Major Disturbance Mitigation Study – Milestone 2

Final Report Summary

Prepared for:

New York State Energy Research and Development Authority

(NYSERDA)

Albany, NY

Prepared by:

EnerNex LLC

Sarina Adhikari, Ph.D.   Aaron F. Snyder, Ph.D.

David Mueller, P.E.

Director

Robert Zavadil, P.E.

Executive Vice President

Date: April 17, 2017

EnerNex

Notice

Abstract

This is the final report of the Major Disturbance Mitigation Study (MDMS) project. The major outcomes from the Major Disturbance Mitigation Study (MDMS) are summarized in the Executive Summary section. Chapter 1 provides a brief description of all of the tasks included in this study. Chapter 2 presents a summary of the requested literature for method(s), advantages (pros), and disadvantages (cons). The requested literature included topics such as wide area blackouts, phasor measurement unit (PMU) applications, Controlled Systems Separation Study (CSSS), and the power system protection schemes. These topics, among others, were considered most relevant to and that could provide some background for the present study. The rationale and compilation of the simulation library decided and used during the testing of the developed algorithm are also listed. Chapter 3 provides the details on the proposed two Kalman filter based angle estimation and prediction algorithm. This algorithm accurately predicts the evolution of angle difference between the buses of main New York power system interfaces. A brief description on the mitigation options used in this project is also provided. In Chapter 4, detailed results from the testing of the algorithm in different dispatch conditions for various internal, external, and normal disturbance scenarios are presented. Finally, Chapter 5 summarizes the major outcomes and the lessons learned from the MDMS project.

Keywords

Phasor measurements, mitigation, wide area stability, angular instability detection, Kalman filter, protective measures, Controlled Systems Separation, Under Frequency Load Shedding, and prevention of wide area blackouts.

Table of Contents

Notice ii
Abstract iii
Keywords iii
Table of Contents iv
Acronyms and Abbreviations List v
Executive Summary vi
1 Introduction 1
1.1 Project Task 1 Description 1
1.2 Project Task 2.1 Description 1
1.3 Project Task 2.2 Description 2
1.4 Project Task 3.1 Description 2
1.5 Project Task 3.2 Description 3
1.6 Project Task 4 Description 3
1.7 Project Task 5 Description 3

Acronyms and Abbreviations List

BNL	Brookhaven National Lab
CEM	Central-East Margin case
CoO	Center of Oscillation
CSS	Controlled System Separation
CSSS	Controlled System Separation Study
DOE	Department of Energy
DSE	Dynamic State Estimation
DSWG	Defensive Strategies Working Group
EC	Extreme Contingency
Hz	Hertz
IEEE	Institute of Electrical and Electronics Engineers
ISO	Independent System Operator
ISONE	Independent System Operator New England
kWh	kilowatt hours
ms	millisecond
MLE	Maximum Lyapunov Exponent
MW	megawatts
MDMS	Major Disturbance Mitigation Scheme
MRI	Magnetic Resonance Imaging
MSM	Moses Margin case
Mvar	mega volt-amperes reactive
NERC	North American Electric Reliability Corporation
NPCC	Northeast Power Coordinating Council
NYCA	New York Control Area
NYISO	New York Independent System Operator
NYS	New York State
NYSERDA	New York State Energy Research and Development Authority
NYSRC	New York State Reliability Council
OOS	Out of Step
OST	Out-of-step Tripping
PDC	Phasor Data Concentrator
PMU	Phasor Measurement Unit
PJM	Pennsylvania/New Jersey/Maryland
PSB	Power Swing Blocking
PSERC	Power Systems Engineering Research Center
PSRC	Power System Relaying Committee
RE	20% load reduction of summer peak load case
RRI	Inner Blinder
RRO	Outer Blinder
SCE	Southern California Edison
SEL	Schweitzer Engineering Laboratories
SGIG	Smart Grid Investment Grant
SIPS	System Integrity Protection Scheme
SL	Summer Light
SP	Summer Peak
SRP	Salt River Project
SVC	Static VAR Compensator
UFLS	Under Frequency Load Shedding
UPM	Upper NY Margin case
UVLS	Under Voltage Load Shedding
VAR	Volt amperes reactive
W	watts
WAMS	Wide Area Measurement System
WCM	Western-Central Margin case
TEI	Total East Interface
CEI	Central East Interface
TSEFD	Taylor Series Expansion with Finite Difference

Executive Summary

This report is the final deliverable for all of the tasks of the Major Disturbance Mitigation Study (MDMS) project. It includes a literature review on identified past articles and works done in the area of preventing bulk power systems from the severe network disturbances including the mitigation measures. The first phase of the project included a Technology Transfer (TT) plan that was delivered as a separate report. The second phase of the project was a simulation case library that was developed with expert feedback from the representatives from New York Independent Systems Operator (NYISO) and New York State Reliability Council (NYSRC). The development of a very fast and online angle instability detection and prediction algorithm, and implementation and testing of the proposed algorithm for several disturbance scenarios including the mitigation measures are the third and fourth phases of the project respectively. The fifth phase of the project is the execution of the TT plan in terms of publishing of the project outcomes to the involved stakeholders and to the public.

The MDMS project is the follow-on project of the Controlled Systems Separation Study (CSSS) that was completed by EnerNex in 2012. The MDMS project utilized the outcomes from the CSSS as a starting point of research. The CSSS focused on identifying the coherent groups in the NY power system and then testing several disturbance scenarios to come up with answers about some particular scenarios in which Controlled Systems Separation (CSS) along with other protective measures that could help stabilize the New York Control Area (NYCA). This MDMS study followed up by focusing on the development of a very fast, online, and accurate angle instability detection and prediction algorithm driven by data from Phasor Measurement Units (PMUs). This algorithm predicts the impending angle instability and sends a signal to mitigation and protective measures such as CSS along with Under Frequency Load Shedding (UFLS) scheme, or system-wide generator tripping, if required. As a result, the NYCA returns back to a stable operating condition following the major disturbances that are internal or external to the NY power systems. This MDMS study serves to eliminate a large number of offline simulations since the algorithm developed during this project is online, and it is capable of initiating the teleprotection in an automated fashion.

The North American Bulk Electric Systems (BES) comprises the Eastern and Western Interconnection and Electricity Reliability Council of Texas (ERCOT). These are the combination of hundreds of complicated rotating machines along with hundreds of equipment for communication, control, and protection. The complexity of North American power system on one hand provides a very reliable power to the customers, while on the other hand there is an equal risk of initiating a cascading outage following some major disturbances that may result in wide area blackouts. A recent example of wide area cascading blackout is the August 14, 2003 blackout in the northeastern U.S. and southeastern Canada.

In order to prevent the interconnected power systems from descending into wide area blackouts, the system states should be continuously monitored and controlled in real time. System information comprising of phase angles, frequency, rate of change of angles, etc., provide very useful information about the health of the interconnected power systems. In order to enhance the monitoring of the dynamic behavior of the NYCA, NYISO has led an effort to deploy a network of PMUs throughout the system. PMUs on electric power systems have been compared with Magnetic Resonance Imaging (MRI) of a human body. PMUs do provide the information about system states at a sampling rate as high as 120 samples / second, able to capture oscillatory events following any severe disturbances. The technological capability of PMUs is well understood, but the industry is still working out the best ways to use these devices within the well-understood control loops. An important function would be to provide early detection and protection of the power system from system disturbances. The outcomes from this MDMS project provides appropriate ways to utilize the information provided by PMUs with the use of an intelligent angle prediction algorithm able to initiate the protective actions before the system goes unstable. By assisting in the detection and actions necessary to bring the bulk system swinging oscillation centers back to the stable operating range, the algorithms in this project can prevent wide area blackouts, and so provide important functionality to PMU data.

