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Contents

Reliability Standards for the Operation and Planning of Future Electricity Networks

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ABSTRACT

Electricity networks, designed and operated in accordance with the historic deterministic standards, have broadly delivered secure and reliable supplies to customers. A key issue regarding their evolution is how the operation and planning standards should evolve to make efficient use of the existing assets while taking advantage of emerging, non-network (or non-wires) technologies. Deployment of the smart grid will require fundamental changes in the historical principles used for network security in order to ensure that integration of low-carbon generation is undertaken as efficiently as possible through the use of new information and communication technology (ICT), and new flexible network technologies that can maximize utilization of existing electricity infrastructure. These new technologies could reduce network redundancy in providing security of supply by enabling the application of a range of advanced, technically effective, and economically efficient corrective (or post-fault) actions that can release latent network capacity of

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the existing system. In this context, this paper demonstrates that historical deterministic practices and standards, mostly developed in the 1950s, should be reviewed in order to take full advantage of new emerging technologies and facilitate transition to a smart grid paradigm. This paper also demonstrates that a probabilistic approach to developing future efficient operating and design strategies enabled by new technologies, will appropriately balance network investment against non-network solutions while truly recognizing effects of adverse weather, common-mode failures, high-impact low-probability events, changing market prices for pre- and post-contingency actions, equipment malfunctioning, etc. This clearly requires explicit consideration of the likelihood of various outages (beyond those considered in deterministic studies) and quantification of their impacts on alternative network operation and investment decisions, which cannot be undertaken in a deterministic, "one size fits all" framework. In this context, we developed advanced optimization models aimed at determining operational and design network decisions based on both deterministic and probabilistic security principles. The proposed models can recognize network constraints/congestion and various operational measures (enabled by new technologies) composed of preventive and corrective control actions such as operation of special protection schemes, demand side response and generation reserve utilization and commitment, considering potential outages of network and generation facilities. The probabilistic model proposed can also provide targeted levels of reliability and limit exposure to severe low probability events (mainly driven by natural hazards) through the use of Conditional Value at Risk (CVaR) constraints, delivering robust and resilient supplies to consumers at the minimum cost. Through various case studies conducted on the Great Britain (GB) power network, we set out the key questions that need to be addressed in support of the change in network reliability paradigm, provide an overview of the key modelling approaches proposed for assessing the risk profile of operation of future networks, propose a framework for a fundamental review of the existing network security standards, and set out challenges for assessing the reliability and economics of the operation of future electricity network.

1

Context and Objectives

1.1 Motivation

Electricity networks, designed and operated in accordance with the historic deterministic approaches, have broadly delivered secure and reliable supplies to customers. A key issue regarding their evolution is how the operation and planning standards should be adapted to make efficient use of the existing network infrastructure while taking advantage of emerging smart grid technologies (Strbac *et al.*, 2011; Kirschen and Bouffard, 2009; Moreno *et al.*, 2010b; Moreno *et al.*, 2012). In accordance with the conventional deterministic reliability criteria, electricity systems are expected to withstand the occurrence of any one of a defined set of credible outages (e.g., a loss of one or two circuits in accordance with $N-1/N-2$ criterion) without causing overloads or inadequate voltages on any remaining circuits/busbars, and without violating system stability limits. Post-fault network overloads, following credible contingencies, are avoided by preventive operational measures or by a combination of preventive and corrective control (Kundur and Taylor, 2007; Kirschen and Jayaweera, 2007; Glatvitsch and Alvarado, 1998).

