

Mitigation and Prevention of Cascading Outages: Methodologies and Practical Applications

Prepared by the Task Force on Understanding, Prediction, Mitigation and Restoration of Cascading Failures of the IEEE Computing & Analytical Methods (CAMS) Subcommittee*

Abstract— Interconnected power grids throughout the world are very reliable but occasionally suffer massive blackouts with multibillion dollar costs to society. Cascading failures present severe threats to power grid reliability, and thus reducing their likelihood, mitigation and prevention is of significant importance. This paper is one in a series presented by Cascading Failures Task Force, under the IEEE PES Computer Analytical Methods Subcommittee (CAMS) with primary focus on mitigation and prevention of cascading outages. The paper presents the basic methodologies for mitigation, summarizes currently deployed special protection schemes, and lists cases of successful and unsuccessful mitigation of cascading outages and lessons learned. Future developments and challenges in the area of mitigating cascading outages are also discussed.

Index Terms— Mitigating and Preventing Cascading Outages, Special Protection Schemes, Remedial Actions Schemes, Transmission System Reliability, Phasor Measurement Units.

I. INTRODUCTION

The interconnected power system increases the reliability of the electric power supply. At the same time, unforeseen events in these complex systems may lead to cascading failures with catastrophic consequences. The reliable and secure operation of such systems is highly dependent on existence of efficient remedial actions schemes (RAS). RAS are designed for specific foreseen events and may include shedding load or generation, triggered automatically in response to system limits designed to preserve system integrity. Considerable effort over the last several decades has been devoted to the research, various implementation and operation issues of RAS [1] - [9]. Several papers published by committees of CIGRE and IEEE have conducted surveys on the operation performance and reliability of remedial actions schemes installed across the globe [2, 3, 5]. The development and practical applications of the RAS across WECC are presented in [10–15]. Current industry standards that deal with RAS are given in [16–18].

There are presently three equally used acronyms with the same meaning for remedial action schemes. RAS term is used by utilities in the Western part of North America, IEEE community uses the term System Integrity Protection System

(SIPS), and CIGRE uses System Protection System (SPS) [5].

The North Electric Reliability Corporation (NERC) glossary defines a RAS as: *An automatic protection system designed to detect abnormal or predetermined system conditions, and take corrective actions other than and/or in addition to the isolation of faulted components to maintain system reliability* [19]. NERC standards PRC-012-PRC-017 address issues related to RAS under the Protection and Control (PRC) category [18], and ensure that RAS are properly designed and coordinated with other protection systems, meet performance requirements, maintenance and test programs are developed, and misoperations are analyzed and corrected.

The goal of this paper by the IEEE Cascading Failures Task Force is to summarize the state-of-the art in the area of mitigation and prevention of cascading outages, highlight the remaining challenges, and enable further progress.

The remainder of this paper is divided into five sections. Section II describes methodologies for mitigation of cascading outages. Section III summarizes currently deployed special protection schemes. Section IV provides examples of successful and unsuccessful mitigation of cascading outages and lessons learned. Section V provides a description of future developments in the area of mitigating cascading outages. The Task Force's conclusions are summarized in Section VI.

II. A METHODOLOGY FOR MITIGATION

A framework for mitigating cascading outages was developed in [20]. It consists of the following steps:

1. Identify possible initiating events, their spread, and severity.
2. Identify existing resources in the system that might be sufficient to prevent a cascading outage in planning and on-line environments.
3. Apply effective islanding techniques in planning and on-line environments.
4. If a blackout can't be prevented, identify an effective black-start technique.

Measures for mitigating and/or preventing cascading outages depend on the type of an event [21]. The process of determining preventive measures [22] is given in Fig. 1.

Visualization of cascading outages and control actions to prevent cascading is important for improving situational awareness of operators and increasing their preparedness to address the next contingency.

*Task Force Contributing Members: M. Vaiman (Lead), P. Hines, J. Jiang, S. Norris, M. Papic, A. Pitto, Y. Wang, G. Zweigle.

