New York State Wide-Area Protection Study

Final Report

Prepared for:

New York State Energy Research and Development Authority

Albany, New York State

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Notice

Abstract

This is the final report of the New York State Wide-Area Protection Study, also known as Phase 2 of the Major Disturbance Mitigation Study (MDMS2), research project. Through extensive dynamic simulations of the New York power system integrated with large amount of inverter-based renewable resources, MDMS2 has further developed the PMU measurements based mitigation algorithm to prevent and contain possible spread of major system disturbances. Key results and accomplishments are documented in this final report as follows: Section 1 provides an overview of the project and the project tasks. Section 2 summarizes the key results from prior works. Section 3 presents New York power system dynamic stability behaviors. Section 4 describes the components of the Angular Instability Mitigation Scheme (AIMS) which include improved instability prediction and mitigation algorithm and a new system disturbance allocation and severity estimation method. Section 5 presents the evaluation of various mitigation measures in addition to Controlled System Separation and UFLS. Section 6 summarizes the test results of the AIMS via power system dynamic simulations. Section 7 discusses practical considerations in implementing the AIMS. Section 8 summarizes the MDMS2 achievements, observations and conclusions, together with further research and development areas that are deemed necessary.

Keywords

Wide-area protection and control, inverter-based resources, power system stability, dynamic simulation, Synchro-phasor technology, PMU measurements, instability detection and prediction, system voltage and reactive power control, major disturbance mitigation, Controlled Systems Separation, Under Frequency Load Shedding.

Acknowledgments

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- New York State Reliability Council (NYSRC)
- New York State Energy Research and Development Authority (NYSERDA)
- New York Independent System Operator (NYISO)
- Central Hudson Gas & Electric
- Consolidated Edison
- National Grid
- New York Power Authority
- New York State Electric & Gas Corporation
- Orange & Rockland Utilities
- Public Service Enterprise Group – Long Island
- Rochester Gas and Electric Corporation

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Acronyms and Abbreviations

AIMS	Angular Instability Mitigation Scheme
CEII	Critical Energy Infrastructure Information
CSS	Controlled System Separation
CWAPCS	Centralized WAPCS (see WAPCS)
EI	Eastern Interconnection
HVDC	High Voltage Direct Current
IBR	Inverter-based Resource
ISO	Independent System Operator
MDMS	Major Disturbance Mitigation Study
MDMS1	Phase 1 of Major Disturbance Mitigation Study
MDMS2	Phase 2 of Major Disturbance Mitigation Study
NEI	Northeastern Interconnection
NPCC	Northeast Power Coordinating Council
NYCA	New York Control Area
NYISO	New York Independent System Operator
NYSERDA	New York State Energy Research and Development Authority
NYSRC	New York State Reliability Council
NYTOs	New York Transmission Owners
PJM	Pennsylvania/New Jersey/Maryland
PMU	Phasor Measurement Unit
UFLS	Underfrequency Load Shedding
WAPCS	Wide-Area Protection and Control System

Executive Summary

The New York State Energy Research & Development Authority (NYSERDA) "New York State Wide-Area Protection Study" research project (a.k.a. MDMS2) is Phase 2 of the previous NYSERDA "Major Disturbance Mitigation Study" (MDMS). The objective of the MDMS2 project is to expand on the previous work and to develop new and improved mitigation measures that are feasible for near-term field implementation.

The study included a thorough power grid dynamic-simulation analysis of the 2022 electric system with 20% of the New York electric load served by inverter technology based renewable resources. The dynamic analysis included determining the reliability impact and the behavior of inverter-based renewable resources (utility-scale and distributed energy resources) under selected contingency conditions.

The improved instability prediction algorithm through MDMS2 allows continuous prediction of individual bus voltage angles from synchrophasor measurements made available by the Phasor Measurement Units (PMUs) installed in the New York power grid, as well as in the neighboring systems. The combination of angle and magnitude of voltage synchrophasor measurements enables an angular instability mitigation scheme to estimate system disturbance location and severity for selecting the proper actions needed to mitigate the situation when an instability is predicted by the improved instability prediction algorithm.

The study included expanding the mitigation measures from using only controlled system separation, which was explored under the previous MDMS project, to additional measures including generation tripping, HVDC output modulation and/or controlled load shedding after system separation, and preventive real and reactive power dispatch in the face of high-level penetration of the renewable technologies in the grid.

The MDMS2 also explored the operability of a smaller synchronous electric interconnection – the Northeast Interconnection island encompassing the New York State, New England, and Ontario. The goal is to test the island performance when it is isolated from major disturbances originating outside of the island.

