MODELS AND METHODS FOR ASSESSING THE VALUE OF HVDC AND MVDC TECHNOLOGIES IN MODERN POWER GRIDS

Annual Report – Executive Summary

May 2019

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Executive Summary

Evolution of today's predominantly alternating current (ac) transmission grid in to mixed ac transmission – high-voltage direct current (HVdc) systems is expected with the decreasing costs of and advancements in power electronics technologies. The recent technological advancements include the development of more efficient and compact voltage source converters (VSCs) that can provide fast response. Because of their controllability and fast response, HVdc systems provide the ability to enhance reliability of the ac transmission grid through frequency support, voltage control, and congestion relief. The HVdc systems can also provide other ancillary services to enhance the economics and reliability of the ac transmission grids, and to optimize their performance. The tools, models, and methods developed to evaluate their benefits will be key enablers to understanding the value proposition introduced by the fast-acting HVdc systems.

The main motivation of this work was to develop models and methods to explore and quantify the technical and economic benefits of HVdc systems and fast response VSC technologies in the future grid of United States. The models and methods explore the benefits of HVdc systems through provision of controlled active/reactive power and fast response. The fast response can provide much-needed multi-objective services to the grid (e.g., frequency response, voltage control) while moving blocks of energy. The models and methods can be applied to study other power electronics technologies and scenarios such as those undertaken in ongoing studies led by the North American Electric Reliability Corporation (NERC) Inverter-based Resource Performance Task Force (IRPTF). The IRPTF studies identify the problems associated with power electronics-based technologies as they are integrated in to the bulk power system (or the ac transmission system).

Objectives

The main objective of this work included the following:

1. Develop high-fidelity dynamic models of VSCs to enable the study of the fast control response that they can provide. The models that were developed enable planners to make informed choices of the required HVdc technologies (e.g., line-commuted converter [LCC], VSCs) in the future grid expansion using HVdc systems.
2. Include other HVdc control algorithms such as the voltage control algorithm that is feasible due to the introduction of fast-acting and controllable VSCs, in addition to the developments by Makarov et al. (2017). Evaluate the multi-objective control algorithms using the high-fidelity models of VSCs and hybrid simulation of HVdc–ac transmission grid dynamics. The evaluation methods that were developed can be used to identify the improved performance of the ac transmission grid due to the presence of the fast-acting VSCs. The methods can be applied to assess the impact of other fast-acting power electronics technologies on the grid, such as those being evaluated in the NERC-led IRPTF studies.
3. Develop up to seven-terminal multiterminal dc (MTdc) system models with multiple points of injection in asynchronous ac transmission grids based on high-fidelity models of VSCs. Develop multi-objective control methods such as the multiple point-of-injection fast frequency support and voltage control in the MTdc systems. The methods that were developed provide enhanced reliability services that increase the value of MTdc systems and can be applied to future dc technologies and systems.

4. Develop and evaluate different scenarios of HVdc system penetrations in the future grid, thus facilitating the comparison of their benefits. Evaluate technical benefits for frequency and congestion management of several HVdc lines over a continental-level North American power grid model based on utility industry models.
5. Develop advanced models to address computational challenges of high-fidelity models when models need to expand over a large geographic area, such as HVdc Macrogrids. Create two types of modeling approaches: (a) develop reduced, lumped models able to capture voltage behavior near HVdc terminals and (b) configure advanced hybrid co-simulation between high-fidelity, electromagnetic transient models for HVdc and lower-fidelity electromechanical transient models for the continental-level grid.
6. Evaluate economic benefits associated with fast-acting and controllable HVdc systems. The methods applied to identify economic benefits can be extended to identify the benefits of providing fast reliability services in the grid by power electronics technologies or other technologies.

Value proposition

The value proposition of this project includes the following:

1. Enable decision-makers, planners, and investors to make better-informed decisions regarding the HVdc systems as an important grid development option. These decisions usually concern major investments and require multiple analyses of the benefits that can be provided. The analyses carried out in previous studies did not include the technical and economic benefits offered by advanced control methods in VSC-HVdc configurations that connect Eastern Interconnection (EI), Western Interconnection (WI), and Electric Reliability Council of Texas (ERCOT) grids. This project has demonstrated the benefits of these advanced control methods in VSC-HVdc configurations, and different penetrations and configurations of HVdc systems (such as the MTdc systems).
2. Quantify the fidelity requirements of HVdc system – ac transmission grid models as advanced fast control methods are integrated in to VSCs that may further enhance the reliability and reduce operating reserve margins. In this process, the following questions are answered:
   a) Why do we need higher-fidelity models of VSCs? What are the implications of high-bandwidth control methods? What are the trade-offs in speed vs. fidelity? The faster control methods applied to the high-fidelity models of VSC-HVdc technologies exploit the capabilities of the hardware to a greater extent than the conservative slower control methods. The conservative slower control methods can be applied to the lower-fidelity models. These methods have been shown to reduce the benefits that can be extracted from the HVdc system–ac transmission grid. For example, lesser frequency reserves may be shared across interconnections if the slower control methods are utilized, reducing the associated economic benefits.
   b) Why do we need simulation algorithms that speed up the simulation of higher-fidelity models? The simulation of higher-fidelity models takes much longer than today's existing planning models that use lower-fidelity models. This limits the acceptance of the higher-fidelity models. Hence, speedup of the simulation of high-fidelity models is critical for their acceptance in the industry.
3. Identify the methods to evaluate the fast control methods in VSCs. The following questions were answered in this analysis:
   a) How do we perform hybrid simulation of the higher-fidelity models of HVdc systems with the traditional high-fidelity models of the ac transmission grid to identify the impact of the reliability services that can be provided by VSCs? The reliability services provided are based on the multi-objective control methods to provide frequency and voltage support. The traditional high-fidelity models of the ac transmission grid are in transient stability simulators (e.g., PSS®E), and the

higher-fidelity models are developed in an electromagnetic transient (EMT) simulator (e.g., PSCAD). Three tools have been identified to perform hybrid simulation: PSCAD, E-Tran, and PSS®E. The limitations identified in this work that are associated with performing hybrid simulations have been identified with methods proposed to overcome the limitations.

   b) What are the alternatives to hybrid simulation to evaluate the performance of the fast control methods like frequency and voltage support provided by VSCs? Methods to develop an equivalent ac transmission grid model in an EMT simulator that adequately represent frequency and voltage dynamics have been identified. The developed models can then be simulated with the higher-fidelity models of VSCs in one simulator (e.g., PSCAD). The equivalent ac transmission grid models that are required for simulation of the complete grid model in an EMT simulator are extremely expensive (in computational costs and time taken to simulate).

4. Research multiple objectives that can be achieved with advanced HVdc configurations (e.g., VSC-HVdc, MTdc systems) and legacy HVdc systems (e.g., line-commuted converter–LCC HVdc systems), answering the following questions:
   a) Can VSC-HVdc systems provide adequate voltage support? What are gaps in such analysis? In this work, it was identified that VSC-HVdc systems can provide adequate voltage support to improve the reliability of the existing grid, especially the fast response requirements under fault circumstances. The load models in traditional ac transmission grid models need to be updated to accurately represent fault-induced delayed voltage recovery (FIDVR) issues.
   b) How do we control a radial MTdc system with multiple points of injection into an asynchronous ac grid to provide ancillary services? Optimal control methods to provide fast frequency support across multiple points of injection in different asynchronous ac grids (EI, WI, and ERCOT) have been developed in this work.
   c) How do we provide simultaneous frequency and congestion relief? A combined decentralized and centralized control strategy has been developed in this work to address the same and show the feasibility of the method.
5. Evaluate economic benefits associated with providing reliability services such as fast frequency support. Essentially, identify methods to evaluate the impact of fast control methods using high-fidelity models on the ac transmission grid and the associated economic benefits.