The key general concerns associated with this traditional network operation and design philosophy are related to economic efficiency and the ability of this concept to balance the cost of operation and network infrastructure against the security benefits delivered to network customers (Billinton and Li, 1994; Kariuki and Allan, 1996; He *et al.*, 2010). Furthermore, given that network security is provided mainly through asset redundancy, this approach may create a barrier against innovation in network operation and design, and prevent the implementation of technically effective and economically efficient solutions that could enhance the utilization of the existing network assets and maximize value for the users of the network. Over the last decade in particular, significant investigations (Siddiqi and Baughman, 1995; Dalton III *et al.*, 1996; Strbac *et al.*, 1998; Ni *et al.*, 2003; McCalley *et al.*, 1999; McCalley *et al.*, 2000; McCalley *et al.*, 2004; Choi *et al.*, 2005; Xiao and McCalley, 2007; Jirutitijaroen and Singh, 2008; Moreno *et al.*, 2013; North American Reliability Corporation, 1996) have questioned this historical approach to electricity network operation and design, and provided growing evidence that a radically different paradigm may be needed to facilitate a cost-effective delivery of energy policy objectives, particularly in relation to integrating low-carbon generation, and application of smart grid technologies. In several jurisdictions (Strbac *et al.*, 2011; North American Reliability Corporation, 1996; Gleadow *et al.*, 2009; Araneda, 2009; CIGRE, 2010), electricity distribution and transmission network reliability standards and practices have been reviewed and modified.

1.2 Network security standards: impact on network utilization efficiency, renewables integration, application of advance control schemes and consumer choice

Security standards define the level of network capacity that is released to its users in real time, which can affect network congestion and investment and thus not only the security but also the overall economic performance of the power system in the short and long term. In the context of the delivery of large amount of future network investments, it is critical to evaluate the cost effectiveness of the historical $N-1/N-2$

security rules by applying comprehensive cost-benefit analyses that balance network investment costs, operational costs, and risks.

Furthermore, given the pressing need for additional network capacity to accommodate renewable generation, there is a concern that the present deterministic network security standards may be a barrier for the application of a range of advanced technically effective and economically efficient non-network and smart grid solutions and technologies that did not exist when the standard was developed. The concern is that the rules used to determine the amount of capacity that can be released to network users in real time might be inefficient and limited to the application of asset-heavy network solutions to network constraints, i.e., network redundancy, undermining the value of corrective or post-fault control in releasing latent network capacity of the existing network. If updated within an improved cost–benefit framework, this would result in lower network constraints costs and facilitate more efficient connection of renewables. It is expected that the levels of network capacity that are released to users in operational timescales would vary with the magnitude of constraints costs, probability of outages (e.g., weather conditions), cost of post-contingency services, etc. In turn, this could reduce the need for (and substitute) future network investment through applying a range of emerging operational measures supported by information and communication infrastructure, including Special Protection Schemes (SPS), coordinated voltage control techniques, wide-area monitoring and control systems, advanced dynamic security assessment techniques, and Demand Side Response (DSR) (Moreno *et al.*, 2010a).

1.2.1 Specific drivers for a change in security standards

Recently, there have been various debates associated with updates and reviews of network operation and planning standards and practices in a number of jurisdictions. This is driven by a variety of factors including the need to (Strbac *et al.*, 2011; Moreno *et al.*, 2010b; Moreno *et al.*, 2012; Moreno *et al.*, 2010a; Strbac *et al.*, 2009):

- Ensure that network planning and operational standards do not impose unnecessary barriers to entry and do not prevent a timely connection of new generating plant (particularly renewables) and demand.

- Demonstrate that investment in monopoly functions is efficient and delivers the best value for consumers, i.e., provides the right balance between costs involved (paid by the users) and benefits that users derive from it, including reliability improvements (the-concern being that the present standard do not deliver value for money to network users).

- Ensure that the current standards do not impose a barrier for innovation in network operation and design, preventing implementation of technically effective and economically efficient solutions that enhance the utilization of the existing network assets and maximize network users' benefits. Consider the application of advanced communication and information technologies as a part of electricity grid infrastructure, combined with recent developments of SPS, Wide-Area Monitoring and Control Systems, Dynamic Security Assessment techniques, Dynamic Line Rating, grid friendly controllers for Demand Response, etc. These techniques can provide efficient solutions for delivery of network security and reduce the level of network redundancy (Kundur and Taylor, 2007; Moreno *et al.*, 2010a; Sattinger *et al.*, 2006; Anderson and LeReverend, 1996; Begovic *et al.*, 2007; Madani *et al.*, 2008; Leite da Silva *et al.*, 2002). For example, new technologies may allow use of corrective actions in the form of generation and demand response (both reductions and increases) to more efficiently manage network faults. In turn, the management of network injections and withdrawals following a network failure will allow network operators to accommodate increased power transfers through the existing grid, reducing the need for network redundancy.