The project included development of a generalized, wide-area protection system concept with proof-of-concept testing being performed via closed-loop dynamic simulations. The concept calls for coordination between the mitigation action based on the PMU measurements and other system protection devices. Additionally, full redundancy of such mitigation systems was explored, and an architecture has been developed with an eye toward highly reliable operation in the presence of any single-point failures.

Section 1 in this non-CEII version of the report provides an overview of and the tasks performed in the MDMS2 project, and the organization of the CEII version of the report. A detailed summary of findings and results is provided in Section 8 in this non-CEII version of the report. The other chapters can be found in the CEII version of the report.

1 Introduction

This document is the final report of the New York State Wide-Area Protection Study project, also known as MDMS2, the Phase 2 of the Major Disturbance Mitigation Study project. This chapter provides an overview of the project and the project tasks, and the organization of the report.

1.1 MDMS2 Project Overview

Since the 2003 northeastern U.S. (“Northeast”) blackout, various entities in New York State and the Northeast Power Coordinating Council (NPCC) have been conducting research to investigate concepts and methods that can help prevent, contain, and recover from such events. These include the “August 14, 2003 Northeast Blackout Study” by NPCC, the “Controlled System Separation Feasibility Study” by New York Independent System Operator (NYISO), and Phase 1 of the “Major Disturbance Mitigation Study” by NYSERDA.

The objective of the MDMS2 project is to expand on the work of previous studies and to develop new and improved mitigation measures that are feasible for near-term field implementation. This project evaluated the impact of a large number of inverter-based renewables on the system response under major disturbances. This project also evaluated the feasibility of implementing a Wide-Area Protection and Control System (WAPCS) in New York State. The WAPCS leverages the Phasor Measurement Units (PMUs) already deployed in The State to enhance the reliability and resiliency of the New York electric power system during major disturbances.

This project has focused on the following research items:

1. Addition of inverter-based resources (IBRs) to dynamic power system models for evaluating IBRs’ impact on system reliability.
2. Development of dynamic simulation cases to assess the system stability under selected major disturbances.
3. Analysis of the New York Control Area (NYCA) power system’s dynamic responses to such disturbances.
4. Development and improvement of instability detection algorithms based primarily on PMU measurement data.
5. Evaluation of other mitigation measures for containing the impact of the major disturbances in addition to the controlled system separation (CSS) plus underfrequency load shedding (UFLS).
6. Verification of the effectiveness and feasibility of the developed algorithms and the candidate mitigation measures through closed-loop testing.

1.2 MDMS2 Project Tasks

To achieve the objective of the project, the following tasks were performed on the six research items described above.

1.2.1 Task 1 – Develop Technology Transfer Plan

A technology transfer plan was developed at the onset of the project that included the plans to communicate the project results to interested parties in The State, neighboring control areas, and throughout the U.S.

1.2.2 Task 2 – Review Prior Work and Develop Simulation Cases

Task 2 was performed under two subtasks 2.1 and 2.2.

In Subtask 2.1, Quanta Technology reviewed relevant prior works leading up to this project and summarized the key results from these works and the review observations / comments in a report. The main prior works reviewed included (1) the 2003 Northeast Blackout Study reports by U.S.-Canada Power System Outage Task Force and NYISO; (2) "August 14, 2003 Northeast Blackout Study – Task 5" by NPCC; (3) "Controlled System Separation Feasibility Study" by NYISO; and (4) "Major Disturbance Mitigation Study" by NYSERDA. The study cases and the results of the Major Disturbance Mitigation Study project were also reviewed and assessed as part of this prior work review subtask.

In Subtask 2.2, the following were performed as planned:

1. Reviewed and modified the 2022 base cases received from NYISO
2. Selected a list of major disturbances/contingencies to be investigated in this project
3. Modified original base case to create stressed base cases for selected contingencies and to evaluate the system response under the selected contingencies
4. Added IBRs to stressed base cases to evaluate the system response under the selected contingencies with high level of IBRs
5. Modified a stressed base case with added IBRs to become Northeastern Interconnection (NEI) study case and to evaluate the system response to the selected major disturbances for the NEI system topology
6. Documented the cases created and the analysis results of the simulated contingencies

1.2.3 Task 3 – Develop Instability Detection Algorithm and Mitigation Measures

The Task 3 was performed under two subtasks 3.1 and 3.2.

In Subtask 3.1, the phase angle difference prediction algorithm investigated and tested in MDMS project conceptually was modified and improved for practical implementation and a new contingency location and severity estimation method was developed.

In Subtask 3.2, mitigation measures in additional to the controlled system separation (CSS) were investigated. The additional mitigation measures investigated include generator tripping, post-CSS immediate load shedding instead of UFLS, post-CSS HVDC modulation, and voltage/reactive power control as part of any overall mitigation measures.