Approach and Outcomes

The overview of the approach and the corresponding outcomes in this project is provided below:

1. A suite of high-fidelity EMT dynamic models of three multilevel VSCs with up to 10,000 states and the required simulation algorithms was developed. The three multilevel VSCs include an alternate-arm converter (AAC), a cascaded two-level converter (CTL), and a modular multilevel converter (MMC). The MMC dynamic model was developed by Makarov et al. (2017). The multilevel converters are shown in Fig. Ex-1. The simulation algorithms applied include the following characteristics:
   a. A numerical stiffness-based separation of states is applied, as shown in Fig. Ex-2. The simulation of the dynamics of capacitor voltages are separated from those of the inductor currents in AACs and CTLs.
   b. A hybrid discretization algorithm is applied to the separated states. This algorithm reduces the matrix inversion requirements. The reduced matrix inversion requirements reduce the computational burden associated with applying homogeneous algorithms to all the states.
   c. Multi-rate algorithms are applied to the simulation of states in the CTL. The switching frequency of individual switches in the CTL are higher than the corresponding switches in the AAC or MMC. The higher switching frequency affects the dynamics of the capacitor voltages. The multi-

rate algorithms further reduce the computational burden imposed as compared to the homogeneous time-step algorithms applied to all states.

A speedup of up to 12× was observed with these algorithms. The models and algorithms developed to simulate AACs and CTLs have been compared with the simulation in traditional simulators. An error of less than 1% was observed with one of the comparison studies shown in Fig. Ex-3. Further speedup may be achieved through temporal parallelization (of up to *N* times with *N* available cores). The speedup is necessitated due to the very long time (on the order of days) taken to simulate the high-fidelity models of large power electronic systems.

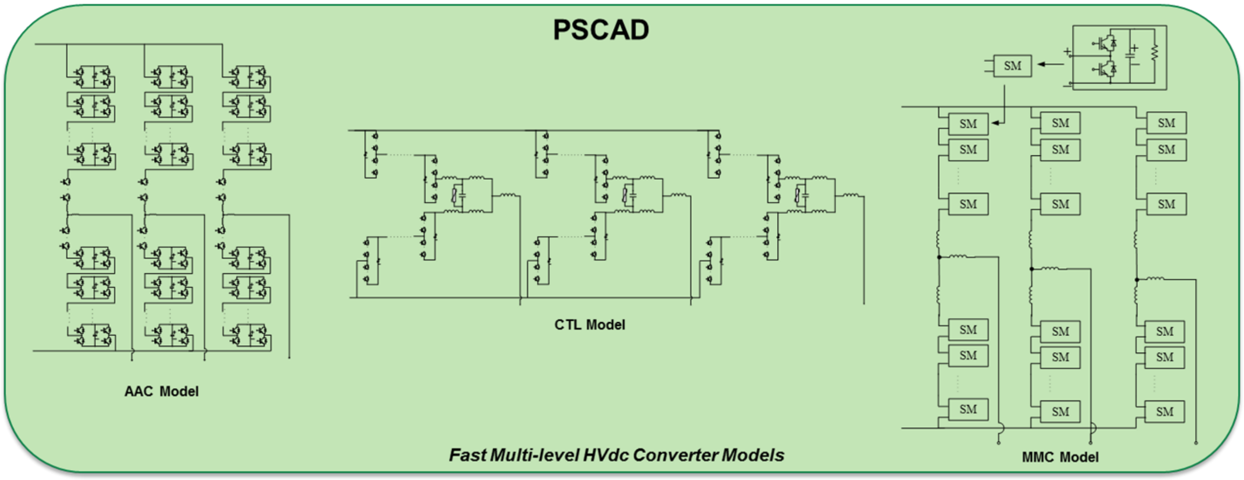
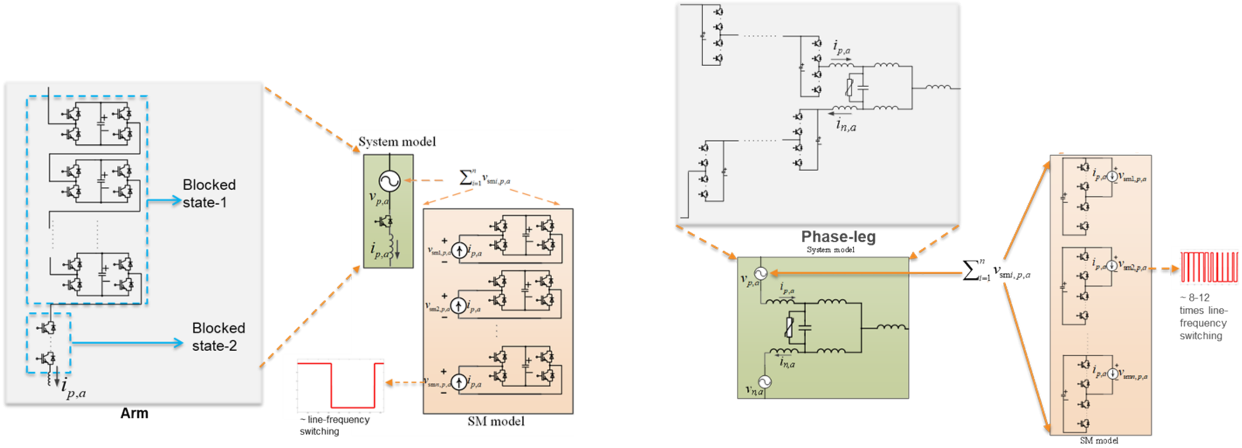


Figure Ex-1: Suite of VSC models available in the PSCAD EMT simulator. SM: submodule.



(a) (b)

Figure Ex-2: Simulation algorithm applied to speed-up the simulation of (a) AACs and (b) CTLs.

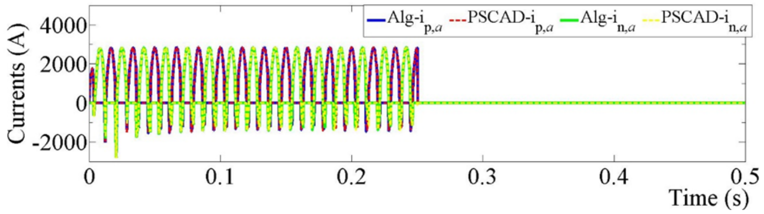


Figure Ex-3: Simulation of AAC-HVdc under blocked scenario.

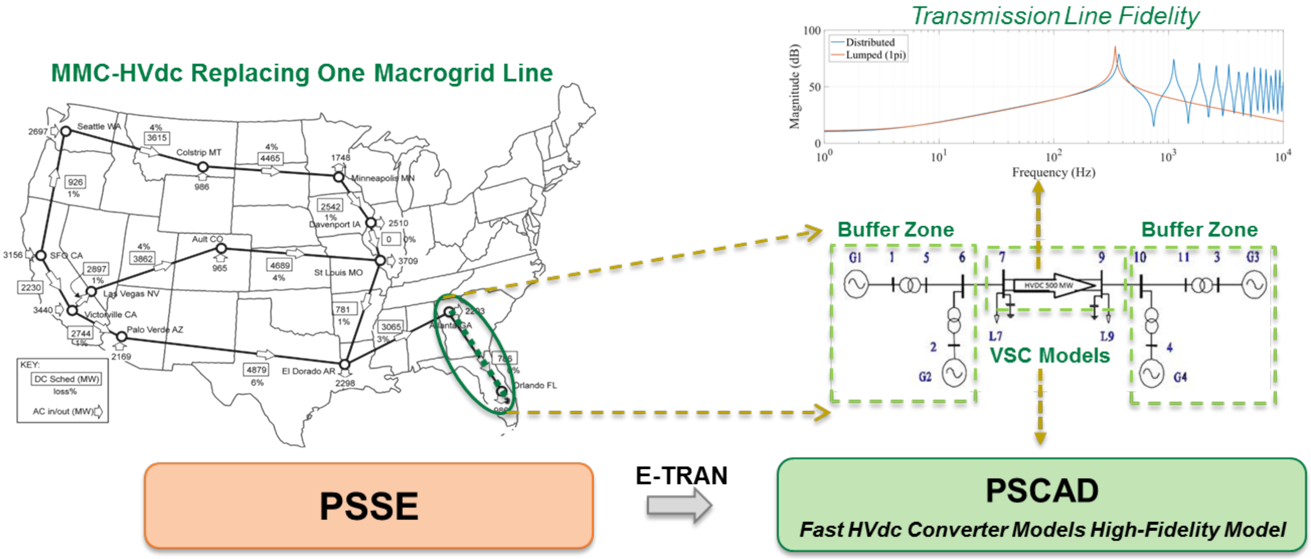


Figure Ex-4: Hybrid simulation framework to simulate VSC-line commuted converter (LCC) HVdc macrogrid as the VSC provides voltage control.