- Facilitate development of user choice driven network operation and investment paradigm. Network users at present (both demand and generation) can exercise very limited choice with regard to their security of supply. Over a longer timescale, the introduction of smart metering may facilitate reliability-based choices of consumption. Rather than having full interruptions and indiscriminate demand curtailment in case of pre- or post-contingency operating difficulties, it may be possible to prioritize categories of demand to be supplied during emergency conditions and hence enhance the reliability of supply delivered by existing networks at lower cost to customers. If such choice is to be offered to users, understanding of the network reliability profile will be essential and this will require probabilistic analysis of system risks. Reliability differentiating charging or reward mechanisms will also need to be developed.

Generic deterministic rules for security at present are fundamentally problematic when addressing the above concerns since the balance of reliability benefits and associated costs is not explicitly considered on a case-by-case basis. Moreover, as discussed by Kirschen and Jayaweera (2007), traditional deterministic security standards rely on a binary measurement of risk: system operation in a particular condition is considered to be exposed to no risk at all if the occurrence of any selected single contingency does not violate the operational limits, while the system is considered to operate at an unacceptable level of risk if the occurrence of a credible contingency would cause some violations of operating limits. Evidently, neither of these is correct, as the system is indeed exposed to risks of failure even if no single circuit outage leads to violations of operating constraints, and the risk of some violations may be acceptable if these can be eliminated by an appropriate post-fault corrective action.

Furthermore, Kirschen and Jayaweera (2007) point out that given that the outage probabilities, failure rates, restoration, and repair times of various network equipment types may vary significantly, it is very difficult to deduce a single value to be used to quantify the risk the system is exposed to. In this context, it is important to recognize that present deterministic standards implicitly assume that all contingencies are equally likely, which is also fundamentally incorrect. For example, faults on a long, exposed line are much more frequent than failures of a closely monitored transformer. Additionally, the present deterministic standards do not deal explicitly with common mode failures (CMF) and do not provide guidance for dealing with high-impact, low-probability (HILP) events.

Also, it is important to note that line outage probabilities change according to the prevailing operating conditions. For instance, during an adverse weather condition (thunderstorms, high winds, ice, etc.) the probability of failure is higher than under fair weather condition. Hence keeping the same levels of redundancy for all types of circuits under all conditions, as dictated by a deterministic standard, is inefficient. Such a deterministic standard might be good on average but it will not be appropriate for any individual event. Therefore, a probabilistic approach must be used to adequately identify the risk for each individual event as shown in Strbac *et al.*, 2011; Moreno *et al.*, 2012; Kirschen and Jayaweera, 2007; Kariuki and Allan, 1996; He *et al.*, 2010; Dalton III *et al.*, 1996; McCalley *et al.*, 2004; Choi *et al.*, 2005; Xiao and McCalley, 2007; Jirutitijaroen and Singh, 2008; Moreno *et al.*, 2013; North American Reliability Corporation, 1996; Gleadow *et al.*, 2009; Araneda, 2009; CIGRE, 2010; and Moreno *et al.*, 2010a.