The results of subtasks 3.1 and 3.2 were combined to develop an Angular Instability Mitigation Scheme (AIMS) for practical implementation.

1.2.4 Task 4 – Testing of Mitigation Measures

In Task 4, the AIMS was implemented and tested to demonstrate its viability for practical implementation, and the implementation considerations, such as the dependability verses security, speed verses selectivity, and the feasibility of using local out-of-step detection to safeguard the AIMS, were also discussed.

1.2.5 Task 5 – Technology Transfer

Following up with the technology transfer plan developed in the Task 1, a working group consisting of NYSERDA, NYSRC, NYISO, and all NYS TOs was formed at the beginning of the project. Regular conference calls and several face-to-face meetings were conducted to communicate the results of the project to all NYS stakeholders.

In addition, Quanta Technology has made presentation of the overall project results to neighboring ISOs (i.e. PJM and ISO-NE), and will publish 1-2 papers to communicate the results that is non-CEII to broader interested parties as was planned.

1.2.6 Task 6 – Final Written Documentation

This final written document is the final deliverable of the project prepared through the Task 6 to provide the information about this project and document the results and overall conclusions and recommendations of the project.

1.3 Organization of The Final Written Document

The final written document of the New York State Wide-Area Protection Study project is organized as follows:

- Section 1 (This section): Is an introduction to the background, objective, focused research items, and the tasks of the project, as well as the overall organization of this document.
- Section 2: Summarizes the results of the prior work reports reviewed by Quanta Technology.
- Section 3: Documents the results of simulation cases developed in Subtask 2.2.
- Section 4: Documents the results of the improvements made to the MDMS angular instability prediction algorithm, the development of a contingency location and severity estimation method, and the development of an angular instability mitigation scheme concept.
- Section 5: Documents the mitigation measures in addition to the CSS investigated that included generator tripping, post-CSS immediate load shedding, post-CSS HVDC modulation, and voltage/reactive power control.
- Section 6: Documents the testing results of the AIMS implemented in Python scripts and tested in a closed-loop testing setup with PSS/E.
- Section 7: Discusses the practical considerations to implement the AIMS in a wide-area protection and control system.
- Section 8: Provides an overall conclusions and recommendations of the project.

2 Prior Work Review

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3 Study Cases and Simulation Results

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4 Instability Detection Algorithms Development

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5 Mitigation Measure Investigation

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6 Angular Instability Mitigation Scheme Testing

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7 Practical WAPCS Implementation Considerations

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8 Overall Conclusions and Recommendations

The MDMS2 research project provided a forum for the NYTOs, NYISO, NYSERDA, and NYSRC to participate in monthly conference calls and four face-to-face meetings to discuss technology advancement and its impacts on the NYCA systems. These in-depth discussions, together with task reports, not only confirmed the merit of CSS concept but also explored and expanded the concept into several new areas. Major observations and conclusions include the following:

1. The stability simulations based on the developed four stressed cases with high-level IBR penetration, representing 20% of the NYCA load supplied by the renewables, have demonstrated that the NYCA system as-is can operate with the presence of this moderate level of renewable penetration.
2. The simulation results, however, have revealed that system frequency and voltage performances and even system stability will be closely coupled as the IBR penetration levels increases. With high IBR presence, IBR tripping during system disturbances due to momentary extreme voltage swings instantaneously introduce unbalances between generation and load, resulting in extra frequency variations and potential instability. It is paramount that distributed energy resources (DER) protection and control performance be accurately modeled in all future dynamic analyses.
3. Generator tripping, if done properly, can be an effective mitigation measure on its own without the need of any load shedding. And while previous studies found generator tripping has some potential, the studies performed in MDMS2 have further revealed some critical aspects to making generator tripping an effective mitigation measure. These aspects include the following:
   - Generator tripping should be applied only to situations wherein a confined area running away from the rest of the system contains only a small group of generators.
   - Tripping all generators in an area that is running away from the rest of the system should be avoided, as it may cause major voltage issues for the area (and the surrounding areas) after the generator tripping.
   - Generators should be tripped in the order of the generators' angle acceleration speed to ensure that the generators running away the fastest will be tripped first. When generator tripping alone is able to stabilize the system, load shedding will not be needed.
4. Using the capacity/inertia ratio to dynamically select generators for generator tripping shows promise. Determining the best generators to trip is one of the critical aspects when using generator tripping as a mitigation measure. However, this approach generally requires the rotor angles at all generators be synchronously measured. When such measurements are not available, the study process essentially becomes one of "trial and error" – making it difficult to determine which generators to trip for each anticipated contingency situation. However, MDMS2 has shown that there is a close correlation between the generator capacity/inertia ratio and the angle acceleration speed under the studied contingency conditions. The higher the ratio, the faster a generator will accelerate. While further study is needed, the use of this ratio (in the absence of direct generator rotor-angle measurements) shows great promise in determining the best generators to trip.

