Data Mining to Characterize Signatures of Impending System Events or Performance from PMU Measurements

Final Project Report

Power Systems Engineering Research Center

Empowering Minds to Engineer the Future Electric Energy System
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Executive Summary

This project applies data mining techniques to characterize signatures of impending system events or performance from phasor measurement units (PMU) measurements. The project will evaluate available data mining tools and analyze the ability of these tools to characterize signatures of impending systems events or detrimental system behavior. The use of PMU measurements from multiple locations will also be considered. The performance of the data mining tools will be verified by comparing the results obtained for measurements corresponding to known events on the system. The basis of the proposed approach is to use a historical data set of PMU measurements, along with information regarding actual events that occurred on the system during the historical period considered in the data set, and apply the decision tree based data mining techniques available in the commercial software Classification and Regression Trees (CART) to identify signature of impending events. A decision tree can be thought of as a flowchart representing a classification system. It consists of a sequence of simple questions regarding critical attributes (CAs).

The project consists of three parts Part 1 deals with the use of data mining in conjunction with PMU measurements to characterize signatures of impending system events. Part 2 deals with power system oscillatory stability and voltage stability based on voltage and current phasor measurements. Part 3 deals with fundamental research to improve the performance of decision trees using robust ensemble decision trees with adaptive learning and also accounting for loss of PMU measurements. Some details of each part are provided below.

Part 1: Data Mining to Characterize Signatures of an Impending Island Formation from PMU measurements

This study is aimed at using real PMU measurements to predict and detect significant system events with the help of the data-mining tool CART. The program CART (classification and regression trees) produced by Salford Systems is a data-mining tool that can be used to analyze problems that contain a large number of variables. The historical PMU data used in this study is from the Entergy power system in Louisiana when hurricane Gustav impacted the network. During the storm, 14 tie lines were lost that created an electrical island containing Baton Rouge and New Orleans. The PMU measurements captured during the storm were studied in a variety of ways to identify signatures that provide critical information regarding the status of the system.

Careful analysis was conducted to determine whether or not the island could be detected by only using the PMU measurements. It was found that the most effective approach of identifying the creation of the island was to use the PMU measurements of voltage phase angle. By comparing the phase angle measurements between PMUs, in this case, the island could have been detected in approximately 4 seconds. Also, by comparing different sets of PMUs, the location of the island could be determined by which PMUs were inside or outside of the affected area. Because this approach only considers the PMU measurements to form conclusions, the same method could be applied
to any system containing PMUs, with only slight modification, and still provide the ability to quickly and reliably detect the formation of an island within the system.

Provided with the system power flow and dynamic data corresponding to the time when hurricane Gustav entered the system, simulations were conducted to attempt to recreate and match the event to the historical PMU data. Load and generation levels across a wide range of the system were adjusted to closely match the phase angle difference seen in the PMU data. Next, the conditions inside the island were adjusted using the known generator dispatch and the available SCADA data. It was found that the direction of the power flowing on the last tie line must have been opposite to the SCADA data. Also, it was found that in order to match the simulation to the PMU frequency measurements, the governor reference at one of the generators must have been reduced just following the creating of the island. Performing these actions allowed the event to closely match to the PMU measurements and provide a better understanding of what happened just after the island formed.

Lastly, the PMU data was used to try to predict the island formation and identify signatures that predicted impending events. Since there was insufficient data to search for signatures by using the single island formation in the available PMU data, 50 simulations were conducted to build a CART database. The simulations were analyzed intuitively and with CART to determine any predicting signatures. It was found that there is a strong correlation between a sudden change in voltage phase angle and the loss of a tie line. A number of simulations also showed a sudden change in voltage within the island area after the loss of a tie line. These different signatures were searched for in the real PMU data at the times when tie lines were reported to have been removed from the system. It was found that when the second to last tie line went offline, there was a 12º change in phase angle measured inside the island. This signature precedes the island formation by 38 minutes and could have alerted system operators that this area needed attention.

This study was successful in using CART, along with an in-depth knowledge of power systems, to analyze PMU data from a historic event. The data-mining tool CART helped quantify and understand the phenomenon observed in the PMU data. The method of identifying an island formation using voltage phase angle measurements is both effective and reliable, and could be used in real applications. The signatures found to predict the island formation is much less reliable. Large changes in load or generation could also create a sudden change in phase angle and the method could be prone to false alarms. This method of island formation prediction could likely be improved by pairing it with additional information, such as SCADA data. However, this study only considers the information that can be drawn from the PMUs alone. In the future as more PMUs are placed in the power system, it is a reasonable assumption that the predicting signatures found in this study will be easier to identify and provide more information.