Controlled Systems Separation (CSS) was one of the recommendations provided in August 14, 2003 Blackout Final Report by the US-Canada Power System Outage Task Force in order to save the system from cascading outage. During CSS, the lines, generators, and loads in the system are intentionally taken out of service following some procedures in order to stop the unintentional breakup of the network due to cascading events. Then, the system is left in a more favorable state for restoration.

With the outcomes from the CSSS, the possibility of getting the NY power system back to the stable operating conditions after severe disturbances through controlled systems separation was proven. Hence, this MDMS project utilizes CSS along with Under Frequency Load Shedding (UFLS), and system wide generator tripping if required, as the mitigation measure to save the system from possible instability.

While the outcomes from this project are very useful in preventing the instability problems in the NY power system based on the PSS/e simulation results, it should be noted that this work is still at a conceptual stage and is not ready to be deployed on the NYISO system. Further feasibility testing is required before actually implementing this work.

This MDMS study has successfully developed an algorithm using PMU measurements that is capable of predicting evolving instability under extreme contingencies both internal and external to the NY power system. The algorithm developed during this project was based on two Kalman filters, guided by the measurement prediction algorithm based on Taylor series expansion and finite difference method. This algorithm was validated in several stable and unstable disturbance scenarios to make sure that the algorithm is capable of providing correct prediction of impending instability for any kind of system disturbances, and also importantly that the algorithm does not give a false alarm during stable system conditions. It was shown from all the testing that the proposed algorithm has a very fast response time and is very accurate in the prediction of angular instability. The cases tested included heavy load cases with heavy transfer conditions. The two Kalman filter prediction algorithm is used to make a decision on the system instability and then, initiate the mitigation measure; i.e., CSS along with the protective options such as UFLS, Out-of-Step Tripping (OST) and, as a last resort, system wide generator tripping. It was shown in CSSS that controlled separation of a defined Total East Interface (TEI) could help in preventing the instability in the NY power system. Hence, the separation of this interface was considered as the first mitigation option in the present study as well. In addition to this, MDMS work also tested the separation of a defined Central East Interface (CEI) as the second mitigation option.

It was observed that the CSS of TEI needed other protective measures such as UFLS and OST for the stable system response after severe NY system disturbances. In the case of CSS of CEI, system wide generator tripping was found to be essential in addition to UFLS and OST to achieve the stable system response of the NY power system. Further investigations should be done in the implementation of Over Frequency Generator Settings instead of applying system wide generator tripping. The major outcomes from the MDMS project are summarized below:

- A new fast, online, and accurate angular instability detection and prediction algorithm is proposed, developed and implemented with Python in PSS/e 30 platform in a full stability model of the NY and the surrounding systems. The algorithm is based on two Kalman filters guided by another algorithm of angle measurement prediction that is based on Taylor series expansion and finite difference. This algorithm is capable of accurately predicting the angular difference between any two important interfaces in the New York bulk transmission system.
- The developed algorithm is capable of converging quickly enough to initiate mitigation measures in a timely fashion to stabilize the NY system.
- The testing included simulated noise on the PMU measurements that is thought to be significantly greater than what exists in present-day technology.
- The algorithm was tested under a wide range of stable situations in addition to the identified unstable situations and it did not falsely predict instability in any of those tested cases.
- The two Kalman filter based angle prediction algorithm is capable of providing the information on impending instability 12 cycles ahead in time scale. Hence, any type of mitigation action can be initiated 12 cycles ahead in case the algorithm senses any type of system instability in future.
- The delay of 4 cycles before initiating the CSS action was considered to account for breaker operation, teleprotection, and communication delays. This is included to represent the practical scenario of the system under CSS.
- The MDMS reduces a large amount of offline simulations to find out the exact time when the CSS should start, because the two Kalman filter prediction algorithm is capable of finding the exact time at which the separation should begin and initiate the protection measures automatically. This adaptive capability is very important.
- Mitigation measures included controlled separation of critical interfaces upon detection of instability across those interfaces. The mitigation measures required operation of the UFLS in places where the load/generation mismatches occurred after the controlled separation. A slight reduction in the timing of both Stage 1 and 2 settings of the UFLS was required to achieve stability.
- This MDMS project also confirms (agreeing with the earlier CSSS study) that the UFLS scheme needs to be adaptive and should be adjusted as needed from the settings under NPCC criteria according to the system conditions after any severe disturbance.