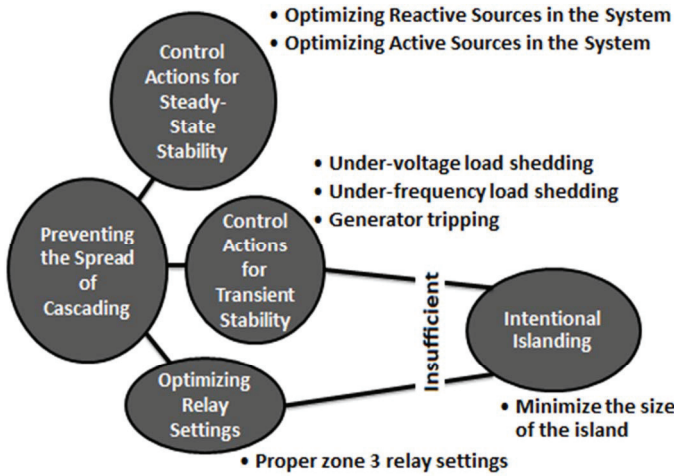


Fig. 1. Preventive measures/islanding for different types of cascading events

Given the variety of disturbances occurring in power systems, the European Network of Transmission System Operators for Electricity (ENTSO-E) has recently proposed an incident classification scale methodology [23] aimed to rank grid disturbances. A four-degree scale has been suggested, ranging from local events with low effect on reliability to widespread and major incidents in one transmission system operator (TSO), which consist of massive loss of load or even in a regional blackout. ENTSO-E provides recommendations [24] for automatic actions to manage critical system conditions to prevent the Continental Europe (CE) Synchronous Area or parts of it from the loss of stability and cascading effects leading to major blackouts. They act as a basis for the future development of technical standards.

III. SPECIAL PROTECTION SCHEMES CURRENTLY DEPLOYED FOR MITIGATION OF CASCADES

There is a wide variety of special protection schemes. This Section summarizes schemes installed at WECC and ERCOT systems in the US, and in the Italian system.

A. Remedial Action Schemes at WECC

WECC members have used RAS extensively to ensure adequate system reliability, maintain or increase the transmission system capability, mitigate certain low probability/high consequence system events resulting from NERC Category C and D contingencies, and prevent events spreading out across large regions or system wide basis.

The most common RAS in WECC are given in Fig. 2.

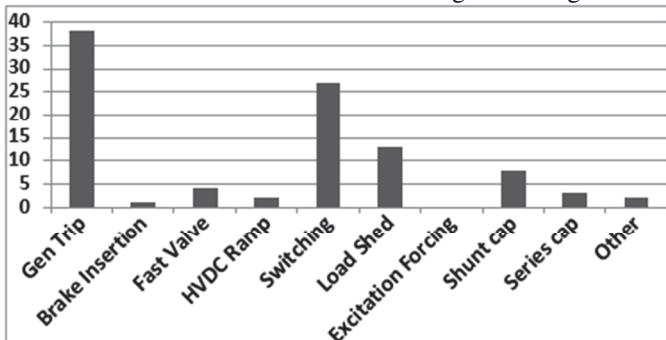


Fig. 2. Percentages of Typical RAS actions in the WECC

They include generation trip, brake insertion, fast valve/gen ramp, HVDC ramp; configuration changes/islanding, load shed or rejection, excitation forcing, shunt capacitor/reactor switching, series capacitor/reactor switching.

There are over 190 RAS in WECC transmission system, and their number has grown in the recent past, see Fig. 3.