2. The simulation tools and fidelity of models required to study fast control methods in VSCs (e.g., voltage control) and their effect on ac transmission grids were established through the scenario shown in Fig. Ex-4. The chosen scenario was based on the replacement of one of the point-to-point LCC-HVdc systems from the HVdc macrogrid described by Makarov et al. (2017) by a point-to-point VSC-HVdc system. The location chosen for the VSC-HVdc system was based on the strength of ac transmission grid and the previous study completed by Midcontinent Independent System Operator (MISO) (MISO 2014). The VSC considered in this scenario is an MMC.

   The use cases to evaluate the fast voltage control methods in VSCs were transmission line faults and tripping of shunt compensators and generators. The following requirements were identified (and summarized in Fig. Ex-4) to accurately capture the impact of fast control methods in VSCs on the ac transmission grids during the defined use cases:

   a. High-fidelity EMT dynamic models of VSC-HVdc systems with their fast control methods (e.g., the voltage control method developed in this study).
   b. EMT dynamic models of buffer zones. The buffer zones are regions near the VSC-HVdc terminals. They are extracted from the transient stability (TS) dynamic model of the ac transmission grid. The extraction uses a sensitivity-based method through injection of reactive power at the VSC-HVdc terminals.
   c. A distributed line model of transmission lines in the EMT dynamic models of the buffer zones and VSC-HVdc systems. The characteristics of the distributed line model with respect to the lumped line model are highlighted in Fig. Ex-4 in the “Transmission Line Fidelity” plot. The plot

indicates the differences observed in the characteristics at higher frequencies that correspond to the bandwidth of the fast control methods.

d. Hybrid simulation of EMT-TS models that include the TS dynamic model of the rest of the ac transmission grids and the EMT dynamic models mentioned in points a-c above.

In this study, the EMT dynamic models were developed in PSCAD, the TS dynamic models were based in PSS®E, and the hybrid simulation of EMT-TS models was facilitated using E-Tran. The TS dynamic models were converted to EMT dynamic models using E-Tran. The conversion is required to extract buffer zone models.

The following tests were performed to evaluate the necessity of the requirements identified above:

a. **Evaluate Lower-fidelity Model of VSCs**: Multi-rate simulation methods were applied to the high-fidelity EMT dynamic models of VSC-HVdc system. The VSC considered in this study was the MMC. The multi-rate simulation of MMCs reduced the fidelity of the model. The lower fidelity was due to the lower sampling rate of the external measured signals in the multi-rate simulation of MMCs. The multi-rate simulation methods reduced the imposed computational burden. The comparison of the states observed is performed with the high-fidelity model of VSCs (that is, MMCs in this case). The corresponding results are shown in Fig. Ex-5, which highlights the instability observed in the VSC-HVdc control system when simulated with a lower-fidelity model. The instability was observed in the reactive power, as shown in Fig. Ex-5. The instability is not observed with a high-fidelity model of VSCs.

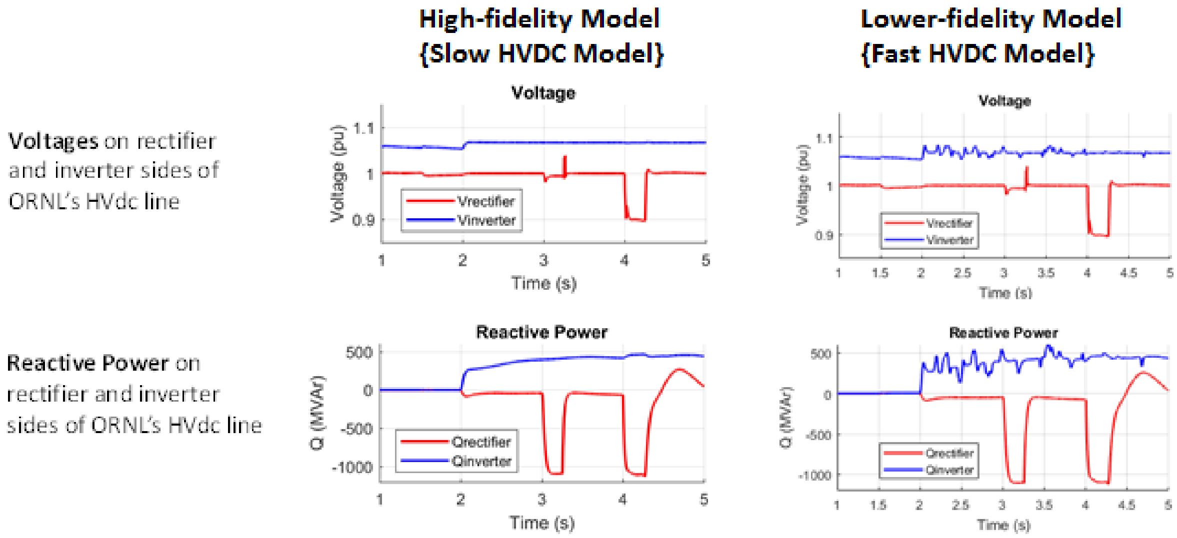


Figure Ex-5: Comparison of states observed in simulation of high and lower fidelity models of MMCs.

b. **Buffer Zone Size Reduction**: Size of the buffer zone was varied in hybrid simulations to identify the sensitivity to the size of buffer zones. A comparison between the states observed in hybrid simulation of the systems with a small buffer zone and with a large buffer zone was performed, and the corresponding results are shown in Fig. Ex-6. The results indicate that variations are observed in the dynamics of the VSC-HVdc control system, as highlighted in Fig. Ex-6.

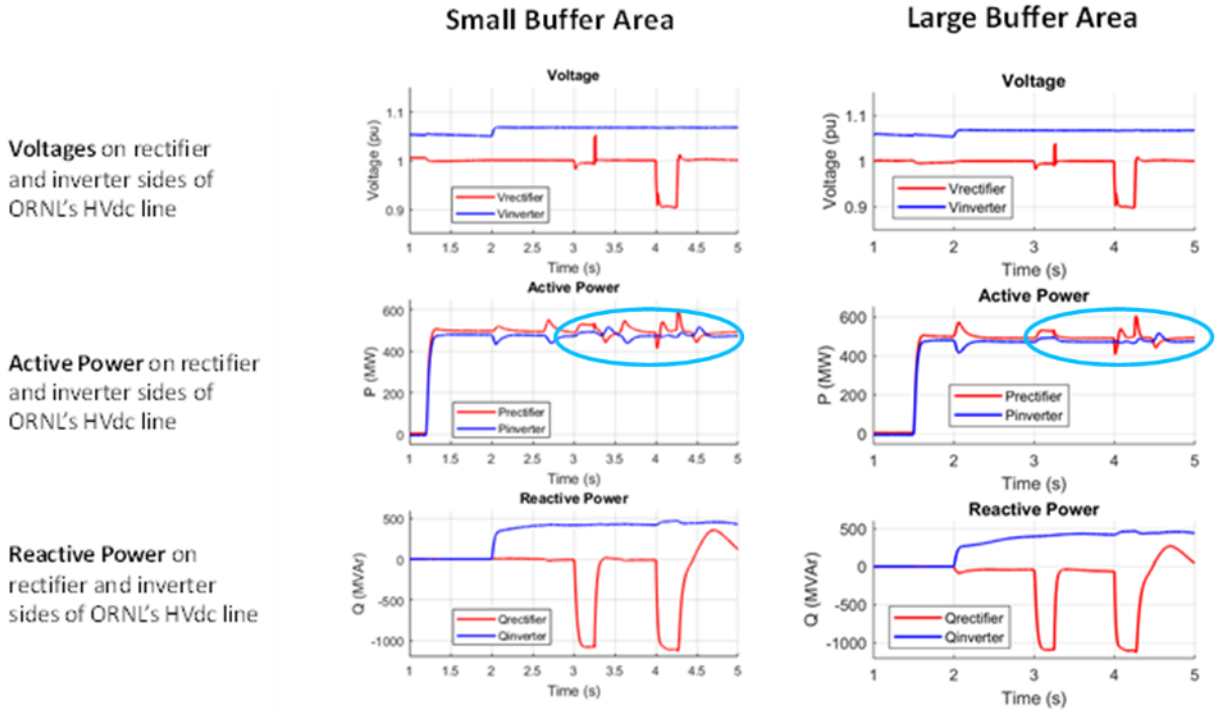


Figure Ex-6: Comparison of states observed in EMT simulation only and hybrid EMT-TS simulation.

c. **Reduced Fidelity of Transmission Lines**: Lumped line models were applied to the transmission line models in a smaller Kundur two-area system with a point-to-point VSC-HVdc system. The VSCs included the fast voltage control method. The states observed in the simulation of the system with lumped line model were compared to that observed in the system with the distributed line model. The corresponding results are shown in Fig. Ex-7. The results indicate that the system with a distributed line model is stable, whereas the system with a lumped line model is not stable. This difference can be attributed to the higher damping in the response observed in the distributed line model as compared to the lumped line model at the bandwidth of the control system.

