



Improving Voltage Stability Margin Estimation through the use of HEM and PMU Data

Final Project Report

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Power Systems Engineering Research Center
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Executive Summary

Recently, a novel non-iterative power flow (PF) method known as the Holomorphic Embedding Method (HEM) was applied to the power-flow problem. The method has been shown to produce reduced-order network models (from analytical model data) that accurately captured the nonlinear behavior of the network models and were able to predict the nearness of the operating point to the saddle-nose bifurcation point (SNBP), a measure of voltage stability margin. The goal of this work was to explore whether HEM could be used with PMU measurements to similarly calculate this metric.

The work progressed in five stages. The first stage was to produce reduced-order nonlinear Thévenin-like network models using HEM and analytical model data. These reduced-order models served as accurate reference cases for the models built using PMU measurement. This first stage was completed successfully, showing the wide range of conditions over which such models were both valid and could be developed.

The second stage involved showing that the traditional maximum power transfer theorem (MPTT) used for linear models was not applicable to nonlinear models and a new nonlinear MPTT successfully derived.

The third state involed identifying ways in which the nonlinear reduced order Thévenin-like models could be used to predict the SNBP. Of the methods identified, two methods were singled out for further testing: (1) The MPTT method (using the nonlinear MPTT); (2) The Roots method (using the roots of Padé approximant of the voltage function for the bus at which the PMU measurements were taken).

In the forth stage of work, numerical methods for approximating the needed functions from measured data were proposed. Recognizing that appxoimations of the functions from measured data were senstive to precision, multiple numerical methods for both the MPTT and Roots methods were tested using psuedo-measurment from the network models identified in the first stage of this work. Advantages and limitations of both methods were identified and both methods were shown to be viable provided sufficient accuracy in the measurments and calculations was assumed.

In the fifth stage, noise was added to the pseudo-measurements and the various numerical methods proposed were reevaluated. With this test, the performance was less accurate than hoped and future work was identified to improve the performance.

Project Publications:

- [1] S. Rao, D. J. Tylavsky, "Two-Bus Holomorphic Embedding Method-Based Equivalents and Weak-Bus Determination," *arxiv.org/ftp/arxiv/papers/1706/1706.01298.pdf*, Aug. 2017, pp. 1-4.
- [2] S. Rao, D. J. Tylavsky, V. Vittal, W. Yi, D. Shi, Z. Wang, "Fast Weak-Bus and Bifurcation Point Determination using Holomorphic Embedding Method," *IEEE PES General Meeting*, July. 2018, pp. 1-5.
- [3] S. Rao, S. Li, D. J. Tylavsky and Di Shi, "The Holomorphic Embedding Method Applied to a Newton Raphson Power Flow Formulation," *2018 North American Power Symposium*, pp. 1-6, Sep. 2018.
- [4] S. Li, Q. Li, D. J. Tylavsky and Di Shi, "Robust Padé Approximation Applied to the Holomorphic Embedded Power Flow Algorithm," *2018 North American Power Symposium*, pp. 1-6, Sep. 2018.
- [5] S. Li, D. J. Tylavsky, "Analytic Continuation as the Origin of Complex Distances in Impedance Approximations," *International Journal of Electrical Power and Energy Systems*, Volume 105, Feb. 2019, pp. 699-708.
- [6] S. Rao, D. J. Tylavsky, D. Shi, Z. Wang, "A measurement-based approach to estimate the saddle-node bifurcation point using Padé approximants," *IEEE Trans on Power Systems*, (in preparation).
- [7] S. Li, D. J. Tylavsky, D. Shi, Z. Wang, "Stahl's Theorem Part 1: Implications to Theoretical Convergence," *IEEE Trans on Power Systems*, (in preparation).
- [8] A. Dronamraju, S. Li, Q. Li, Y. Li, D. J. Tylavsky, D. Shi, Z. Wang, "Stahl's Theorem Part 2: Implications to Numerical Convergence," *IEEE Trans on Power Systems*, (in preparation).
- [9] S. Li, D. J. Tylavsky, D. Shi, Z. Wang, "The Padé Matrix Pencil Method," *Society of Industrial and Applied Mathematics*, (In Preparation), 2019.
- [10] S. Li, Q. Li, D. J. Tylavsky, D. Shi, Z. Wang, "Estimation of the Saddle Node Bifurcation Point using HEM and PMU Data," *IEEE Trans on Power Systems*, (in preparation).

Student Theses:

- [1] Shruti Rao, "Exploration of a Scalable Holomorphic Embedding Method Formulation for Power System Analysis Applications," PhD Dissertation, Completed Summer, 2017.
- [2] Qirui Li, "Numerical Performance of the Holomorphic Embedding Method," MS Thesis, Completed Summer, 2018.
- [3] Songyan Li, "Application of HEM to SNBP Prediction and the OPF Problem," PhD Dissertation, in progress.