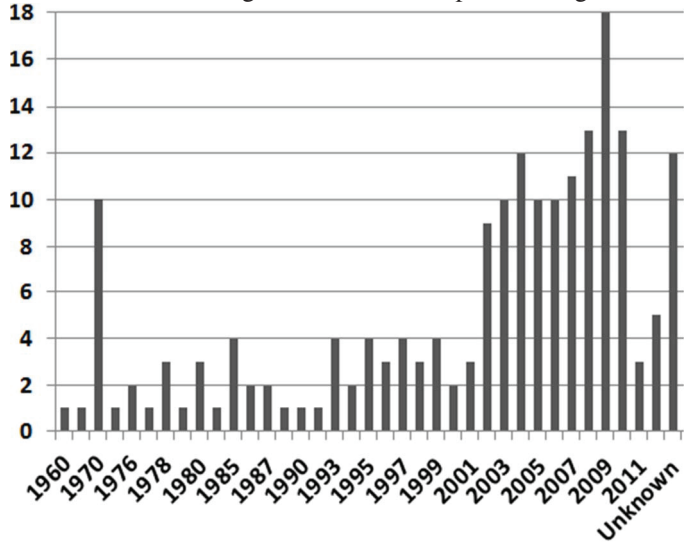


Fig. 3. Initial Year of RAS Operation in WECC

RAS systems are designed, maintained, and evaluated in accordance with the WECC RAS Guide and Procedure to submit a RAS for assessment [16]. WECC standard PRC-004-WECC-1 ensures that all RAS installed at generation or transmission side of the system are analyzed [15].

WECC identifies three types of RASs, depending on their potential impact:

- Local Area Protection Scheme (LAPS)
62% of installed RAS at WECC are LAPS
- Wide Area Protection Scheme (WAPS)
31% of installed RAS at WECC are WAPS
- Safety Net (SN)
7% of installed RAS at WECC are SN

Local Area Protection Scheme (LAPS):

LAPS is used to meet an owner's performance requirements within their system. LAPS failure may result in the NERC Category Events 1-2, [16]. The failure to operate the LAPS would NOT result in any of the following:

- Violations of TPL – (001 thru 004) – WECC – 1 – CR - System Performance Criteria,
- Maximum load loss ≥ 300 MW,
- Maximum generation loss ≥ 1000 MW

Wide Area Protection Scheme (WAPS):

WAPS is needed to meet WECC performance requirements and operating standards. WAPS failure may result in any of the NERC Category Events 1-5, [16]. The failure to operate the WAPS would result in any of the following:

- Violations of TPL – (001 thru 004) – WECC – 1 – CR - System Performance Criteria,
- Maximum load loss ≥ 300 MW,
- Maximum generation loss ≥ 1000 MW.

Safety Net (SN):

SN scheme provides defense against extensive cascading or

complete system collapse. An SN is intended to handle more severe disturbances resulting from extreme events. Such events are within or beyond NERC Category D contingencies defined by NERC TPL-004 planning standard. The SN is intended to minimize the impact of extreme events when such impacts cannot be entirely avoided.

B. Remedial Action Schemes at ERCOT

The ERCOT Operating Guides [25] describe SPSs in ERCOT as "*protective relay systems designed to detect abnormal ERCOT System conditions and take pre-planned corrective action (other than the isolation of faulted elements) to provide acceptable ERCOT System performance.*" SPS actions include changes in demand, generation, or system configuration. An SPS does not include under-frequency or under-voltage load shedding. A "Type 1 SPS" is any SPS that has wide-area impact and includes any SPS that is designed a) to change generation output or constrain generation or imports over DC Ties, or b) to open 345 kV transmission lines or other lines that interconnect Transmission and/or Distribution Service Providers and impact transfer limits. Any SPS that has only local-area impact and involves only the Facilities of the owner is a "Type 2 SPS".

At the same time, "ERCOT shall conduct a review of proposed or modified SPS before the SPS is placed in service. This review shall verify that the SPS complies with ERCOT and NERC criteria and guides. The review shall include system studies verifying that failure of a single component of the SPS, which would result in failure of the SPS to operate when required, would not result in cascading transmission outages" [26].

C. System Protection Schemes in Italy

The Italian Defense Plan [27] consists of four Lines of Defense and includes remedial actions aimed at: (a) preventing cascade tripping and consequent uncontrolled network separations (this is the 3rd defense line, which includes fast tripping of critical generating units triggered by outages in weak areas, manual emergency tripping of MV & HV loads, blocking of on load tap changers); (b) limiting the impact of network separation in case measures identified in (a) above that do not meet their target (this is the 4th defense line).