- Separation of TEI was the primary focus of this study; however, testing was also performed with controlled separation of the CEI. Some advantages involving load shedding and settling frequencies were observed for the CEI. However, in one case, stability with realistic delays could not be achieved.

- Use of local OOS relays at key interface points, as a redundant measure to provide added security to the central algorithm was also investigated. Consideration was given to use them on all lines of the TE interface; however, testing indicated that complete operation of OOS relays on all lines could not be achieved.

- Added security through independent redundancy of some form is required for any "Special Protection System" per NPCC criteria. Further research in this area is recommended.

- Finally, it was shown in this MDMS study that proper utilization and processing of the PMU measurement data can help in saving the NY bulk transmission system from instability, reducing the possibility of wide area blackouts.

1 Introduction

The objective of this project is to study the online and real-time instability detection and mitigation measures for enhancing the reliability and stability of the New York bulk electric power system when subject to major disturbances. This work includes developing dynamic simulation cases with a wide range of disturbance scenarios, developing algorithms for instability detection based on phasor measurement units and other new measurement devices, developing mitigation measures for major disturbances, and verifying the effectiveness of candidate detection algorithms and mitigation measures in dynamic simulations.

The project was broken into several tasks and phases, which included:

1. Technology Transfer Plan
2. Literature Review and Simulation Case Development
3. Phase Angle Instability Detection and Mitigation Measures Development
4. Testing of Algorithms and Mitigation Measures
5. Technology Transfer

1.1 Project Task 1 Description

The first task of this project was to develop a Technology Transfer (TT) plan for NYSERDA review and approval that was designed to communicate project results to interested parties in New York and throughout the United States. The TT plan was developed as a separate deliverable in which EnerNex identified the venues and methods of presenting the project outcomes to the project team as well as in the form of a technical journal or conference articles.

1.2 Project Task 2.1 Description

The task 2.1 summarizes the state-of-the-art analytical approaches on bulk power system phase angle stability and mitigation schemes of major disturbances for the New York bulk electric power system. The following sources are the foundation of the report:

1. the NYISO's controlled system separation scheme feasibility study report
2. the NYISO's 2003 blackout study reports
3. the New York control area defensive strategies study reports
4. the NYSRC working group meeting materials
5. the Northeastern Power Coordinating Council oscillation study reports

Each identified source has a summary, the methodologies, pros and cons noted where practical. The value of this template is that future derivative efforts will have more than a simple referential listing of the source.

1.3 Project Task 2.2 Description

This task involved developing dynamic simulation cases for a wide range of disturbance scenarios for algorithm and methodology verification for other tasks of the project. The project team analyzed the tradeoffs between a set of cases used for the Controlled System Separation Study (CSSS) project and more contemporary cases, and agreed to use a down-selected subset of the CSSS project case library for this project. The rationale was that the approach is independent of any particular notable topology changes or loading that may be different. In addition, the time to ensure the cases would be usable on the project team hardware/software and would be better spent on the actual measures development. The measurement and algorithm should be exchanged more readily than the case library.

The case library consists of those contingencies that are likely to cause instability, uncontrolled separation, and possible major loss of load. The disturbance scenarios include:

- Major External Disturbances - (1) extreme power flows through the NY system that result from cascading external transmission outages; (2) voltage collapse external to the NY system; and (3) "beyond criteria" losses of generation external to the NY system.
- Major Internal Disturbances - (1) extreme contingencies within the NY system, including the simultaneous loss of multiple transmission lines, multiple sequential loss of multiple transmission lines, multiple generation unit losses, (2) voltage collapse within the NY system, and (3) "beyond criteria" losses of generation within the NY system.
- Normal Disturbances - the single contingency events that the NY system is designed and operated to withstand and are included to test any control schemes that are developed in this study to insure that they “operate properly.”

