



Modeling, Control, and Protection of Multi-Terminal DC Transmission for Improving Power Grid's Performance

Final Project Report

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Power Systems Engineering Research Center

*Empowering Minds to Engineer
the Future Electric Energy System*



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Project Team

Maryam Saeedifard, Project Leader
Georgia Institute of Technology

Jiangchao Qin
Arizona State University

Ali Mehrizi-Sani
Washington State University

Graduate Students

Jingfan Sun
Mahmoud MehrabanKhomartash
Georgia Institute of Technology

Yuntao Zou
Arizona State University

Armin Teymouri
Washington State University

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For information about this project, contact:

Maryam Saeedifard
Georgia Institute of Technology
777 Atlantic Dr.
Atlanta, GA 30308
Phone: 404-894-4834
Email: Maryam@ece.gatech.edu

Power Systems Engineering Research Center

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For additional information, contact:

Power Systems Engineering Research Center
Arizona State University
527 Engineering Research Center
Tempe, Arizona 85287-5706
Phone: 480-965-1643
Fax: 480-727-2052

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Executive Summary

High Voltage DC (HVDC) transmission is a long-standing technology with many installations around the world. Over the past few years, significant breakthroughs in the Voltage-Sourced Converter (VSC) technology along with their attractive features have made the HVDC technology even more promising in providing enhanced reliability and functionality and reducing cost and power losses. Concomitantly, significant changes in generation, transmission, and loads such as (i) integration and tapping renewable energy generation in remote areas, (ii) need for relocation or bypassing older conventional and/or nuclear power plants, (iii) increasing transmission capacity, and (iv) urbanization and the need to feed the large cities have emerged. These new trends have called for Multi-Terminal DC (MTDC) systems, which when embedded inside the AC grid, can enhance stability, reliability, and efficiency of the present power grid. Amid the optimism surrounding the MTDC grids, the following fundamental research questions must be addressed (i) what control strategies are required to operate the MTDC converter stations, (ii) how will the MTDC grid interact with its surrounding AC system and what kind of services (e.g., frequency support and power oscillation damping) can it provide, (iii) how can DC faults be detected, identified, and cleared. To this end, a multi-pronged research effort is proposed: (i) Development of suitable dynamic models of the MTDC systems, which can be efficiently solved together with the AC systems; (ii) Design of advanced control strategies enabling the MTDC systems to support the resulting hybrid AC/DC systems; and (iii) Development of strategies for DC fault detection, identification, and protection of MTDC systems.

Part I – 1. Backup Protection of Multi-Terminal HVDC Grids Based on Quickest Change Detection

Amid the optimism surrounding the benefits of MTDC grids, their protection against DC-side faults remains one of their major technical challenges. MTDC grid protection is far more difficult than AC grids as DC fault phenomenon is more complex. The protection philosophy of the MTDC grids, nevertheless, is similar to the AC counterparts in the sense that both primary and backup protection schemes are required. In case the primary protection fails to act properly, backup protection should trip as quickly as possible to minimize the loss of power in-feed. In this part, a new backup protection algorithm based on quickest change detection (QCD) method is proposed for MTDC grids. In backup protection settings, the signals from voltage measurements are observed by a decision maker, which monitors any abrupt change in the voltage distribution using sequential measurements. The objective is to detect the change as fast as possible subject to a constraint on the false alarm rate. With sequentially monitoring of signals, the QCD method proposed here is able to quickly trip the breakers under noisy signals with a negligible computation effort. The method is applicable to general N-terminal MTDC grids.

Part I – 2. Reducing the Fault Transient Magnitudes in Multi-terminal HVDC Grids by Sequential Tripping of Hybrid Circuit Breaker Modules

