<http://www.diva-portal.org>

This is the published version of a paper presented at *2014 International Conference on Probabilistic Methods Applied to Power Systems, PMAAPS 2014, 7 July 2014 through 10 July 2014, Durham, United Kingdom*.

Citation for the original published paper:

Babu, S., Hilber, P., Jürgensen, J. (2014)

On the status of reliability studies involving primary and secondary equipment applied to power system.

In: *2014 International Conference on Probabilistic Methods Applied to Power Systems, PMAAPS 2014 - Conference Proceedings* (pp. 6960653-). IEEE

<http://dx.doi.org/10.1109/PMAAPS.2014.6960653>

N.B. When citing this work, cite the original published paper.

Permanent link to this version:

<http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-157937>

On the Status of Reliability Studies Involving Primary and Secondary Equipment Applied to Power System

Sajeesh Babu, Patrik Hilber and Jan Henning Jürgensen

School of Electrical Engineering
KTH Royal Institute of Technology
Stockholm, Sweden
sbabu@kth.se

Abstract—Growth in infrastructure and energy utilization consistently put forward the demand for added quality and quantity of electric power. Reliability concerns over power systems are widespread within its different associated divisions like ‘primary’ power system structure, protection system, control equipment, ICT (Information and Communication Technologies) etc. This paper is a review of the present status of practices regarding reliability analysis in these divisions and works towards collectively assessing some of the studies in the respective areas. The idea of integrating reliability analysis from the above areas is introduced along with pointing out the major challenges associated. A set of tools for operators to make use in these reliability evaluations and modelling are mentioned. The earlier attempts towards combined overall system reliability analysis are discussed and the approach in this regard with the help of ‘control functions’ is emphasised. The paper includes works dealing with theory, different methodologies and data associated with power system reliability.

Keywords—power system reliability; power system control; substation automation; protection system reliability; power system modeling.

I. INTRODUCTION

The demand for reliable supply of electric power is an important research topic which gains more and more significance over the years. The performance level of the power system is being consistently challenged to keep up with the variations and expansions in power utilisation. Reliability concerns over the power systems are distributed within different areas. Hence, for clearly understanding the requirements of an advanced reliability analysis method, it is crucial to have a grip on the present state of reliability evaluation on the overall setup of power system.

This paper presents an overview of the status of practices concerning reliability of both primary and secondary equipment applied to power systems. Primary grid components such as overhead lines, cables, transformers, bus-bars, circuit breakers (CB) etc. are those through which the actual flow of electricity between the generation and consumers occurs. Whereas, the secondary equipment comprises all the units employed to monitor, manage, control and communicate the data and information concerning the primary side. In other words, the secondary system components include the control and ICT (Information and Communication Technologies) apparatus present in power system management. Even though

this division can be stated by definition, certain inherent units like protection systems, measurement systems, voltage control etc. may not be featured to be confined to one side alone. Their functional behaviour overlaps in varying degrees over both primary and secondary divisions.

Even though a number of studies on the active management of power systems have been done, the reliability influence of the control and ICT system which closely associates with the former has not yet been captured as required. Today, about 30% of the failures occurring in distribution substations are recognised to be triggered from the secondary equipment [1]. The communication between primary and secondary system is expected to grow noticeably with all proposed advancements in power grid technology. Hence the respective impact on the system reliability should be more in the coming generations of grid structure.

Chapter II gives a short description on what reader gets from this work, the context of general discussion in the paper, and how similar studies are addressed in different literature sources. Chapter III reviews some of the reliability analysis studies conducted specifically on a set of equipment and then some excluded sets. Chapter IV introduces a set of tools that can be employed in modelling and analysis of power system reliability. Chapter V is on the challenges, overview of the state of the art and some description of a specific approach in reliability analysis which associatively consider the influence of both primary and secondary systems. Finally Chapter VI concludes the work.

II. CONTEXT OF STUDY

Apart from the foreseen enhanced impact of secondary system on power grid, one motivation to produce this paper is that the background of the overall reliability concerns on advanced power systems may possibly be found widespread in study and literature sources relating different areas. Advancing studies in primary and secondary systems separately can lead to sub-optimal decisions in respective areas. The context of collectively assessing reliability of power systems is approached by various studies till date in different perspectives. Cyber physical modelling in control engineering performing a number of studies involving co-simulation platforms can be seen increasingly, during recent years[2-4]. Here, mathematical relations are observed between control equations concerning some feature of power grid and they relate to the corresponding control equations of the secondary system.

Project sponsored by the Risk Analysis program supported by Elforsk
<http://www.elforsk.se/>

We also thank Mathias Ekstedt, Associate Professor, ICS department, and members of RCAM group at KTH for the valuable review and comments.