During the initial phase of the project, the project team agreed to use a scenario to replicate the August 2003 blackout case as far as possible. However, later, during the project implementation, it was found out that this case library was only in PSS/e version V28 whereas the version used during the MDMS study was PSS/e V 30.3. In addition, as the MDMS study already covered the testing of the most severe disturbances internal and external to the New York system, reproducing 2003 blackout scenario was considered redundant.

1.4 Project Task 3.1 Description

Task 3 was the bulk of the research and development of algorithm and methodology for phase angle instability detection and mitigation measures. In Task 3.1, EnerNex was required to develop the algorithm for real-time and online detection of system angle instability in the New York (NY) power system by utilizing the capabilities of new measurement devices such as Phasor Measurement Units (PMUs). The monitored signals such as generator phase angles and speed, electrical bus phase angles, electrical bus voltages, system frequencies, critical interface power flows, and circuit breaker statuses could be utilized in defining the proposed algorithms.

In order to fulfill this objective of the project, EnerNex developed a very fast, online, and accurate angle prediction algorithm based on two Kalman filters guided by Taylor series expansion with finite difference algorithm and demonstrated the effectiveness of this algorithm in the NY power system.

1.5 Project Task 3.2 Description

In this task, EnerNex was required to develop and implement the mitigation measures to avoid adverse impacts of large disturbances to the NY bulk electric power systems. The mitigation options considered in the MDMS project was Controlled Systems Separation (CSS) supported by Under Frequency Load Shedding (UFLS) scheme, Out of Step Tripping (OST), and system wide generation tripping if required.

1.6 Project Task 4 Description

In Task 4, EnerNex was required to test the angle instability detection and prediction algorithm developed in Task 3.1 and the mitigation options identified in Task 3.2 against the entire disturbance scenarios developed in Task 2. In order to fulfill this task, EnerNex tested the developed algorithm with several stable and unstable disturbance scenarios.

1.7 Project Task 5 Description

In this task, EnerNex was required to contact all technology transfer tasks outlined in the Technology Transfer Plan developed in Task 1 to the NYSERDA's Project Manager's satisfaction. EnerNex should determine the target audience and hold a workshop to present the results and findings.

In line with the TT plan, during the course of this project, EnerNex had organized a recurring (bi-monthly) webinar with the project team including the representatives from NYSERDA, NYISO, NYSRC, and the regional utility staff in order to disseminate the progress and outcomes of the project on a continuous basis. In addition, EnerNex and the project team had a face-to-face meeting at NYISO, Rensselaer, NY held on May 12, 2015 and Oct 07, 2015 in order to discuss the project progress and outcomes with the team.

The MDMS project was conducted on the NYISO system and hence, the project outcomes are categorized as Critical Energy Infrastructure Information (CEII). Therefore, the project results cannot be published in a public domain without any modifications. In order to effectively present the outcomes from the project to the public, EnerNex is working on a draft conference article with the implementation of angle instability detection and prediction algorithm proposed and implemented in this work in a four-machine example test system. EnerNex is targeting to publish this article in either IEEE Transmission and Distribution Conferences and Exposition 2018 or IEEE PES General Meeting 2018.

Notice

The remaining chapters and sections of the final Major Disturbance Mitigation Study (MDMS) report that are not present in this summary report contain Critical Energy Infrastructure Information (CEII) and therefore cannot be released to the public. The complete final MDMS report has been reviewed and approved by New York State Reliability Council (NYSRC) and New York Independent System Operator (NYISO) and is available on a NYISO-maintained storage system. Questions concerning access to the complete final project report should be directed to Michael Razanousky of NYSERDA at Michael.Razanousky@nyserda.ny.gov.