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| **Paper 1** | |
| **Title of the Paper** | A Scalable Transmission and Distribution Co-simulation Platform for IBR-heavy Power Systems |
| **Year and Journal** | 2023, 8th IEEE Workshop on the Electronic Grid (eGRID) |
| **Authors and Affiliations** | Yousu Chen, Yuan Liu, Xiaoyuan Fan, Wei Du, Dexin Wang, James Ogle (Pacific Northwest National Laboratory); Johan Enslin (Clemson University) |
| **Tools Used** | GridPACK, GridLAB-D, HELICS, HPC environment |
| **Aim of the Paper** | To develop a scalable co-simulation platform for analyzing the impact of grid-forming (GFM) and grid-following (GFL) inverters on the dynamic stability of transmission and distribution systems at varying penetration levels. |
| **What They Analyzed** | Dynamic behavior under contingencies, frequency response, and grid stability with different mixes of GFL and GFM inverters at high renewable penetration levels. |
| **Results and Conclusion** | GFM inverters enhance frequency stability and overall system performance during contingencies. The platform is scalable and facilitates detailed analysis of IBR impacts, which cannot be achieved with aggregated models. |
| **Novel Contributions** | Introduced a scalable T&D co-simulation platform supporting high penetration of GFM and GFL inverters. Enhanced IBR modeling capabilities and the ability to simulate distribution-side contingencies comprehensively. |
| **Simulation Scenarios** | Small-scale: IEEE 39-bus transmission system with two IEEE 34-node feeders; Large-scale: 120-bus transmission system with 19 IEEE 8500-node feeders. Contingencies included generator and feeder tripping scenarios. |
| **Challenges Addressed** | Lack of comprehensive dynamic IBR models, limitations of aggregated models, need for scalable co-simulation platforms to handle high renewable penetration and analyze interactions across T&D systems. |
| **Impact of Work** | Facilitates understanding of IBR impacts on grid dynamics, aiding in the design of more resilient and stable power systems. Provides a platform for integrating emerging technologies like 5G for grid monitoring and control. |
| **Comparison to Existing Work** | Builds on previous co-simulation efforts but significantly expands scalability and fidelity with detailed IBR modeling and distribution-side contingency analysis, surpassing traditional aggregated approaches. |

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| **Paper 2** | |
| **Title of the Paper** | Highly-Scalable Transmission and Distribution Dynamic Co-Simulation With 10,000+ Grid-Following and Grid-Forming Inverters |
| **Year and Journal** | 2024, IEEE Transactions on Power Delivery |
| **Authors and Affiliations** | Yuan Liu, Renke Huang, Wei Du, Ankit Singhal, Zhenyu Huang; Affiliations include PNNL (Pacific Northwest National Laboratory), Shanghai Jiao Tong University, IIT Delhi. |
| **Tools Used** | GridPACK, GridLAB-D, HELICS, HPC resources |
| **Aim of the Paper** | To develop and validate a scalable co-simulation platform capable of dynamically modeling T&D systems with over 10,000 GFM and GFL inverters, and to analyze their impact under various high IBR penetration scenarios. |
| **What They Analyzed** | Dynamic stability, frequency responses, voltage regulation, and minimum grid-forming inverter penetration for stable operation under 100% inverter-based resource (IBR) penetration scenarios. |
| **Results and Conclusion** | Demonstrated that GFM inverters significantly enhance stability. Only 12% GFM inverters are required for stable operation at 100% IBR penetration. Highlighted the platform's scalability and its potential for future studies. |
| **Novel Contributions** | Developed the largest dynamic T&D co-simulation platform to date, introduced an iterative T&D initialization method, and demonstrated new insights into GFM inverter control under extreme scenarios. |
| **Simulation Scenarios** | Analyzed scenarios ranging from 0% to 100% IBR penetration. Modeled 10,450 inverters (5,225 GFL and 5,225 GFM). Included generator tripping and inverter mix experiments to assess performance under stress conditions. |
| **Challenges Addressed** | Limitations of aggregated models for IBRs, instability in initializing co-simulations at high IBR penetration, and lack of platforms that combine detailed distribution and transmission dynamic modeling. |
| **Impact of Work** | Enables deeper analysis of IBR impacts, helping design more resilient power systems. Demonstrates how even a small percentage of GFM inverters can stabilize grids at extreme renewable penetration levels. |
| **Comparison to Existing Work** | Surpasses earlier studies by incorporating detailed inverter models, addressing dynamic interactions, and scaling co-simulations to unprecedented sizes, enhancing both fidelity and applicability to real-world scenarios. |