The 3rd defense line also includes System for Automatic Shedding to avoid cascading on "critical sections" defined as "sets of 400 kV lines so that their cascade tripping could evolve to network separation" [28]. The amount and location of load shedding depends on which lines were out of service in the pre-fault conditions, lines where threshold has been exceeded, and which line has been tripped. Remedial actions are defined by off-line steady-state and transient studies on different grid configurations and loadflow conditions.

IV. SUCCESSFUL AND UNSUCCESSFUL MITIGATION OF CASCADING OUTAGES: LESSONS LEARNED

This section presents lessons learned after investigation of successful and unsuccessful mitigation of cascading events.

A. Cases of Unsuccessful Mitigation

In 2012, the largest case of unsuccessful mitigation occurred in India with the loss of nearly 700 million customers [29]. With the initial cause still under investigation, a severely weakened system coupled with large unscheduled interchanges led to highly loaded tie lines. Load encroachment (apparent impedance entering the protective zone) tripped these tie-lines after inadequate operator relief actions. The resulting power swings split-up the system where lines continued to trip from under-frequency/over-voltage actions which eventually caused total collapse of all three grids.

A significant disturbance on the WECC system in 2011 [30] led to disconnection of 2.7 million customers. The system was not operating in an N-1 secure state, where peak demand hours and lower than peak generation combined with a 500 kV line trip to cause sizeable voltage deviations, equipment failure and a cascade which triggered load shedding throughout the region. The SONGS (TSO) inertia separation scheme tripped the final line carrying power into San Diego along with additional nuclear units leaving San Diego without power. Coordination issues with the existing protection systems contributed to the event progression. When the corridor between TSOs IID and SDG&E tripped, the RAS operated as per IID's design to protect a transformer on the single interconnect, but this had changed with the installation of a second interconnect and was not updated. Meanwhile the SONGS separation scheme was intended to isolate five 230 kV lines simultaneously for extended overloads, but it caused generators at SONGS to unexpectedly trip due to poor coordination with generator protection.

B. Cases of Successful Mitigation

In 2008 [31], an exceptionally rare event on the UK network resulted in frequency being outside the statutory limit for 9 minutes. Two large generators tripped within 2 minutes, which already exceeded the maximum credible loss, followed by two further units. This loss and further tripping of embedded generation in the distribution system caused frequency to drop to 48.795 Hz. This frequency drop was stopped by load shedding schemes and National Grid (TSO) was then able to restore system frequency and instructed affected Distribution Network Operators (DNOs) to restore the dropped load within a range of 20-40 minutes. Only 1.5% of demand was shed instead of the expected 6.5% due to relay design accuracy. Successful coordination between the TSO and the DNOs meant that fewer customers were disconnected and system collapse avoided.

In 2006, a major disturbance in Europe [32] showed the importance of coordination between operators. The event was initiated with a planned outage by E.ON Netz (TSO), which was not properly evaluated for N-1 security. One tie-line connecting E.ON Netz and a neighboring TSO used different relay settings in each area - this was not accounted for. This line tripped and initiated cascades throughout the UCTE system due to over-current distance protection and out of synchronism relays. As a result, the UCTE system split into three asynchronous areas. A blackout was narrowly avoided

due to the actions of TSOs in their individual control areas. In the two under-frequency areas, all TSOs began load shedding and generator scheduling which allowed the restoration of normal frequency within 20 minutes. In the over-frequency area, the wind farms that had tripped in the disturbance came back on line unexpectedly and further increased frequency. Therefore, restoration took longer which was due to a lack of coordination between TSOs and DNO's generation.

C. Lessons Learned

While each grid disturbance event is unique, they share many common factors such as a lack of coordination in key areas. Several events highlighted the lack of coordination and information between TSOs operating in an interconnected region. All recommendations point towards increased coordination between operators in terms of protection settings, real time exchanges, system studies and planning and role in an emergency state, and system conditions of neighboring TSOs. Also, a recommendation from [30] looked at the WECC Reliability Coordinator for coordinating actions in emergency situations as they have a bigger picture of events. Not only are there lessons to be learned from coordination between operators, but the WECC 2011 event highlighted the need for RAS and SPS to be properly coordinated for protection within the TSOs own regions, as well as with interconnected regions.