It is fundamentally problematic to apply corrective control in a deterministic framework since its post-fault cost impacts, which could be significant, would be ignored (for instance, post-fault cost associated with operating SPS over demand and generation can be as high as £30,000/MWh and £400,000/trip, respectively).[1] Hence deterministic criteria can be applied through mainly preventive control since applying corrective control actions in a deterministic framework that fundamentally ignores corresponding costs, would clearly lead to a suboptimal solution. This security philosophy favors application of preventive control and will hence lead to low utilization of network infrastructure, increasing network congestion and the need for further asset-heavy investment. There are cases, however, when corrective control actions could also be applied within a deterministic framework, particularly if there are no associated utilization costs (e.g., post-fault re-optimization of FACTS set-points). It is important to highlight that these cases may be of limited scope particularly in context of the optimization of

[1] Actual costs in GB used in the assessments within the Fundamental Review of the Security and Quality of Supply Standards.

the full set of post-contingency actions (including network components, generation, and demand) in a probabilistic framework as demonstrated by Moreno *et al.* (2015).

Similarly, the degree of security provided by traditional deterministic criteria is unlikely to be optimal in any particular instance, as the cost of providing the prescribed level of security is not compared with the reliability benefit delivered.[2] In contrast, approaches that are established within a cost–benefit context (probabilistic) are, in principle, superior over the present deterministic framework, as it balances more accurately the reliability (and other) benefits against operation and investment costs incurred to deliver these benefits. Given the developments in reliability analysis techniques over the last 20 years, the evaluation of appropriate levels of security within a cost–benefit framework is feasible, although the scope for further enhancement of reliability assessment methodologies is very significant.

In the above context, the objectives of this paper are:

- Set out the key questions that need to be addressed in support of the change in network reliability paradigm,
- Provide an overview of the key modelling approaches proposed for assessing the risk profile of operation of future transmission and distribution networks,
- Propose a framework for the evaluation of cost effectiveness of existing network standards and development of probabilistic approaches to operation and design of future networks,
- Set out challenges for assessing the reliability and economics of the operation of future electricity network.

This paper is structured as follows. Section 2 describes the modelling principles of both deterministic and probabilistic approaches that are

[2] The reliability benefit of an investment reflects the reduction in risk of service interruptions that accounts for the probability of an undesirable outcome and for the consequences of such an outcome.

used in Sections 3 and 4 for impact assessment, and quantitative comparisons and demonstrations of main advantages of a probabilistic approach. Section 5 summarizes the key benefits and challenges associated with a probabilistic approach, and Section 6 concludes and recommends.

References

Anderson, P. M. and B. K. LeReverend. 1996. "Industry experience with special protection schemes". *IEEE Transactions on Power Systems*. 11(3): 1166–1179.

Araneda, J. C. 2009. *Market Based Transmission Planning (Chilean Experience). SQSS International Workshop*. London, UK: Imperial College.

Baldick, R., B. Chowdhury, I. Dobson, Z. Dong, B. Gou, D. Hawkins, H. Huang, M. Joung, D. Kirschen, F. Li, J. Li, Z. Li, C. Liu, L. Mili, S. Miller, R. Podmore, K. Schneider, K. Sun, D. Wang, Z. Wu, P. Zhang, W. Zhang, and X. Zhang. 2008. "Initial review of methods for cascading failure analysis in electric power transmission systems IEEE PES CAMS task force on understanding, prediction, mitigation and restoration of cascading failures". In: *Proceedings of IEEE PES 2008 General Meeting*. Pittsburgh, USA.

Begovic, M., V. Madani, and D. Novosel. 2007. "System integrity protection schemes (SIPS)". In: *VII iREP Symposium — Bulk Power System Dynamics and Control — Revitalizing Operational Reliability*. Charleston, SC, USA.

Belivanis, M. and K. Bell. 2011. "Representative GB network model". Documents of the Department of Electronic and Electrical Engineering, University of Strathclyde.

Bezerra, B., A. Veiga Filho, L. A. Barroso, and M. Pereira. 2016. "Stochastic long-term hydrothermal scheduling with parameter uncertainty in autoregressive streamflow models". *IEEE Transactions on Power Systems*. Available online.

Billinton, R. and W. Li. 1994. *Reliability Assessment of Electric Power Systems Using Monte Carlo Methods*. New York: Plenum Press.