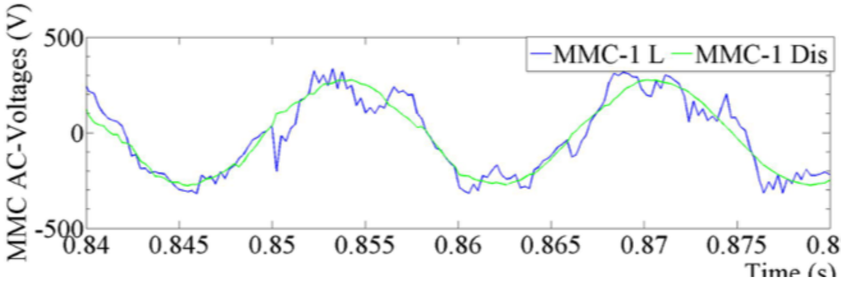


Figure Ex-7: Comparison of the response of a point-to-point VSC-HVdc system with fast control methods utilizing a lumped line model (MMC-1 L) and a distributed line model (MMC-1 Dis) in the transmission lines in the buffer zones of a small system (known as the Kundur two-area system).

d. **EMT Simulation Only**: EMT dynamic simulation only is performed in PSCAD, neglecting the response of the rest of the ac transmission grid. The comparison is performed with the states observed in hybrid simulation with respect to simulation only in PSCAD. The corresponding results are highlighted in Fig. Ex-8. The comparison of the results indicates varied dynamic performance of the VSC-HVdc control system during contingency events as highlighted in Fig. Ex-8. The varied dynamic performance affects the tuning of the VSC-HVdc control system.

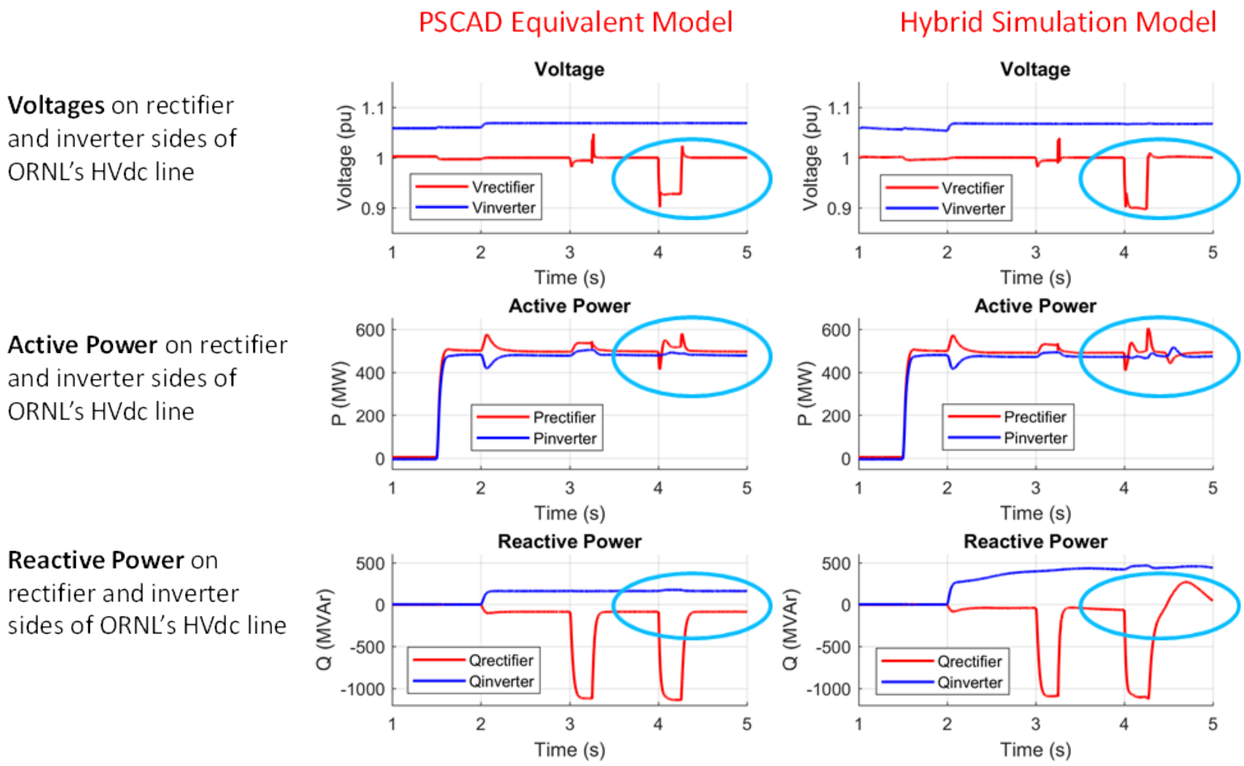


Figure Ex-8: Comparison of states observed in EMT simulation only and hybrid EMT-TS simulation.

The highlights of the computational performance of PSCAD-PSS®E hybrid simulation are summarized below:

a. About seventy-seven percent of computational burden was imposed by the EMT simulation in PSCAD, and ~23% was imposed by the TS simulation in PSS®E and communication between PSS®E and PSCAD.
b. The lower-fidelity point-to-point VSC-HVdc system model with the multirate simulation method resulted in up to 3.9× speed-up in hybrid simulation and up to 6x speed-up in Kundur two-area simulation in PSCAD only.
c. A speedup of up to 1.9× was observed with a smaller buffer zone model.

The highlights on accuracy of the PSCAD-PSS®E hybrid simulation are summarized below:

a. The multirate simulation methods applied to the simulation of VSC-HVdc systems (or, lower fidelity model) showed instability in the controller of the VSC-HVdc systems. The instability occurred as a fast voltage control method with a higher sampling rate was utilized. The instability was not observed in the simulation of the high-fidelity models of VSC-HVdc systems. The instability was not observed as the higher sampling rate is accurately captured, indicating the need for high-fidelity models for these studies.
b. The simulation results of the states from a smaller and larger buffer zone indicated the requirement of buffer zones. The larger buffer zone adequately captured the dynamics of the VSC-HVdc control system that is important to tune controller parameters, which influences the effect on the ac transmission grid.
c. The lumped line model of transmission lines does not adequately capture the high-frequency dynamics in the system. The high-frequency dynamics arise from the fast control methods in VSC-HVdc systems. They are also necessary to tune the controller parameters.

d. There are differences observed in the dynamics of the states observed in PSCAD-only and hybrid simulations. These differences arise due to the interaction of the fast control methods in VSCs with the other portions of the ac transmission grid. These components are not adequately captured in the PSCAD-only simulation. One possible solution is to convert a very large buffer zone from the ac transmission grid model in PSS®E to PSCAD. However, this solution imposes a large computational burden. The other solution is to perform hybrid simulation for such studies.

Limitations have been identified in hybrid simulation and model conversion using E-Tran:

a. Machine parameter Xp = X'p is not allowed in PSCAD (PSS®E does not have a problem with those reactances being equal). This issue was fixed by making these reactances different for a few generators.
b. Some generator output set with excessive reactive power can cause initialization problems for some exciter's models in PSCAD.
c. E-Tran by default defines several measurement channels per generator, when converting from PSS®E to PSCAD. When the system model in PSS®E has many generators (e.g., the EI lumped model has 300 generators), the total number of channels becomes unmanageable by PSCAD. An efficient and automated method has been suggested to fix the problem by the PSCAD support team to remove all the channels.
d. E-Tran software was not initially set up to handle the full PSS®E WI-EI-HVdc macrogrid model with over 100,000 buses. Only full nodal EI model has been used in this work.
e. Zero resistance lines are converted into PSCAD as ideal lines. When some of these lines are in a loop configuration, the model presents problems when executing PSCAD simulations (this configuration has no problem in PSS®E).
f. Negative loads in PSS®E are converted into PSCAD as voltage sources. Voltage sources significantly modify the dynamic behavior of the system, distorting the frequency response. This problem is avoided by identifying and eliminating or replacing negative loads.
g. HVdc systems in PSS®E are not directly translated into PSCAD with E-Tran. Instead, E-Tran places an ideal voltage source at each substation terminal. E-Tran currently cannot represent CDC6T model. The user is expected to include HVdc models in PSCAD.