When acting in an emergency state, operators need to be trained to deal with these situations and understand and act in an urgent manner. The lack of urgency may have severe consequences, as the 2003 Italian blackout showed [33]. Also maintenance practice and schedules play an important role in blackout prevention. Lessons can also be drawn from the events of both Italy and India, where a common problem was seen in terms of the exchanges across the interconnections. In both cases, there were larger imports than agreed, which makes security analysis for all TSOs more difficult when operators are not sticking to agreed transfers, and neighboring TSOs can be left with systems that were thought to be secure based on previous agreed exchanges.

V. FUTURE DEVELOPMENTS IN THE AREA OF MITIGATING CASCADING OUTAGES

Both technical and cooperative advances are enabling new ideas to improve power system reliability. Driving demand for these new ideas are changes in generation characteristics, limitations in infrastructure installations, along with modern society's increasing dependence on electric power.

An important technical advance is the ability to measure the power system network state with precise time-stamps, and communicate these synchrophasor measurements at a high rate. Advances in communication infrastructure allow streaming measurements both between distributed control devices and between these devices and the control center. In North America, the American Recovery and Reinvestment Act (ARRA), [34] has participated with the installment and interconnection of hundreds of phasor measurement units

(PMU) across the power system. Measurements are communicated within each utility and between the utilities and their regional coordinating center. This is bringing new monitoring capability which increases the situational awareness at each entity.

PMUs provide a set of initial measurements that aid in detecting and mitigating voltage collapse [35]. Their advantages include a high processing rate and immunity from the convergence problems of nonlinear state estimation. For transient stability related outages, adding time-synchronized measurements of the generator rotor angle [36] will enable new protection and automated control [37]. The result is that generators stay synchronized during severe contingencies.

Coordination between utilities provides the opportunity for future mitigation measures. In Europe, ENTSO-E proposed new recommendations [24], which include harmonization among UFLSs; developing a standard for the blocking of On Load Tap Changers (OLTC) and for Under-Voltage Load Shedding (UVLS) in the CE Synchronous Area. A major research target for European TSOs is risk-based assessment and control methodologies for analysis of cascades [38].

Effective coordination between different protection schemes is also important. Consequences of an action or their combinations under contingencies in stressed system conditions could be significant, and these are difficult to model, compute and understand. Continuously changing operating conditions and actual contingencies reduce the validity of the results of scenario-based mid-term or short-term analyses, so appropriate actions have to be computed or adjusted for current conditions in a very short time frame. These challenges will require serious efforts of advanced research and technology development in the area of mitigation and prevention of cascading outages.

VI. CONCLUSIONS

This paper has presented the work of the IEEE Task Force on Understanding, Prediction, Mitigation and Restoration of Cascading Failures. An analysis framework of general mitigation and prevention, as well as different types of measures that are required to perform mitigation and prevention, has been discussed. Measures for mitigating and preventing cascading outages depend on the type of the cascading event. Practical examples of special protection schemes being deployed in the WECC, ERCOT and the Italian system have been discussed. Different interconnections have their own considerations for the SPS design.

Some unsuccessful mitigation examples, such as the recent Indian blackout and South California blackout, have been discussed, as well as the successful experience in two European disturbances. The main lesson learned from these events is that the coordination between each TSO needs to be enhanced. This includes improving coordination between operators, as well as SPS/RAS designs within and among TSOs, and across interconnections.

The increasing deployment of PMUs and advanced communication infrastructure provides new capabilities and

opportunities to minimizing the impact caused by cascading failures, while new challenges exist on how to quickly convert large amounts of data into actionable information. With these new advantages, and further improving coordination among utilities/TSOs, it is possible to improve the functionality of cascade mitigation schemes, and reduce cascading failure risk.