**Part 2: Data Mining to Characterize Impending Oscillatory and Voltage Stability Events**

Traditionally, time-domain simulation based on system modeling is used as the primary tool to analyze power system stability. This method is straightforward and accurate as long as an adequate system model and measurements are used. However, two obstacles have prevented this method from being applied in real-time applications: 1) it is
computationally involved; 2) when a simplified model is used, concerns may be raised over approximate analysis results. As the importance of real-time stability monitoring and early detection of system events has been increasingly emphasized in literature recently, an alternate approach based on data mining methods, with a focus on the Decision Tree (DT) method, has been explored in this project.

This report first presents the use of classification trees for rapid evaluation of power system oscillatory stability and voltage stability based on voltage and current phasor measurements. An operating point is grouped into one of several stability categories based on the value of corresponding stability indicator. A new methodology for knowledge base creation has been elaborated to assure practical and sufficient training data sets. Encouraging results are shown using the generated knowledge base and the explored methodology. The impact of DT growing method and node setting on the classification accuracy has been explored in detail.

After that a regression tree-based approach to predicting the power system stability margin and detecting impending system events is proposed. The input features of the regression tree (RT) include the synchronized voltage and current phasors from measurement points across the power grid, gathered using PMUs. Modal analysis and continuation power flow are the tools used to build the knowledge base for off-line RT training. Corresponding metrics include the damping ratio of the critical oscillation mode and MW-distance to the voltage collapse point. The robustness of the proposed predictor to measurement errors and system topology variation is analyzed. The optimal placement for the PMUs based on the importance of RT variables is proposed. The differences in performance between regression tree and several other data mining tools have also been explored.

Next, by using a probabilistic learning tool in the proposed active learning scheme to interactively query a learning data set based on the importance of unlabeled data points, we show that much fewer operating conditions need to be processed via time domain simulation for accurate voltage stability and oscillatory stability estimation. The proposed methodology significantly reduces the computational burden of creating a learning data set.

A measurement-based approach to analyzing the actual PMU measurements without knowledge of detailed system model parameters is presented at the end. DT is used to estimate useful information of inter-area electromechanical oscillations, such as mode frequency and damping ratio, for online oscillatory stability assessment.

Part 3: Data Mining for Online Dynamic Security Assessment using PMU Measurements

This study focuses on online dynamic security assessment (DSA) of power systems by using DTs and real-time PMU measurements. While previous studies have proven the effectiveness of DTs for power system security assessment, two practical issues can compromise the performance of DTs when applied to online DSA: 1) power system operating condition (OC) variations and topology changes, which can result in different critical decision rules and inaccurate decisions of DTs; 2) missing PMU measurements of the critical attributes of DTs, which may make data-mining-based
online DSA infeasible. In this study, ensemble DT learning-based online DSA approaches are developed to handle these challenges.

Part 3 first presents a novel approach for handling OC variations and topology changes in online DSA. Different from existing approaches that rely on a single fully-grown DT, the proposed approach utilizes an ensemble of small-height DTs, each of which is assigned a voting weight for final security decision making. These small-height DTs and the corresponding voting weights are identified by using a rigorous gradient-descent algorithm in offline training. As new cases are added to the knowledge base in online DSA, the small-height DTs and the corresponding voting weights are updated, so that the classification model could smoothly track the changing situations of power systems.

Next, online DSA with missing PMU measurements is studied by using ensemble DT learning and a novel random subspace method. Specifically, each small-height DT is trained in a random attribute subspace (i.e., trained by using a randomly selected attribute subset). The random subspace method exploits the hierarchy of wide-area monitoring system (WAMS), the locational information of attributes, and the availability of PMU measurements, so as to improve the overall robustness to missing data. Particularly, in case of missing PMU measurements, the voting weights of small-height DTs are recalculated for accuracy assurance.

The proposed approaches have been applied to the Western Electricity Coordinating Council (WECC) system, as well as IEEE test systems for illustrative purposes. The effectiveness of the proposed approaches is demonstrated via several case studies, by using a variety of realized system OCs and practical WAMS reliability indices.

**Project Publications**

**Student Theses:**

Trevor Werho – Arizona State University – “Application of Data Mining Techniques to PMU Measurements to Detect Impending Signatures of System Failures,” PhD, Anticipated Date of Graduation: May 2014.


**Conference Papers:**


Journal Papers:

