

Further, this paper shows that it is possible to run integrated analyses in a prototype consisting of a power market simulator, a power system simulator and a reliability analysis tool, while taking protection system misoperations, temporal variation in interruption costs and reliability data, as well as alternative strategies for corrective actions in the contingency analysis into account. The impact of the integration is demonstrated by applying a realistic test case studied with respect to reliability of supply indices.

A first conclusion is that the choice of operating state(s) for the assessment is of vital importance for the reliability results. The test case also shows that the enhanced modelling options of protection system reliability, time dependency, and corrective actions have considerable influence on the results in terms of aggregated indices for the entire network. It is shown that they may affect the reliability differently for single load points. Including corrective actions, as well as protection and control may be of vital importance for the results, while there is less, but still negative, effect from the temporal variation of reliability data in this particular case. This is mainly due to the choice of only including seasonal variation in the reliability data in the case study presented in this paper.

Altogether, this implies that care has to be taken when utilising the results, e.g., in network expansion studies. What is identified as the best candidate for expansion will depend on the modelling choices, underlining the importance of knowledge of the network under study.

The significance of the individual aspects relative to each other not only gives valuable input on which factors should be definitely included in a comprehensive reliability analysis, but also valuable information on where the highest potential for improvement in the reliability lies. For instance for the test network studied in this paper it is clear that the ability to reschedule generation quickly increases the reliability significantly.

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X. REFERENCES

- [1] M. Rausand, Risk assessment: Theory, methods, and applications, John Wiley & Sons, 2013.
- [2] G. Kjølle and O. Gjerde, "Integrated approach for security of electricity supply analysis," *International Journal of Systems Assurance Engineering and Management*, vol. 1, pp. 163-169, 2010.
- [3] H. Kile, K. Uhlen, and G. Kjølle, "Scenario selection in composite reliability assessment of deregulated power systems," *International Journal of Electrical Power & Energy Systems*, vol. 63, pp. 124-131, Dec. 2014.
- [4] V. V. Vadlamudi, O. Gjerde, and G. Kjølle, "Impact of protection system reliability on power system reliability: A new minimal cutset approach," *Proc. 13th Intl. Conference on Probabilistic Methods Applied to Power Systems*, Durham, U. K., Jul. 2014, pp. 1-6.
- [5] G. Kjølle, I. B. Sperstad, and S. H. Jakobsen, "Interruption costs and time dependencies in quality of supply regulation," *Proc. PMAFS 2014*, Durham, U. K., United Kingdom, Jul. 2014.
- [6] I. B. Sperstad, S. H. Jakobsen, and O. Gjerde, "Modelling of corrective actions in power system reliability analysis," in *Proc. IEEE PowerTech*, Eindhoven, The Netherlands, Jul. 2015.
- [7] O. Gjerde, L. Warland, L. Aleixo, and I. H. Døskeland, "Integrated approach for reliability of electricity supply analysis – studies of demonstration network," *Proc. CIGRE Session*, Paris, France, Aug. 2012.
- [8] V. V. Vadlamudi, O. Gjerde, and G. Kjølle, "Consideration of transmission protection system response in reliability of electricity supply analysis – case study," *Proc. CIGRE Session*, Paris, France, Aug. 2014.
- [9] EPRI Report, "Transmission system reliability methods – mathematical models, computing methods and results," EPRI EL-2526, Jul. 1982.
- [10] H. Kile, K. Uhlen, and G. Kjølle, "The important role of feature selection when clustering load and generation scenarios," *Proc. 5th IEEE PES Asia-Pacific Power and Energy Engineering Conference*, Hong Kong, Dec. 2013, pp. 1-5.
- [11] R. Billinton, R. N. Allan: Reliability evaluation of power systems, Plenum Press, New York, second edition, 1996.
- [12] V. V. Vadlamudi, O. Gjerde, and G. Kjølle, "Dependability and security-based failure considerations in protection system reliability studies," *Proc. IEEE Innovative Smart Grid Technologies Europe Conference*, Copenhagen, Denmark, Oct. 2013, pp. 1-5.
- [13] IEC 60050-448:1995, International Electrotechnical Vocabulary - Chapter 448: Power system protection
- [14] V. V. Vadlamudi, O. Gjerde, and G. Kjølle, "Impact of substation configuration on protection system failure propagation and its effect on reliability of supply," *Proc. 18th Power Systems Computation Conference*, Wroclaw, Poland, Aug. 2014, pp. 1-8.
- [15] G. H. Kjølle, K. Samdal, and K. Brekke, "Incorporating short interruptions and time dependency of interruption costs in continuity of supply regulation," *Proc. CIGRE*, Prague, Czech Republic, Jun. 2009
- [16] "Regulations governing financial and technical reporting, income caps for network operations and transmission tariffs," Reg. No. 302 of 11 March 1999, changed as of 7 Dec. 2007, <http://www.nve.no>.
- [17] G. H. Kjølle, K. Samdal, B. Singh, and O. A. Kvitastein, "Customer costs related to interruptions and voltage problems: Methodology and results," *IEEE Trans. on Power Systems*, vol. 23, pp. 1030-1038, Aug. 2008.
- [18] R. Billinton, W. Li, "Reliability assessment of electric power systems using monte Carlo Methods," Plenum Press, New York, 1994.
- [19] K. Alvehag, "Risk-based method for reliability investments in electric power distribution systems," Doctoral Thesis, Royal Institute of Technology, Sweden, 2011
- [20] G. H. Kjølle and A. T. Holen, "Reliability and interruption cost prediction using time dependent failure rates and interruption costs," *Quality and Reliability Engineering International*, vol. 14, no. 3, pp. 159-165, May/June 1998.
- [21] K. Alvehag and L. Söder, "An activity-based interruption cost model for households to be used in cost-benefit analysis," *Proc. IEEE Powertech Lausanne*, Switzerland, Jul. 2007.
- [22] G. H. Kjølle, A. T. Holen, G. G. Lovås, and K. A. Opskar, "Reliability and interruption cost prediction: Comparison of a chronological, weather type driven mechanism with statistical based time dependent patterns," *Proc. Intl. Conference on Probabilistic Methods Applied to Power Systems*, Vancouver, Canada, Sep. 1997.
- [23] O. Wolfgang, A. Haugstad, B. Mo, A. Gjelsvik, I. Wangensteen, and G. Doorman, "Hydro reservoir handling in Norway before and after deregulation," *Energy*, vol. 34, pp. 1642-1651, Oct. 2009.
- [24] C. Grigg *et al.*, "The IEEE reliability test system -1996: A report prepared by the reliability test system task force of the application of probability methods subcommittee," *IEEE Transactions on Power Systems*, vol.14, no.3, pp.1010-1020, Aug. 1999.
- [25] R. Billinton *et al.*, "A reliability test system for educational purposes-basic data," *IEEE Power Engineering Review*, vol. 9, no. 8, pp. 67-68, Aug. 1989.