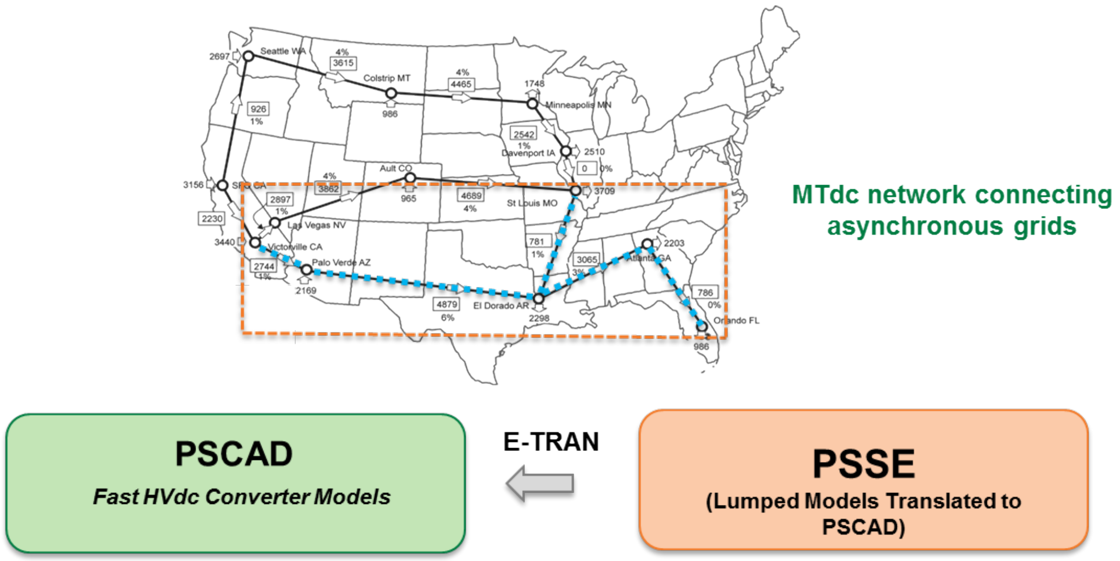


Figure Ex-9: Models of seven-terminal MTdc system and lumped ac transmission grid EMT dynamic models

3. Models and methods to evaluate the fast response that could be provided by MTdc systems were established. MTdc systems are one of the futuristic HVdc–ac transmission grid scenario. Six- and seven-terminal MTdc system EMT dynamic models were developed based on the high-fidelity EMT dynamic models of the VSC (like MMC utilized in this study). These models were applied on a portion of the HVdc macrogrid shown in Fig. Ex-9. The six-terminal MMC-based MTdc system connecting EI and WI grids is shown in Fig. Ex-9. The additional seventh terminal in the seven-terminal MMC-based MTdc system was considered in the ERCOT grid.

   The MTdc system can provide fast frequency support across multiple asynchronous interconnections based on the application of fast control methods in the VSCs (like MMCs in this study). The use of slower control methods in the HVdc macrogrid (or the MTdc system in this study) reduces the reduction in primary reserves. A comparison of the fast and slow control methods in HVdc systems is shown in Fig. Ex-10. The reduction in primary reserves is improved by 33% by the use of fast control methods, indicating the value of applying fast optimal control methods in MTdc systems. The faster control methods optimally exploit the capabilities of the HVdc hardware better than the conservative slower control methods. While the slower control methods can be studied on lower fidelity models, the fast control methods require high-fidelity models of the HVdc technologies (like the MTdc system in this study). The frequency support can also be provided through multiple points of injection in each interconnection, rather than only at the interconnection boundaries. This feature improves the reliability of the system with greater probability to share primary reserves across interconnections under various operating conditions. That is, in the event of the terminals at the interconnection boundaries being fully loaded, other terminals can provide means to share primary reserves.

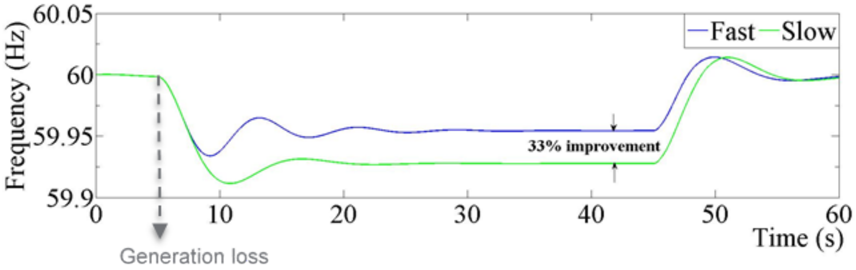
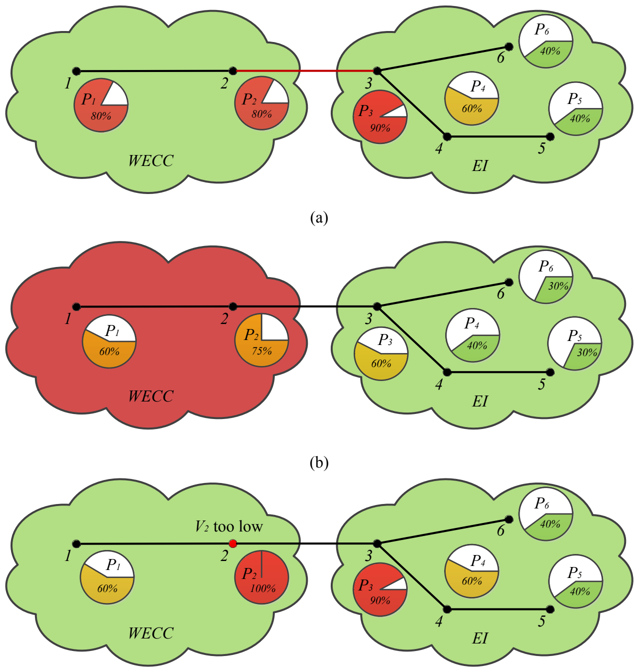


Figure Ex-10: Comparison of the frequency support provided by fast and slow control methods in HVdc systems.

The multi-objective optimal control method arises from the need to meet multiple objectives of high-efficiency operation and provision of fast frequency support across asynchronous interconnections. The constraints involved include the limits placed on dc-link voltage and power processed at each terminal. The conflicting multiple objectives and the constraints are summarized in Fig. Ex-11.



(a)

(b)

(c)

Figure Ex-11: Conceptual diagram of six-terminal MTdc system: (a) stress on line-23 is high; (b) frequency deviation is too high, not sufficient power provided; (c) voltage on terminal-2 is too low. Pie charts indicates the percentage of potential active power utilized in a converter. Red and black lines indicate the transmission line is over-loaded and within limits, respectively. Green and red clouds indicate that the frequency deviation is low and high, respectively. Red and black converter terminal dot indicate that dc-link voltage is out of bounds and within bounds, respectively.

One of the methods to evaluate the fast control methods in VSCs (and by extension in MTdc systems) is to perform EMT simulations of combined dynamic models presented below. This method is an alternative to the hybrid simulation of EMT dynamic models of VSCs and buffer zones, and TS models of rest of the ac transmission grids. Lumped ac transmission grid EMT dynamic models of EI, WI, and ERCOT grids were developed to represent the frequency dynamics of the grids. These models were used to evaluate the impact of multi-objective optimal control in MTdc systems. The optimal control provided fast frequency support at multiple points in an asynchronous grid. The lumped models were needed as the full nodal models of the grids cannot be simulated in EMT simulators (like PSCAD) due to the large size of the model and the time taken to simulate them. These models were developed based on conversion of models from PSS®E to PSCAD, as summarized in Fig. Ex-9. They can simulate up to 100x faster than the full nodal models of the grid. To incorporate the voltage behavior of the ac transmission grid at the MTdc terminals, combined dynamic model of the grid was developed. The combined dynamic model was developed based on incorporation of buffer zones at the MTdc terminals in to the lumped models. The buffer zones provided adequate representation of the dynamic voltage behavior of the local ac transmission grid.