Bouffard, F., F. Galiana, and J. M. Arroyo. 2005. "Umbrella contingencies in security-constrained optimal power flow". In: *The 15th Power Systems Computation Conference*. Liege, Belgium.

Capitanescu, F., J. L. Martinez Ramos, P. Panciatici, D. Kirschen, A. Marano Marcolini, L. Platbrood, and L. Wehenkel. 2011. "State-of-the-art, challenges, and future trends in security constrained optimal power flow". *Electric Power Systems Research*. 81(8): 1731–1741.

Choi, J., T. Tran, A. A. El-Keib, R. Thomas, H. Oh, and R. Billinton. 2005. "A method for transmission system expansion planning considering probabilistic reliability criteria". *IEEE Transactions on Power Systems*. 20(3): 1606–1615.

CIGRE Working Group C4.601. 2010. "Review of the current status of tools and techniques for risk-based and probabilistic planning in power systems". URL: https://www.researchgate.net/publication/272482844_Review_of_the_Current_Status_of_Tools_and_Techniques_for_Risk-Based_and_Probabilistic_Planning_in_Power_Systems.

Conejo, A., M. Carrion, and J. M. Morales. 2010. *Decision Making Under Uncertainty in Electricity Markets*. New York: Springer.

Da Costa Jr, L. 2016. "Implementation and assessment of alternative risk aversion methodologies for large-scale stochastic hydrothermal scheduling". In: *XIV International Conference on Stochastic Programing*. Buzios, Brazil.

Dalton III, J. G., D. L. Garrison, and C. M. Fallon. 1996. "Value-based reliability transmission planning". *IEEE Transactions on Power Systems*. 11(3): 1400–1408.

Doucet, A., N. De Freitas, and N. Gordon. 2001. *An Introduction to Sequential Monte Carlo Methods*. New York: Springer.

ENSG. 2009. "Our electricity transmission network: A vision for 2020". URN:09D/717 DECC, July. Available online at: http://webarchive.nationalarchives.gov.uk/20100919181607/http:/www.ensg.gov.uk/assets/ensg_transmission_pwg_full_report_final_issue_1.pdf.

Fanzeres, B., A. Street, and L. A. Barroso. 2015. "Contracting strategies for renewable generators: A hybrid stochastic and robust optimization approach". *IEEE Transactions on Power Systems*. 30(4): 1825–1837.

Gammons, S., R. Druce, R. Brejnholt, G. Strbac, C. V. Konstantinidis, D. Pudjianto, and R. Moreno. 2011. "Project TransmiT: Impact of Uniform Generation TNUoS". Report prepared by NERA and Imperial College for RWE npower. Available online at: http://www.nera.com/67_7261.htm.

Glatvitsch, H. and F. Alvarado. 1998. "Management of multiple congested conditions in unbundled operation of a power system". *IEEE Transactions on Power Systems*. 13(3): 1013–1019.

Gleadow, J., S. Todd, and B. Smith. 2009. *Advanced Grid Reliability Standards. SQSS International Workshop*. London, UK: Imperial College.

He, J., L. Cheng, D. S. Kirschen, and Y. Sun. 2010. "Optimising the balance between security and economy on a probabilistic basis". *IET Generation, Transmission & Distribution*. 4(12): 1275–1287.

IFRWG. 2010. "Interconnector frequency response report". Interconnector Frequency Response Working Group, National Grid, 13th May. Available online at: http://www.nationalgrid.com/NR/rdonlyres/26617B09-3CC8-4543-ADB1-D6D3A2906C1C/41171/IFRWGReport_V01_Panel.pdf.

Jirutitijaroen, P. and C. Singh. 2008. "Reliability constrained multi-area adequacy planning using stochastic programming with sample-average approximations". *IEEE Transactions on Power Systems*. 23(2): 504–513.

Kariuki, K. K. and R. N. Allan. 1996. "Applications of customer outage costs in system planning, design and operation". *IEE Proceedings — Generation, Transmission and Distribution*. 143(4).

Kirschen, D. S. and D. Jayaweera. 2007. "Comparison of risk-based and deterministic security assessments". *IET Generation, Transmission & Distribution*. 1(4): 527–533.

Kirschen, D. and F. Bouffard. 2009. "Keeping the lights on and the information flowing". *IEEE Power & Energy Magazine*. 7(1): 50–60.

Kirschen, D. and D. P. Nedic. 2002. "Consideration of hidden failures in security analysis". In: *14th Power Systems Computation Conference*. Sevilla, Spain.

Kundur, P. and C. Taylor. 2007. "Blackout experiences and lessons, best practices for system dynamic performance, and the Role of new technologies". *IEEE Task Force Report*.

Leite da Silva, A. M., J. Guilherme de Carvalho Costa, L. Antonio da Fonseca Manso, and G. J. Anders. 2002. "Transmission capacity: Availability, maximum transfer and reliability". *IEEE Transactions on Power Systems*. 17(3): 843–849.

Li, W. 2011. *Probabilistic Transmission Systems Planning*. Wiley.

London Economics. 2013. "The value of lost load (VoLL) for electricity in Great Britain". Report for OFGEM and DECC, July 2013. Available online at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/224028/value_lost_load_electricty_gb.pdf.

Maceira, M. E., L. G. Marzano, D. D. Penna, A. L. Diniz, and T. C. Justino. 2015. "Application of CVaR risk aversion approach in the expansion and operation planning and for setting the spot price in the Brazilian hydrothermal interconnected system". *International Journal of Electrical Power & Energy Systems*. 72: 126–135.

Madani, V., D. Novosel, and R. King. 2008. "Technological breakthroughs in system integrity protection schemes". In: *16th Power Systems Computation Conference*. Glasgow, Scotland.

McCalley, J. D., V. Vittal, and N. Abi-Samra. 1999. "An overview of risk based security assessment". In: *IEEE Power Engineering Society General Meeting*. Canada.

McCalley, J. D., V. Vittal, and N. Abi-Samra. 2000. "Use of Probabilistic Risk in Security Assessment: A Natural Evolution". In: *International Conference on Large High Voltage Electric Systems (CIGRE)*. Paris, France.

McCalley, J., S. Asgarpoor, L. Bertling, R. Billinion, H. Chao, J. Chen, J. Endrenyi, R. Fletcher, A. Ford, C. Grigg, G. Hamoud, D. Logan, A. P. Meliopoulos, M. Ni, N. Rau, L. Salvaderi, M. Schilling, Y. Schlumberger, A. Schneider, and C. Singh. 2004. "Probabilistic security assessment for power system operations". In: *IEEE Power Engineering Society General Meeting*. Denver, USA.

Molina, J. D., J. Contreras, and H. Rudnick. 2014. "A risk-constrained project portfolio in centralized transmission expansion planning". *IEEE Systems Journal*: 1–9. Available online.

Moreno, R., Y. Chen, and G. Strbac. 2015. "Evaluation of Benefits of Coordinated DC & AC Flexible transmission systems with probabilistic security and corrective control". In: *IET International Conference on Resilience of Transmission and Distribution Networks (RTDN)*. Birmingham, UK.

Moreno, R., D. Pudjianto, and G. Strbac. 2010a. "Future transmission network operation and design standards to support a low carbon electricity system". In: *IEEE Power Engineering Society General Meeting*. Minnesota, USA.

Moreno, R., D. Pudjianto, and G. Strbac. 2012. "Integrated reliability and cost–benefit-based standards for transmission network operation". *Proceedings of the Institution of Mechanical Engineers Part O: Journal of Risk and Reliability*. 226(1): 75–87.

Moreno, R., D. Pudjianto, and G. Strbac. 2013. "Transmission network investment with probabilistic security and corrective control". *IEEE Transactions on Power Systems*. 28(4): 3935–3944.