5. HVDC modulation can be an effective post-CSS mitigation measure to reduce the amount of load being shed. Boosting the imported power into the load shedding area helps reduce the amount of load being shed (an amount approximately equal to the boosted HVDC imported power).
6. Post-CSS immediate load shedding is more advantageous than UFLS. Immediate post-CSS load shedding helps recover the system frequency much faster by avoiding large frequency excursions associated with UFLS (in addition to reducing the amount of load being shed compared to UFLS).
7. Voltage and reactive power control should be an integral part of any mitigation measures. Abnormal voltage conditions – whether occurring after the contingency and/or after certain mitigation actions such as CSS and generator tripping are taken – can lead to IBRs tripping once their voltage ride-through capability has been exceeded. Other types of generators can also trip off-line under such abnormal voltage conditions by their respective protections. Maintaining proper voltage levels through voltage and reactive power controls after a contingency and/or after a CSS action can avoid the loss of generation resources, which in turn will prevent additional load from being shed to balance the generation losses from the tripping. Thus, voltage and reactive power control is as important as the mitigation measures for balancing demand and supply of the active power.
8. Improved the MDMS1 algorithm in a number of areas for practical implementation:
    - Replaced the error-prone three-point Taylor Expansion predictor with a new predictor mimicking a second-order mechanical system.
    - Made less prone to sudden changes in angle value predications with signal switching.
    - Applied to individual phase angle instead of phase angle difference, which provides important information regarding individual bus angle movement during and after a contingency. Predicted phase angle differences are derived using differences between filtered and predicted individual phase angles as opposed to differencing the phase angles first then filtering and predicting the differences.
    - Used multiple PMUs to increase the resiliency of the algorithm in the case of occasional loss of PMU measurements.
9. The Contingency Location and Severity Estimation (CL&SE) method is a critical part of any mitigation scheme. The CL&SE method uses the voltage magnitude measurements from PMUs to identify the bus with the lowest voltage magnitude (i.e., the estimated location for a fault-related contingency) and the duration of a contingency (i.e., the estimated contingency severity). The CL&SE method is critical for selecting the phase-angle monitoring locations for the MDMS2 algorithm and the mitigation actions appropriate to the contingency at the estimated location with the estimated severity.

The angular instability mitigation scheme (AIMS) is one major step forward towards a practical implementation – AIMS is based on the MDMS2 algorithm and the CL&SE method. AIMS has been implemented in Python and successfully tested using the same PSS/E + Python closed-loop test setup as in MDMS1 to confirm its performance. Practical aspects (e.g., dependability & security and selectivity & speed) in implementing AIMS in a New York state-wide Centralized WAPCS (CWAPCS) was considered and discussed. The concept of using local line Out-of-Step (OOS) relays to safeguard the CSS control actions (as proposed in MDMS1) was evaluated. The evaluation concluded that this approach may cause some lines of an interface selected for CSS to be blocked from tripping, as the local OOS relay may not "see" the OOS condition on those lines.

Aside from the major discoveries above, the MDMS2 project has made several achievements that would provide direction for (and enable) further investigation into the design and control of the NYCA systems. Specifically, the MDMS2 has:

- <u>Successfully created new 2022 study cases with a high amount of IBR modeled and dispatched:</u> Using the base case received, and after identifying and resolving a few issues, the following study cases were created:
    - Study cases for Eastern Interconnection (EI) topology: Adjusted the dispatch of the base case to 1) stress the interfaces near each selected extreme contingency location to create stressed 2022 study cases without added IBRs, and then 2) dispatch the added IBRs to create new stressed 2022 study cases with added IBRs.
    - Study cases for the Northeastern Interconnection (NEI) topology: One of the above "stressed" study cases was successfully modified to create study cases for operating the NPCC region as a separated small interconnection (i.e., NEI) – a concept of break-before-external-event to avoid NPCC region from being impacted by future major disturbances coming from rest of the EI (as was the case in 2003 blackout). These cases are used to validate the viability of this concept.
- <u>Modeled a high level of IBRs penetration in the stressed NYCA system:</u> Utility-scale wind and solar IBRs were added to the study cases based on the NYISO project queue, and behind-the-meter solar IBRs were added based on the NYISO 2018 Load & Capacity Data Report (Gold Book) projections. The IBRs are dispatched at 80% of the installed capacity that serves approximately 20% of the NYCA load in these cases. In these study cases, all utility scale IBRs were modeled with voltage and frequency ride-through capabilities according to the NERC[1] PRC-024-2 standard, and behind-the-meter IBRs were modeled with voltage and frequency ride-through capabilities according to the IEEE 1547 standard.