The multi-objective optimal control in MTdc systems can provide up to 64% improvement in the frequency response, as shown in Fig. Ex-12. This method can be applied to other dc technologies.

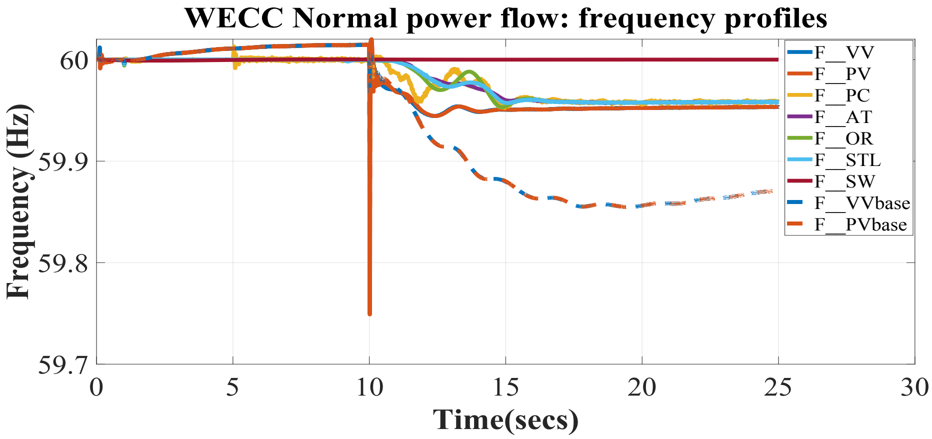
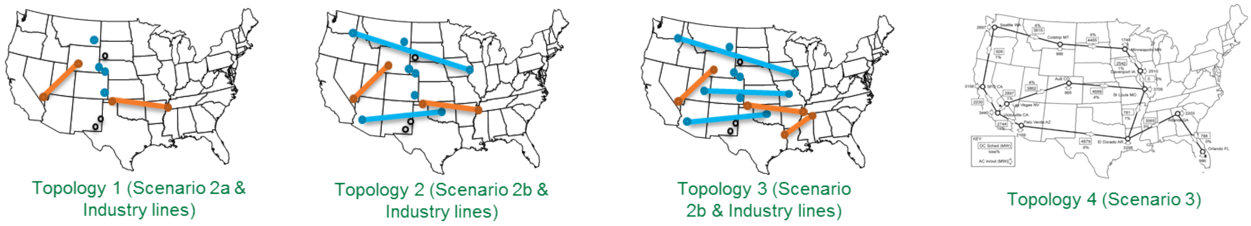


Figure Ex-12: Comparison of frequency response of the WI grid with and without the frequency support provided by the MTdc system. In the figure, F_VV and F_PV are the frequency measured at Victorville and Palo Verde from simulation of MTdc system with the ability to provide frequency support. Similarly, F_VVbase and F_PVbase are the corresponding frequencies measured without the frequency support being provided in the WI grid. The other frequencies are measured in the EI grid when providing frequency support to the WI grid through the MTdc system.

In future, expansion of the MTdc system to all the nodes of the HVdc macrogrid to create an MTdc macrogrid can be considered. The MTdc macrogrid can provide higher reliability due to the meshed architecture, as compared to the radial 7-terminal MTdc system in Fig. Ex-9. The MTdc macrogrid can also be evaluated to identify other value models like resilience and security through firewalling disturbances using the HVdc network. The same can be achieved through the ability of MTdc macrogrids to provide islanding capability, black-start, voltage support, and negative-sequence based control.


Topology 1 (Scenario 2a & Industry lines)

Topology 2 (Scenario 2b & Industry lines)

Topology 3 (Scenario 2b & Industry lines)

Topology 4 (Scenario 3)

Figure Ex-13: Summary of HVdc penetration scenarios evaluated.

4. Several HVdc penetration scenarios were evaluated and compared with the HVdc macrogrid for a scenario in 2025-26 with respect to the ability to provide congestion relief and frequency support. The various penetration scenarios studied provide an understanding of the benefits provided by the increased presence of dc lines in the system. The various penetration scenarios studied are shown in Fig. Ex-13. For topology 1 to be feasible in the 2025-26 scenario, significant ac transmission grid upgrades are required. And, topology 2 is an intermediate scenario to topology 3 with potential major reliability problems caused by the outage of one of the East-West HVdc lines. Hence, only topology 3 is studied in detail and compared with the HVdc macrogrid. The HVdc lines and terminals in topology 3 are sized to maintain similar power transfer capability between the East and the West of the HVdc macrogrid. Both the topology 3 and HVdc macrogrid are able to provide similar frequency support (or have similar capability to share primary reserves across EI and WI grids). The HVdc

macrogrid can provide better congestion relief due to the presence of a larger number of HVdc lines, as shown by the study in Fig. Ex-14.

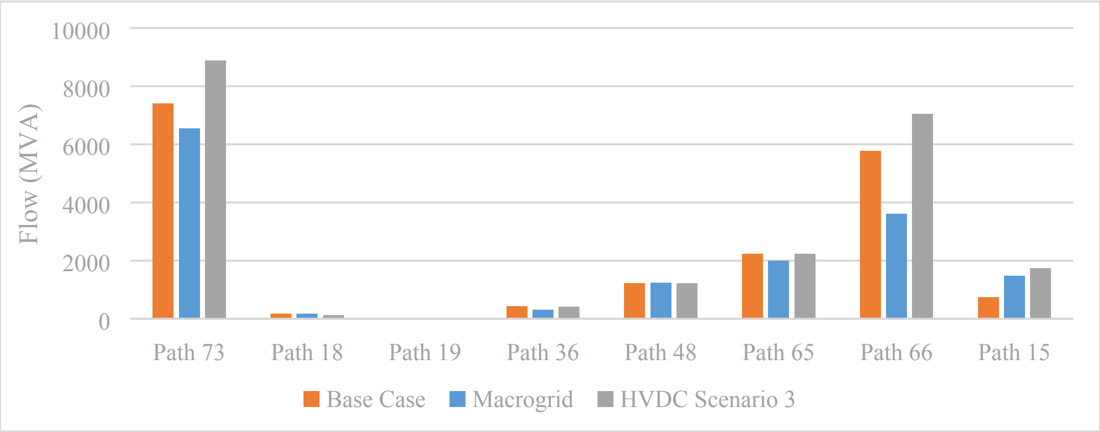


Figure Ex-14: Congestion relief provided by various HVdc configurations. Topology 3 and 4 are referred to as HVDC Scenario 3 and Macrogrid, respectively, in the figure.

Combined congestion management and frequency support is explored in both topology 3 and HVdc macrogrid. The combined method utilizes a combination of centralized and decentralized controller shown in Fig. Ex-15. The decentralized controller consists of the frequency controller that locally controls the lines crossing the interconnection borders during a frequency event. The centralized controller can perform fast rescheduling of all HVdc lines to reduce congestion after the decentralized controller completed its operation.