VII. REFERENCES

- [1] E.K Nielsen, M.E. Coulters, D.L. Gold, J.R. Taylor, P.J. Traynor, "An operations view of special protection systems", IEEE Trans. Power Syst., vol. 3, pp. 1078-1083, Aug. 1988.
- [2] W.H. Winter, and B. K. LeReverend, "Operational Performance of Bulk Electricity System Control Aids", Electra No. 123, pp. 97-101, March 1989.
- [3] P.M. Anderson and B. LeReverend, "Industry experience with special protection schemes", IEEE Trans. Power Syst., vol. 11, pp. 1167-1179, Aug. 1996.
- [4] C. W. Taylor and D. C. Erickson, Recording and analyzing the July 2 cascading outage, Comput. Applicat. Power Syst., vol. 10, no. 1, pp.26-30, Jan. 1997.
- [5] D. Karlsson and X.Waymel, Eds., System protection schemes in power networks, Report, CIGRE Task Force 38.02.19, June 2001.
- [6] W. R. Lachs, "A New Horizon for System Protection Schemes", IEEE Trans. Power Syst., vol. 18, No. 1, pp. 334-338, Feb. 2003.
- [7] C. W. Taylor, K. E. Martin and V. Venkatasubramanian, WACS – Wide-Area Stability and Voltage Control System: R & D and Online Demonstration, Proceedings of the IEEE, Vol. 93, No. 5, May 2005.
- [8] Power Systems Engineering Center (PSERC) Publication 10-19, System Protection Schemes: Limitations, Risks, and Management, Final Project Report, Dec., 2010.
- [9] V. Madani, M. Begovic, et al., "Global Industry Experiences with System Integrity Protection Schemes," IEEE PSRC Working Group C4, Oct., 2009.
- [10] Sykes, J., Adamiak, M., Brunello, G., Implementation and Operational Experience of a Wide Area Special Protection Scheme on the SRP System, Power Systems Conference: Advanced Metering, Protection, Control, Communication, and Distributed Resources, 2006, pp. 145 – 158.
- [11] S.C. Pai, J. Sun, BCTC's experience towards a smarter grid – increasing limits and reliability with centralized intelligence Remedial Action Schemes, Electric Power Conference, IEEE Canada, Oct. 2008, pp. 6-7.
- [12] M. Varghese, J. Licheng; S. Ghosh, G. Lin, B. Pek, "The CAISO experience of implementing automated Remedial Action Schemes in Energy Management Systems", IEEE PES GM, 2009.
- [13] P. L. Arons, SCE Pilots the Next Level of Grid Protection, Southern California Edison, Transmission and Distribution World, 2007.
- [14] AESO Discussion Paper, RAS in the Planning Stage, 2009 Available online: http://www.aeso.ca/downloads/RAS_Guideline_Discussion_Paper_July_03_2009.pdf.
- [15] C. W. Taylor, BPA's Wide-Area stability and voltage Control System (WACS), Imperial College, London, 2006, available online: <http://www3.imperial.ac.uk/pls/portallive/docs/1/4859962.PDF>
- [16] Western Systems Coordinating Council, Remedial Action Scheme Design Guide, Feb. 2007.
- [17] Western Systems Coordinating Council Standard PRC-004-WECC-1 – Protection System and Remedial Action Scheme Misoperation, Oct 2011.
- [18] North Electric Reliability Corporation (NERC) Protection and Control Standards, PRC-012 through PRC-017, website <http://www.nerc.com/page.php?cid=2%7C20>.
- [19] IEEE, Voltage Stability of Power Systems: Concepts, Analytical Tools, and Industry Experience, IEEE Publication, 90TH0358-2-PWR, 1990.
- [20] "Prevention of Occurrence of Major Catastrophic Events: Demonstration for Con Edison System", NYSERDA award to V&R Energy, 2010.
- [21] M. Vaiman, K. Bell, Y. Chen, B. Chowdhury, I. Dobson, P. Hines, M. Papic, S. Miller, P. Zhang, "Risk Assessment of Cascading Outages: Methodologies and Challenges", IEEE Transactions on Power Systems, May 2012, Issue 2, pp: 631 - 641.