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| **Paper 3** | |
| **Title of the Paper** | High-Performance Computing-Based Open-Source Power Transmission and Distribution Grid Co-Simulation |
| **Year and Journal** | 2024, IEEE Transactions on Power Systems |
| **Authors and Affiliations** | Lei Zheng, Yuxin Cui, Shuangshuang Jin, Yousu Chen (Clemson University, Pacific Northwest National Laboratory) |
| **Tools Used** | GridPACK, GridLAB-D, HELICS, MPI (Message Passing Interface), HPC environments |
| **Aim of the Paper** | To develop and validate an open-source HPC-based framework for scalable and parallel co-simulation of transmission and distribution systems, addressing dynamic interactions and improving computational efficiency. |
| **What They Analyzed** | Dynamic interactions between T&D systems, simulation scalability, co-simulation accuracy, and parallel performance under various scenarios including branch faults and varying numbers of interconnected distribution grids. |
| **Results and Conclusion** | Demonstrated high scalability and faster-than-real-time (FTRT) performance. Co-simulation captured finer dynamic interactions compared to standalone simulations, proving its effectiveness and potential for large-scale studies. |
| **Novel Contributions** | Introduced an HPC-based T&D co-simulation framework integrating GridPACK, GridLAB-D, and HELICS. Maintained inherent parallelism of GridPACK while enabling large-scale distributed simulations on modern HPC platforms. |
| **Simulation Scenarios** | Tested scenarios include a 3000-bus transmission grid interconnected with IEEE 123-node distribution systems under various configurations (1:1, 1:10, 1:100). Simulated branch faults and assessed rotor speeds and feeder voltages. |
| **Challenges Addressed** | Traditional T&D simulations lacked integrated frameworks for dynamic interactions. Standalone tools were limited in scalability and parallelism. The framework overcomes these by leveraging HPC capabilities and open-source tools. |
| **Impact of Work** | The framework enables efficient large-scale T&D co-simulations for real-time applications, supports grid resilience studies, and provides an open-source platform for advancing research and development in grid dynamics modeling. |
| **Comparison to Existing Work** | Extends previous efforts by retaining parallel computation capabilities, enabling finer dynamic interaction analysis, and achieving superior scalability compared to standalone or less integrated co-simulation frameworks. |

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| **Paper 4** | |
| **Title of the Paper** | High-Performance Transmission and Distribution Co-simulation with 10,000+ Inverter-Based Resources |
| **Year and Journal** | 2022, IEEE Industry Applications Society Annual Meeting (IAS) |
| **Authors and Affiliations** | Yuan Liu, Renke Huang, Wei Du, Ankit Singhal, Zhenyu Huang (Pacific Northwest National Laboratory, PNNL) |
| **Tools Used** | GridPACK, GridLAB-D, HELICS, HPC resources |
| **Aim of the Paper** | To develop a scalable T&D co-simulation platform capable of dynamically modeling over 10,000 inverter-based resources (IBRs) and analyzing their impact on grid stability and transient responses under high penetration levels. |
| **What They Analyzed** | Dynamic stability, frequency response, and voltage regulation under high penetration of grid-forming (GFM) and grid-following (GFL) inverters. Impact of inverter control strategies on large-scale T&D systems. |
| **Results and Conclusion** | GFM inverters significantly enhance stability during contingencies, such as generator tripping. The platform achieved seamless integration of T&D models and provided insights into how IBRs can stabilize weak grids. |
| **Novel Contributions** | Developed a co-simulation platform capable of integrating over 10,000 real inverter models. Introduced an iterative T&D power flow initialization method for enhanced numerical stability. Demonstrated large-scale dynamic simulation capabilities. |
| **Simulation Scenarios** | Simulated 10,450 inverters distributed as 50% GFM and 50% GFL. Studied scenarios including generator tripping, varying IBR penetration, and the impact of inverter control types on frequency and voltage stability. |
| **Challenges Addressed** | Overcame limitations of aggregated inverter models, lack of realistic dynamic models, and challenges in scaling co-simulations for high-penetration renewable systems. |
| **Impact of Work** | Facilitates understanding of how inverter control strategies impact T&D systems under high renewable penetration. Supports the design of more stable and resilient power grids. |
| **Comparison to Existing Work** | Extended previous efforts by incorporating more advanced IBR models, significantly increasing co-simulation scalability, and achieving high-fidelity modeling of dynamic interactions in T&D systems. |

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| **Paper 5** | |
| **Title of the Paper** | Validation of Phasor-Domain Transmission and Distribution Co-simulation Against Electromagnetic Transient Simulation |
| **Year and Journal** | 2024, ELSEVIER |
| **Authors and Affiliations** | Yousu Chen, Yuan Liu (Pacific Northwest National Laboratory) |
| **Tools Used** | GridPACK, GridLAB-D, HELICS, PSCAD (for validation) |
| **Aim of the Paper** | To validate a scalable phasor-domain T&D co-simulation framework against PSCAD for modeling system dynamics with high fidelity, particularly under configurations of grid-forming and grid-following inverters. |
| **What They Analyzed** | Dynamic behaviors of the T&D systems, including voltage magnitudes, inverter frequency, and active power, under a three-phase line-to-ground fault scenario. |
| **Results and Conclusion** | The co-simulation platform demonstrated high fidelity with a 60–100x computational speed-up compared to PSCAD. It provides a scalable and efficient tool for analyzing IBR-heavy systems while maintaining reasonable accuracy. |
| **Novel Contributions** | First validation of a phasor-domain T&D co-simulation framework against an EMT simulation tool. Demonstrates the potential for accurate yet efficient dynamic studies in IBR-rich power systems. |
| **Simulation Scenarios** | Analyzed a small-scale IEEE 39-bus transmission system integrated with an IEEE 34-node distribution feeder under a 0.1-second three-phase-to-ground fault on the transmission side. |
| **Challenges Addressed** | Addressed the computational inefficiencies of EMT simulations for large systems and the lack of validated phasor-domain co-simulation frameworks for T&D systems with high penetration of IBRs. |
| **Impact of Work** | Provides confidence in using phasor-domain co-simulation for efficient and scalable analysis of T&D system dynamics, enabling broader studies of fault detection and control in renewable-rich grids. |
| **Comparison to Existing Work** | Extends prior co-simulation frameworks by validating phasor-domain models against high-fidelity EMT simulations, offering significant computational efficiency without compromising the accuracy of results. |