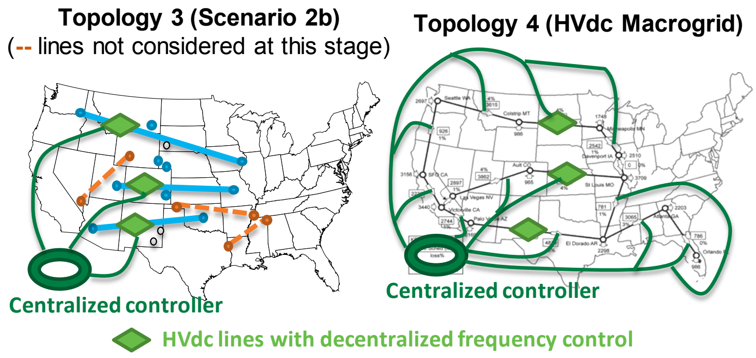
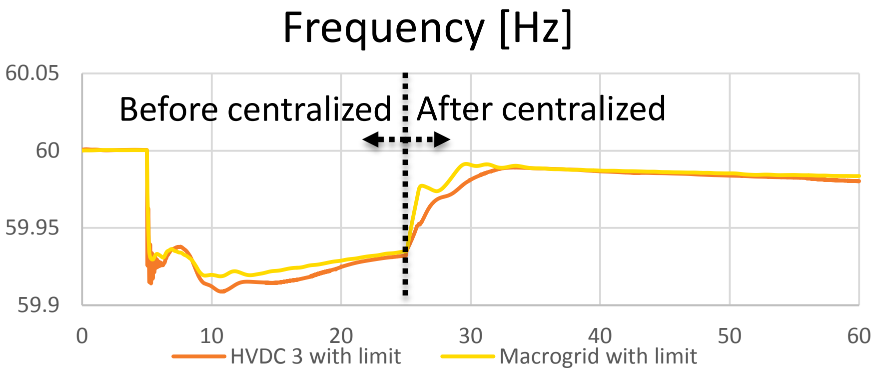
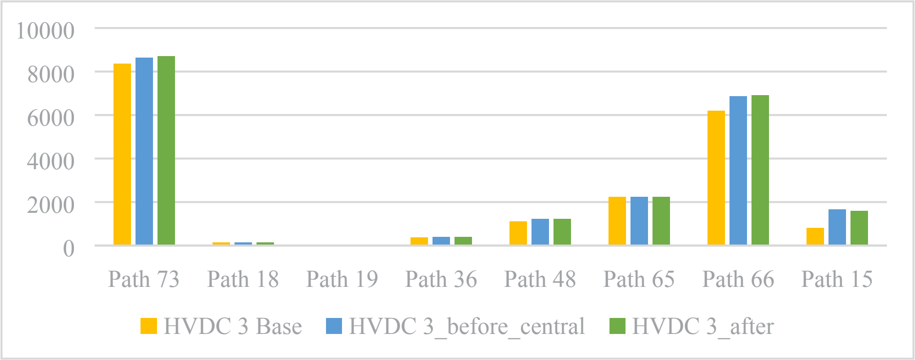


Figure Ex-15: Decentralized controller implemented in HVdc lines that cross the WI and EI borders and centralized controller providing schedules to all HVdc lines

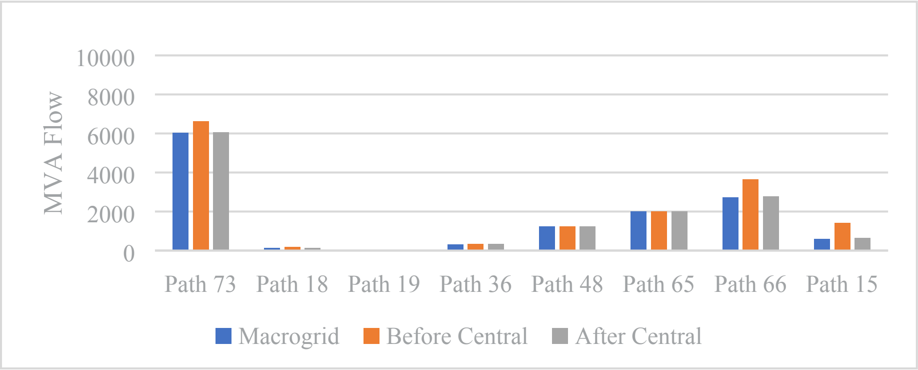
The combined congestion management and frequency response can further enhance the reliability of the existing grid. The corresponding results are shown in Fig. Ex-16. A comparison of the power “before central” and “after central” in the figures show that the combined control method reduces the stress on the lines while the power is exchanged between the East and West to provide frequency support. Topologies 3 and 4 provide similar frequency response benefit. Topology 4 provides greater congestion management through fast rescheduling of more HVdc lines across the full continental-level power grid.



(a)



(b)



(c)

Figure Ex-16: Results of combined frequency control and congestion management (a) Frequency of WI after generation contingency, (b) MVA flows in main WI paths for topology 3 scenario, (c) MVA flows in main WI paths for topology 4 (Macrogrid) scenario

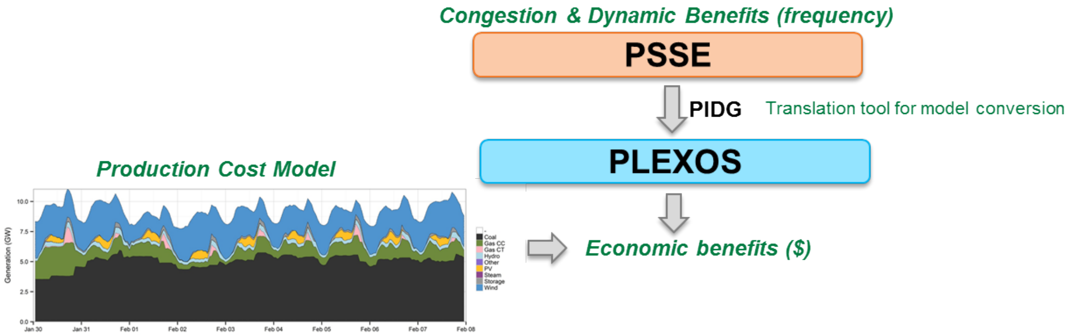


Figure Ex-17: Economic benefits evaluation from congestion relief and frequency support provided by HVdc macrogrid.

5. Updates in PIDG 2.0, the tool that enables model conversion from PSS®E to PLEXOS, resulted in 10x speed-up. The speed-up acts as an enabler to convert large systems from PSS®E to PLEXOS like the over 100,000 bus models of EI and WI grids. PLEXOS is a tool used to simulate production costs associated with operating the grids.
6. The impact of a HVdc national network and accompanying HVdc controls were evaluated in economic and operational context over a simulated year in PCM, as summarized in Fig. Ex-17. This study found potential impacts from the studied scenarios and sensitivities, such as improved resource usage efficiency, decreased production cost, changes to transmission congestion patterns, and decreased spinning reserve requirements. The value of providing fast frequency support has been evaluated through a sensitivity analysis on spinning reserve reduction with the results shown in Fig. Ex-18. Two spinning reserve reductions have been considered that has shown $105 million benefits annually with a 2 GW reduction and $241 million benefits annually with a 6 GW reduction. The former reduction can be obtained using the seven-terminal MTdc system studied and with the fast frequency support. The sensitivity analysis provides an understanding of the advantages of greater spinning reserve reduction using fast frequency support.

Impact & Challenges

The MMC models developed are being utilized by two Universities for research on MTdc systems. There are ongoing discussions with multiple industry partners on ways by which they can access the VSC and MTdc systems models and the various control methods developed in this work. Based on the work completed in hybrid simulation, suggestions have been provided to Electranix Corporation to improve the hybrid simulation tool.

The results from this work have been published in a journal and three conference papers. There are at least three more journal papers and two conference papers that are in press and/or submitted. The results disseminated will aid in utilizing the models and methods developed in this work.

The challenges faced in this project include identifying stable means of parallelization in simulation of power electronics and compatibility issues in use of tools across multiple domains. Some of the challenges associated with linking the tools have been identified like:

1. Compatibility of models in different tools like PSCAD, PSS®E, and PLEXOS;
2. Limitations with respect to the size of the models utilized in individual tools while translating to another tool or co-simulating the models while performing hybrid simulation.