Proper protection of the MTDC grids necessitates the DC circuit breakers (CBs) to selectively and quickly isolate any faulty line without interrupting the entire system. Among the proposed DC CBs, the hybrid solid-state one is the most promising option as its breaking time is in the

order of a few milliseconds while its conduction losses during normal operation are quite low. To speed up the operation of hybrid DC CB and attenuate over-currents and over-voltages, a sequential switching strategy is proposed in this part. This switching strategy enables a step-by-step tripping of breaker modules even before the ultra-fast disconnect switch is fully opened. Based on the proposed approach, the fault is interrupted in an early stage by applying the voltage of the arrester banks within each breaker module in a progressive manner. This earlier interruption of fault reduces the rate of rise of fault current and, consequently, contributes to the attenuation of the overcurrent and overvoltage stresses as well as shorter fault clearance time. To verify the benefits of the proposed sequential switching strategy, performance metrics indicating the current and voltage stresses are quantified through a time-domain analytical modeling approach considering travelling waves on DC transmission lines. The transient performance of the sequential tripping mechanism is confirmed based on both simulation studies in the PSCAD/EMTDC software environment and quantitative analysis.

Part I – 3. Optimum Selection of Circuit Breaker Parameters based on Analytical Calculation of Overcurrent and Overvoltage in Multi-terminal HVDC Grids

Incorporating hybrid DC CBs into the MTDC grid adds another level of complexity as the DC short circuit current increases with commensurate increase in transient overvoltage stress, current limiting reactor and energy absorption capability of arresters. To determine the fault clearing capability and performance of these DC breakers, there is a need for (i) an accurate method to estimate the maximum overcurrent, transient overvoltage stress and energy absorption, and (ii) an optimal parameter selection method to size the CB components to achieve satisfactory performance. Once a quantitative estimation of maximum fault current, overvoltage, clearance time and energy absorption in arresters is obtained, optimum selection of the CB components can be attained. In this part, a time-domain approach is proposed to analytically calculate the transient response of the MTDC system during a DC fault by considering all the corresponding travelling waves. Based on the analysis, the fault behavior within the first few milliseconds is analytically modelled, and consequently, breaker parameters including operation delay, current limiting reactor and arrester can be optimally sized. In that regard, a multi-objective design optimization problem is formulated to explore the Pareto-optimal fronts of the transient response of the system versus the breaker parameters and to establish trade-offs among the breaker parameters and fault transient response. Finally, time-domain simulations in the PSCAD/EMTDC environment are performed to evaluate the accuracy and performance of the proposed method.

Part I – 4. Model Predictive Control-Based AC Line Overload Alleviation in Meshed AC/MTDC Grids

MTDC grids can support the future AC grid by improving its frequency response of the AC grid, inter-area oscillation damping, and reducing the operational cost of the electricity grid. In addition to the aforementioned functions, a MTDC grid can play a major role in AC line overload alleviation. The contribution of this part is a Model Predictive Control (MPC)-based strategy, which uses MTDC converter stations along with the AC grid generators for transmission line overload alleviation. The objective is to reduce active powers of the overloaded AC lines by deploying the MTDC converters and AC generators. The advantage of the proposed

controller is to simultaneously use the MTDC converter stations and AC system generators to relieve the overloads of AC lines. The proposed controller is integrated with the conventional Automatic Generation Control (AGC), thereby following a contingency, the system regulates frequency and mitigates AC line overloads, simultaneously. The controller receives the measurements within regular sampling time periods. When an outage imposes overloads on AC lines, the controller computes and dispatches the optimum setpoints of the active powers of the MTDC converters and the AC grid generators within each sampling time period. The optimum setpoints are computed by a MPC strategy to bring the active powers of the overloaded AC lines below their limits. To implement the MPC strategy, the sensitivity matrices relating the AC line active powers, DC line currents and DC bus voltages to the converters' active power setpoints and the generator active powers are calculated. Furthermore, all the operational constraints including constraints of the DC bus voltages, the DC line currents, the ratings of the MTDC converter stations, AC bus voltages, and the ramp rates are meticulously considered. The proposed controller constantly checks a voltage stability criterion to ensure that it does not push the system towards the voltage instability boundaries. The performance of the proposed controller is evaluated and demonstrated using time-domain simulation studies on two test systems, i.e., the 39-bus New England test system integrated with a 5-bus MTDC grid and the IEEE 118-bus test system integrated with a 6-bus MTDC grid.