All of these cases were used to obtain the following results:

- When NYCA is operating in the EI topology, the following results are obtained:
    - <u>The IBRs show mixed impact during the selected extreme contingencies</u>: IBRs were found tripping near the contingency locations during the extreme contingencies when abnormal voltage and frequency conditions existed longer than IBRs' ride-through capability. The

[1] North American Electric Reliability Corporation

system's dynamic response to selected extreme contingencies have shown that there are some differences with a high level of IBRs dispatched (e.g., IBR tripping during the contingency may have slowed down the acceleration of the nearby generators) when the contingencies cause IBRs to trip, but the general outcomes (i.e., whether the system will remain stable or become unstable) are similar between cases with or without a high level of dispatched IBRs.

  - IBRs will trip for prolonged, abnormal, post-contingency/post-mitigation voltage conditions: If abnormal voltage conditions persist after the contingency has ended, or mitigation actions have been taken, IBRs will trip when their voltage ride-through capability has been exceeded. Such tripping could further worsen the condition for areas where load shedding is needed, as more load will need to be shed to balance the demand and supply. In this case, the voltage problem has led to frequency control issues through the IBR tripping for voltage problems.

- When NYCA is operating in the smaller NEI, the following results are obtained:
  - The NEI could be a viable concept: The studies in MDMS2 have shown that the NPCC region could be operated as a smaller interconnection (i.e., NEI) by disconnecting all AC-line interties to the region but keeping all existing HVDC connections without adding any new HVDC connections. The NEI as simulated was able to withstand several selected normal and extreme contingencies without losing the stability, except for one extreme contingency that was stable in the EI case but became unstable in the NEI case. This shows that, while the concept could be viable, the ability of the NEI to withstand the same contingency may have been weakened, and the limits of all interfaces and the system dispatching would need to be adjusted as a result.
  - Adding more HVDC connections may help to strengthen the NEI: HVDC modulation to boost the import when there is a loss-of-source contingency in NEI has been shown to reduce the frequency drop of the NEI. It can be inferred that the NEI could be strengthened by adding more HVDC connections at the appropriate locations.

- With the NYCA system continuing evolution into a carbon-neutral future, the following areas are recommended for further researches:
  - Reliability assessment of a carbon-neutral NYCA system: The State is working towards a carbon-neutral electric energy supply by 2040. Many states within the EI control area have also set very aggressive targets for reducing the carbon footprint. Extensive reliability assessment studies for the future NYCA grid are needed in anticipation of such major changes. More accurate IBR models than what currently exist for DER are critical for testing resiliency, identifying needs, and informing reliability rules for the NYCA systems.
  - Pilot implementation and testing of AIMS: While useful for conceptual development, a Python + PSS/E closed-loop test setup is not a real-time implementation and testing environment. Before deploying AIMS in a New York state-wide CWAPCS, AIMS needs to be implemented in a pilot implementation on a real-time platform or controller and be tested in a real-time, hardware-in-the-loop test setup using real-time digital simulators.
  - Building study cases for proper coordination studies: One important aspect in deploying instability mitigation schemes is to ensure the actions taken by the mitigation schemes are

coordinated with other system protections. New study cases need to be developed to include the generator and transmission line protection systems for performing such coordination studies.

Appendix A: References

The following reports were reviewed by Quanta Technology in Task 2 of this project:

1. Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations, April 2004, U.S.-Canada Power System Outage Task Force
2. Blackout August 14, 2003 Final Report, February 2005, NYISO
3. August 14, 2003 Northeast Blackout Study – Task 5, November 2011, NPCC
4. Controlled System Separation Feasibility Study Final Report, December 2012, NYISO
5. Major Disturbance Mitigation Study – Milestone 2 Final Report, March 2017, NYSERDA

Appendix B: Modifications Made to the Base Case

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Appendix C: Geographic Location of the Renewables

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Appendix D: List of Contingencies Simulated

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Appendix E: Detailed Results Under Stressed Base Cases

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Appendix F: Detailed Results Under Stressed Base Cases with Added IBRs

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Appendix G: Detailed Results for Northeast Interconnection (NEI) Cases

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Appendix H: Bus Name Mapping

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Appendix I: MDMS1 Test Cases and Python Scripts Assessment

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