Moreno, R. and G. Strbac. 2015. "Integrating high impact low probability events in smart distribution network security standards through CVaR optimisation". In: *IET International Conference on Resilience of Transmission and Distribution Networks*. Birmingham, UK.

Moreno, R., G. Strbac, F. Porrua, S. Mocarquer, and B. Bezerra. 2010b. "Making room for the boom". *IEEE Power & Energy Magazine*. 8(5): 36–46.

Nedic, D. P., I. Dobson, D. Kirschen, B. A. Carreras, and V. E. Lynch. 2006. "Criticality in a cascading failure blackout model". *International Journal of Electrical Power & Energy Systems*. 28: 627–633.

NGC. 1994. *A Review of Transmission Security Standards*. UK: National Grid Company.

Ni, M., J. D. McCalley, V. Vittal, and T. Tayyib. 2003. "Online risk-based security assessment". *IEEE Transactions on Power Systems*. 18(1): 258–265.

North American Reliability Corporation. 1996. *Available Transfer Capability Definitions and Determination*. New Jersey, USA: NERC.

Panteli, M. and P. Mancarella. 2015. "Influence of extreme weather and climate change on the resilience of power systems: Impacts and possible mitigation strategies". *Electric Power Systems Research*. 127: 259–270.

Pham, T. T. H., Y. Besanger, and N. Hadjsaid. 2009. "New challenges in power system restoration with large scale of dispersed generation insertion". *IEEE Transactions on Power Systems*. 24(1): 398–406.

Rios, M. A., D. Kirschen, D. Jayaweera, D. P. Nedic, and R. N. Allan. 2000. "Value of security: Modeling time-dependent phenomena and weather conditions". *IEEE Transactions on Power Systems*. 17(3).

Rockafellar, R. T. and S. Uryasev. 2000. "Optimization of Conditional Value-at-Risk". *Journal of Risk*. 2(3): 21–41.

Sattinger, W., A. G. Etrans, J. Bertsch, and P. Reinhardt. 2006. "Operational experience with wide area monitoring systems — Paper SC B5-216". CIGRE Biennial Session, Paris, France.

Siddiqi, S. N. and M. L. Baughman. 1995. "Value-based transmission planning and the effects of network models". *IEEE Transactions on Power Systems*. 10(4): 1835–1842.

SQSS. 2010. "Working group reports 1 to 6. Fundamental Review of the NETS SQSS, April 2010 Consultation". Available at: http://www.nationalgrid.com/uk/Electricity/Codes/gbsqsscode/fundamental.

Strbac, G., S. Ahmed, D. Kirschen, and R. Allan. 1998. “A Method for computing the value of corrective security”. *IEEE Transactions on Power Systems*. 13(3): 1096–1102.

Strbac, G., R. Moreno, D. Pudjianto, and M. Castro. 2011. “Towards a risk-based network operation and design standards”. In: *IEEE Power Engineering Society General Meeting*. Detroit, USA.

Strbac, G., C. Ramsay, and R. Moreno. 2009. “This sustainable isle — Can regulated markets deliver on the United Kingdom’s green power challenges?” *IEEE Power & Energy Magazine*. 7(5): 42–52.

Street, A., L. A. Barroso, B. Flach, M. V. Pereira, and S. Granville. 2009. “Risk constrained portfolio selection of renewable sources in hydrothermal electricity markets”. *IEEE Transactions on Power Systems*. 24(3): 1136–1144.

Sun, K., D. Z. Zheng, and Q. Lu. 2003. “Splitting strategies for islanding operation of large-scale power systems using OBDD-based methods”. *IEEE Transactions on Power Systems*. 18(2): 912–923.

Xiao, F. and J. D. McCalley. 2007. “Risk-based security and economy tradeoff analysis for real-time operation”. *IEEE Transactions on Power Systems*. 22(4): 2287–2288.

Xiong, P., P. Jirutitijaroen, and C. Singh. 2016. “A distributionally robust optimization model for unit commitment considering uncertain wind power generation”. *IEEE Transactions on Power Systems*. Available online.