Part II: A Hybrid Nonlinear Droop Control for MTDC Systems with Improved Dynamic Performance and Stability

Droop control is extensively applied to MTDC systems. However, in the case of large active power disturbance, the constant derivative of the linear droop curve leads to large voltage deviation and longtime regulation. In this part, a hybrid droop control is proposed with a cubic accelerated term and reference self-correction algorithm for voltage source converter-based MTDC systems. The proposed method can improve performance of the MTDC systems during transient and steady-state operations. The cubic accelerated term can provide fast regulation speed and low voltage deviation during transient due to the proposed nonlinear droop curve. The reference self-correction algorithm is developed to move the curve to the new operating point for eliminating voltage deviation and maintaining the constant dynamic performance. In the steady state, the proposed droop curve is approximated to a linear one by neglecting the cubic accelerated term due to its much smaller value. Therefore, the negative influences of the conventional nonlinear droop curve on regulation speed, voltage deviation, and power oscillation can be avoided. The simulation results of a four-terminal system in the PSCAD/EMTDC software environment demonstrate the effectiveness of the proposed droop control.

Part III: Feedforward Accurate Power Sharing and Voltage Control for Multi-Terminal HVDC Grids

This part presents a power sharing and voltage control scheme for MTDC grids. A generalized hierarchical droop-based controller is designed to control the DC-side voltages and dispatched powers. To improve the steady-state performance of the MTDC grid, this project proposes a feedforward mechanism to make the current controller of the voltage-sourced converters independent of the AC-side load conditions. The performance of the proposed scheme is evaluated under several case studies. A comparison between the proposed controller and

traditional controllers is also made with time-domain simulation studies in PSCAD/EMTDC software. Results show that the proposed controller can successfully control the real powers and DC voltages while having a stable performance during AC-side load changes.

Project Publications:

- [1] Y. Song, J. Sun, M. Saeedifard, S. Ji, L. Zhu, A.P. Meliopoulos, and L. Graber, "Optimum Selection of Circuit Breaker Parameters based on Analytical Calculation of Overcurrent and Overvoltage in Multiterminal HVDC Grids," *IEEE Trans. on Industrial Electronics*. Accepted.
- [2] M. Mehraban, M. Saeedifard, and S. Grijalva, "Model Predictive Control-Based Thermal Overload Alleviation in Meshed AC/MTDC Grids," *IEEE Trans. on Power Systems*. Accepted.
- [3] Y. Song, J. Sun, M. Saeedifard, S. Ji, L. Zhu, A.P. Meliopoulos, and L. Graber, "Reducing the Fault Transient Magnitudes in Multi-terminal HVDC Grids by Sequential Tripping of Hybrid Circuit Breaker Modules," *IEEE Trans. on Industrial Electronics*, vol. 66, no. 9, pp. 7290-7299, 2019.
- [4] J. Sun, M. Saeedifard, and A.P. Meliopoulos, "Backup Protection of Multi-terminal HVDC Grids Based on Quickest Change Detection," *IEEE Trans. on Power Delivery*, vol. 34, no. 1, pp.177-187, 2019.
- [5] J. Sun, M. Saeedifard, and AP. Meliopoulos, "Sequential Tripping of Hybrid DC Circuit Breakers to Enhance the Fault Interruption Capability in Multi-Terminal DC Grids," CIGRE US National Committee 2018 Grid of the Future Symposium, October 2018.
- [6] M. Mehrabankhomartash and M. Saeedifard, "The Impact of Multi-Terminal DC Grids on AC Line Overload Alleviation: A Model Predictive Approach," IEEE Energy Conversion Conference and Exposition, 2019.
- [7] Y. Zou and J. Qin, "A Hybrid Nonlinear Droop Control for MTDC Systems with Improved Dynamic Performance and Stability," *IEEE Trans.*, in preparation.

Student Theses:

- [1] Jingfan Sun, Protection of Multi-Terminal HVDC Grids, Ph.D, Georgia Institute of Technology, May 2020 (expected).
- [2] Mahmoud MehrabanKhomartash, Control and Coordination of Multi-Terminal HVDC Grids, Georgia Institute of Technology, May 2021 (expected).
- [3] Yuntao Zou. Control and Stability of MTDC Systems and DC Grids. Ph.D. dissertation, Arizona State University, May 2021(expected).