- [22] M. Koenig, P. Duggan, J. Wong, M. Y. Vaiman, M. M. Vaiman, M. Povolotskiy, "Prevention of Cascading Outages in Con Edison's Network", 2010 PES T&D Conference and Exposition, 10.1109/TDC.2010.5484278.
- [23] ENTSO-E, "Incidents classification scale methodology", 2012.
- [24] ENTSO-E, "Technical background and recommendations for defense plans in the continental Europe synchronous area", Jan 31, 2011.
- [25] ERCOT Operating Guides, August 2010.
- [26] J. Adams, ERCOT Cascading Outage Practice & Possible Improvement, Presentation, May 2005.
- [27] CIGRE C2.02.24, "Defense Plan against extreme contingencies", TB 316, April 2007.
- [28] G. Giannuzzi, R. Salvati, M. Sforza, A. Danelli, M. Pozzi, and M. Salvetti, "A DSA-integrated shedding system for corrective emergency control", PSCC (Power System Computation Conference), 2005. ", TB 316, April 2007.
- [29] Ministry of power, Government of India, "Grid Disturbance in Northern Region on July 30, 2012 and in Northern, Eastern & North-Eastern Region on July 31 2012", Report of the Enquiry Committee, Aug 2012.
- [30] Federal Energy Regulatory Commission and North American Electric Reliability Corporation, Arizona-Southern California Outages on September 8, 2011 - Causes and Recommendations, April 2012.
- [31] National Grid (UK), Report of the National Grid Investigation into the Frequency Deviation and Automatic Demand Disconnection that occurred on the 27th May 2008, Feb. 2009.
- [32] UCTE, Final Report- System Disturbance on 4 November 2006, 2007.
- [33] UCTE, Final Report of the Investigation Committee on the 28 September 2003 Blackout in Italy, April 2004.
- [34] J. Dagle, "North American Synchrophasor Initiative - An Update of Progress", 44th Hawaiian International Conference on System Sciences, pp. 1 - 4, 2011.
- [35] M. Y. Vaiman, M. M. Vaiman, S. Maslennikov, E. Litvinov, X. Luo, "Calculation and Visualization of Power System Stability Margin Based on PMU Measurements", SmartGridComm 2010, pp: 31-36, 10.1109/SMARTGRID.2010.5622011.
- [36] G. Zweigle and V. Venkatasubramanian, "Model Prediction Based Transient Stability Control," IEEE Transmission and Distribution Conference and Exhibition, pp. 1 - 8, May 7 - 10, 2012.
- [37] E.O. Schweitzer, D. Whitehead, G. Zweigle, K.G. Ravikumar, "Synchrophasor-Based Power System Protection and Control Applications", 63rd Annual Conference for Protective Relay Engineers, pp. 1 - 10, Oct. 2010.
- [38] E. Ciapessoni, D. Cirio, S. Massucco, A. Pitto, "A Risk-based methodology for operational risk assessment and control of power systems", PSCC, Stockholm, Aug 22-26, 2011.

VIII. BIOGRAPHIES

Marianna Vaiman (M'97) is with V&R Energy, Los Angeles, CA, USA (e-mail: marvaiman@vrenergy.com).

Paul Hines (M'07) is with University of Vermont, USA (e-mail: paul.hines@uvm.edu). He is the Task Force Co-Chair.

John Jiang (SM'07) is with University of Oklahoma, Norman, OK, USA (email: jnjiang@ou.edu)

Seán Norris (S'10) is with Durham University, Durham City, United Kingdom (email: s.w.norris@durham.ac.uk).

Milorad Papic (SM'05) is with Idaho Power Company, Boise, ID, USA (e-mail: mpapic@idahopower.com). He is the Task Force Chair.

Andrea Pitto (M'10) is with RSE S.p.A., Milan, Italy (e-mail: andrea.pitto@rse-web.it).

Yezhou Wang (SM'10) is with UT-Austin, Austin, TX, USA (email: nickncwang@utexas.edu)

Greg Zweigle (M'90) is with Schweitzer Engineering Laboratories, Pullman, WA, USA (e-mail: Greg_Zweigle@selinc.com).