjarapu, "Voltage Stability Oriented Conservative Voltage Reduction Using Integrated Transmission and Distribution Analysis," The 49th North American Power Symposium, Morgantown, WV, September 17-19, 2017.
- [12] K. Zhang, W. Shi, H. Zhu, and T. Basar, "Distributed equilibrium-learning for power network voltage control with a locally connected communication Network," in IEEE American Control Conference (ACC), Milwaukee, MI, USA, June 2018.
- [13] K. Zhang, W. Shi, H. Zhu, E. Dall'Anese, and T. Basar, "Dynamic Power Distribution System Management with a Locally Connected Communication Network," IEEE Journal of Selected Topics in Signal Processing (JSTSP), accepted for publication.
- [14] A.K. Bharati and V. Ajjarapu "Importance of Modeling Distribution Systems and Impact of CVR on VSM through T&D Co-Simulation", IEEE Transactions in Power Systems, under review.
- [15] Q. Zhang, Z. Wang, and K. Dehghanpour, "Distributed CVR in Unbalanced Distribution Systems with PV Penetration", IEEE Transaction in Smart Grid, under review.

Student Theses:

- [1] Alok Kumar Bharati. *T&D co-simulation framework to investigate the impact of high penetration of distributed resources on voltage stability assessment and control*. PhD Dissertation, Iowa State University, Spring 2020 (expected).
- [2] Qianzhi Zhang. *Machine learning based operations of power distribution systems and microgrids*. PhD Dissertation, Iowa State University, Fall 2021 (expected).