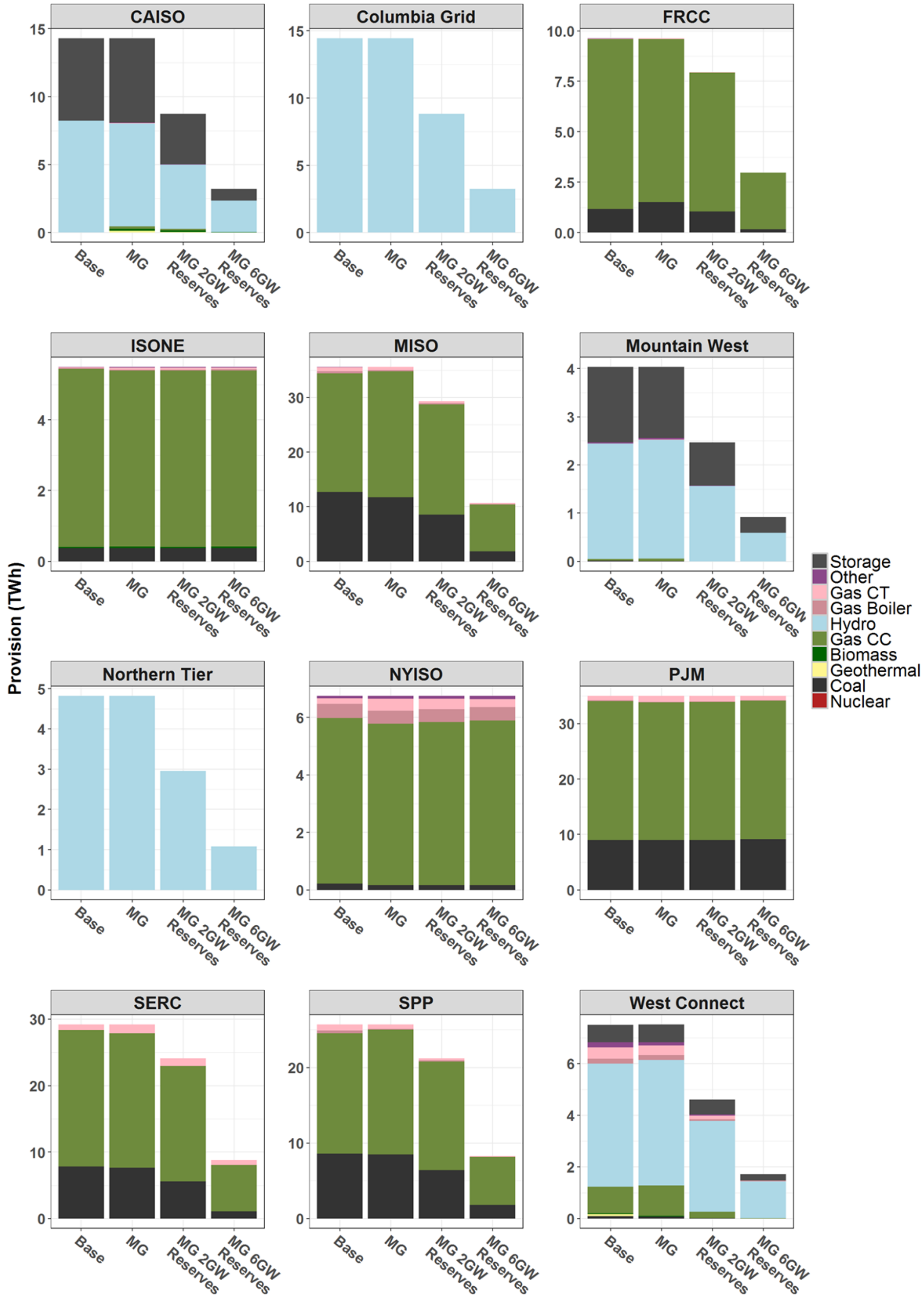


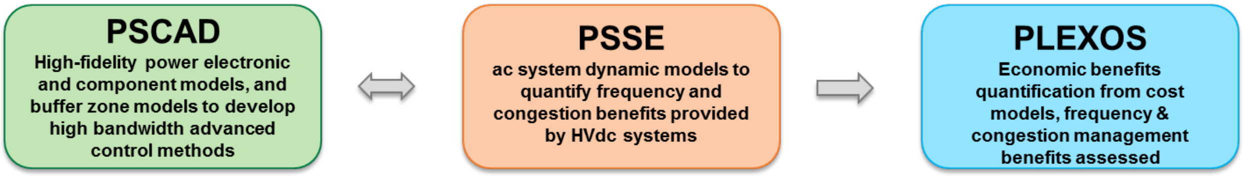
Figure Ex-18: Spinning reserves provisions by fuel type and technology across two scenarios and two sensitivities

Lessons Learned

Several HVdc penetration scenarios like a 7-terminal MTdc systems, VSC-LCC HVdc macrogrids, and point-to-point HVdc systems were studied in this work utilizing multiple tools (PSCAD, PSS®E, and PLEXOS). The requirement of high-fidelity models of these penetration scenarios to understand the stability and impact of advanced control methods like voltage and frequency control on ac transmission grid were identified. The models required included EMT switched system and hierarchical control system models of VSCs, distributed line model of transmission lines, EMT dynamic models of buffer zones in the region with VSCs, and TS model of ac transmission grids. The buffer zones are regions near the VSC-HVdc terminals. The EMT dynamic models of the buffer zones enable the understanding of the high-bandwidth dynamics associated with VSCs and the corresponding stability of such systems. The EMT dynamics models take a long time (or, more computational resources) to simulate, and there is a requirement for advanced simulation and modeling of components as has been performed with the EMT dynamic model of VSCs in this work. Future extensions of this work could include detailed EMT dynamic modeling and fast simulation of other components as well as buffer zones. It could also consider temporal parallelization that has been briefly studied in this project.

The tools required to quantify the impact of the advanced control methods on ac transmission grid include PSCAD, E-Tran, and PSS®E. While the EMT dynamic models were simulated in PSCAD, the TS dynamic models were simulated in PSS®E. The co-simulation between the EMT and TS dynamic models were enabled by E-Tran. The E-Tran tool also enabled model conversion from TS dynamic model to EMT dynamic model, which was useful to develop EMT models of buffer zones.

Economic benefits were quantified from the impact of the advanced control methods in MTdc system/ HVdc macrogrid on the ac transmission grid. The tools utilized for the same included PSS®E, PIDG 2.0, and PLEXOS.



PSCAD
High-fidelity power electronic and component models, and buffer zone models to develop high bandwidth advanced control methods

PSSE
ac system dynamic models to quantify frequency and congestion benefits provided by HVdc systems

PLEXOS
Economic benefits quantification from cost models, frequency & congestion management benefits assessed

Figure Ex-19: Tools and relationship to establish economic benefits from advanced control methods applied to large-scale HVdc-ac systems

The ability to utilize information across multiple tools have been successfully demonstrated in this work, with the capability to identify economic benefits associated with advanced control methods applied to power electronics. This is summarized in Fig. Ex-19. One of the successes included the capability to identify the impact of advanced control in power electronics on the underlying ac transmission grid. The other included the means to evaluate the economic benefits associated with such advanced control methods through the impact quantified in ac transmission grids. While the former was achieved through hybrid simulation using E-Tran, the latter was achieved using PIDG 2.0.

The feasibility of utilizing MTdc systems to provide fast frequency response at multiple points of injections have also been demonstrated in this project. The ability to provide combined congestion management and frequency response utilizing a higher penetration HVdc system (like the HVdc macrogrid) has also been demonstrated.

Future Work

Future extensions of this work could include the following:

1. Large-scale HVdc-ac system model that incorporates up to 15-terminal MTdc systems that will be needed in the MTdc macrogrid (or, higher as desired for other HVdc configurations) with vendor agnostic VSC configurations. These models would provide means to explore other applications of MTdc grids like transportation electrification, integration of renewables (solar, wind), and others.
2. Detailed EMT dynamic modeling and fast simulation of other components (like HVdc breakers, transmission lines) as well as buffer zones. This work could also explore the advanced dynamic load models required for this type of analysis. These modeling efforts would equip planners to incorporate dc technologies into future grids.
3. Parallel-in-time simulation algorithm application to EMT simulations and/or hybrid simulations. The algorithm can speed-up simulation and incorporate higher fidelity models that can be simulated in reasonable time-frame. The higher fidelity models provide means to evaluate value models that are not explorable with lower fidelity models like the fast frequency support demonstrated in this work.
4. Contingency analysis in MTdc-ac systems with fault identification mechanism and post-fault operation methods. This analysis would provide further insights in to the reliability of dc-ac systems from contingency studies in the dc systems, beyond the reliability aspects studied in the ac system in this work.
5. Hybrid simulation with large-scale HVdc-ac systems that incorporates advancements in hybrid simulation tools and simulation methods to enable and speed-up such simulations. Such simulations to study contingencies in HVdc and ac systems to understand reliability and resiliency. This analysis enhances the tools to study large-scale dc-ac systems, studies in the NERC-led IRPTF, and others.
6. Develop dynamic models for futuristic scenarios (like 2038 grid) that include high-penetration of inverter-based resources (like generation and loads).
7. Additional modeling and analysis on the HVdc controls is necessary to expand industry expertise in the indirect benefit of reduced reserve requirements due to frequency support provided by HVdc. Another opportunity is to investigate coordinated control of multiple dc lines, both existing and future facilities. These opportunities could be explored not only from the point of view of automatic dynamic control in short time scales, but also including coordinated scheduling in longer terms and HVdc interactions and their roles in real-time electricity markets.

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