Certain research in computer technologies as [5] address similar objective while attempting to extend cyber control and security towards substation architectures as an application case. Another significant approach is the study on reliability impacts of advanced automation involved in coming generation of power system management [6]. A number of studies particularly focusing with in the sub-area of advanced protection schemes as in [7] also are concerned with a combined reliability concept, as protection systems operate closely connected to control equipment. The authors of this paper work towards bringing the reliability analysis for primary system and secondary system to a unified platform with consideration to their logical and functional relation.

III. EQUIPMENT SPECIFIC RELIABILITY ANALYSIS

Reliability evaluations in power systems conducted till date are mostly focused on one individual set of equipment but not the overall system. Examples are primary components in substation, control room ICT system, protection equipment, etc. This chapter briefly reviews such studies conducted specifically within a sub-section of power system. Some discussion on the reliability concerns put forward by the human operator and situation awareness is included. Indications to the general availability of information sources specific to each section according to authors' opinion are also given. Understanding these individual methods and respective features is a pre-requisite for associating them.

A. Traditional Primary Reliability Analysis

Traditional reliability analysis signifies the evaluation of reliability constraints of critical primary system components like lines, cables, bus-bars, transformers, switchgear equipment etc. from their respective performance observation records and statistical analysis. Not much attention is given to the reliability consequences reflected from the secondary equipment side. Fig. 2 displays the interaction of some of these components with system reliability. In this popular way of analysis, average rate of failures and repair durations observed over a period of time are the key indices.

Statistical and probabilistic measures applied to reliability studies in generation, transmission, distribution levels along with plant and station reliability are discussed in [8] in detail. The book covers the respective evaluation theory for these levels, significant analysis methodologies in practice, commonly used indices and calculation. Popular reliability analysis methods are Fault Tree Analysis (FTA), Markov modelling, Reliability Block Diagrams (RBD), Bayesian systems, Monte Carlo simulation etc. Theories and application of these methods with case studies are covered in quite many projects in different range and complexities [8-11]. There are a number of other literature sources as [12] and studies on substation operation and maintenance records [13, 14] which discusses the statistical observation and available data. Hence it may be summarized that there are quite a few information sources available both for theoretical studies and practical observations when it comes to traditional reliability studies on the primary system.

B. Secondary Equipment Reliability

The secondary equipment, in the context of this paper, comprises the set of systems employed in the monitoring, management, control and communication of the data and information concerning the primary part. Though the background of control and ICT equipment may be observed independently within the area of computer technologies, here the discussion holds on to the context mentioned above. Survey [15] is a detailed study of the different network architectures, communication media, protocols and standards along with their features employed in electric systems. It provides a framework which aids electric utilities in planning system automation with advanced communication networks such as Power Line Communications (PLC), wireless communication, internet based virtual private networks and satellite communication. The survey also helps to compare these networking options along with data observations on component availability which can form a base for generalized secondary component reliability evaluations.

A highly reliable and cost effective communication framework is the core of system automation. While looking at reliability analysis of the secondary side, it is important to identify the layers and functionally interconnected components. As shown in Fig. 1, the ICT framework in substation management can be seen distributed in 3 layers: bay level, remote level and substation level [6, 16]. The local bay computer connected to the management of specific equipment should reliably communicate with the higher control levels. An automated remote control capable of communicating within these layers resulting in optimal decision support is the objective of system automation. [11, 16-18] explain the reliability representation of bay level control units along with some corresponding data and Fig 2 illustrates interaction of some of these units with overall system.

Fig. 1. Hierarchial Layers of ICT framework in Substation Automation

Some more related works within this area were reviewed. Reliability Block Diagram models of a variety of substation automation architectures along with a component importance analysis is conducted in [19]. Based on object-role modeling, [20] introduces a reference model for control and automation systems, and develops fundamental concepts for security based on the analysis of the model. To have deeper clarity on the functionality of automation systems, where interconnected depended structures cause complexity in physical, operational and economic aspects, the relationship between constituent elements should be modelled. Not many studies till date appear to have covered much on further complexities and considerations while evaluating the system influence of secondary equipment reliability and hence the availability of background information is comparatively scarce. Clarifying the dependencies in terms of data and control flow on the

secondary side, affecting the overall system performance is critical. One way forward can be the careful analysis of substation failure registers and tracking back to the causal particulars of failures triggered from secondary side.

C. Protection System Reliability

The operation of switchgear protection equipment functionally overlaps with both primary and secondary systems. It is one part of the power system which consistently communicates with control and ICT components so as to bring desired protective switching actions in the primary network. Hence this particular subsection of reliability study is popular and a number of research works have been taking place in this field over the years. For example [21] is a paper that presents the results of an extensive survey based on the disturbance reports and special investigation reports for the period 1976-2002 on incorrect protection operations occurred in Sweden on the power network owned by E.ON Sverige, (then known as Sydkraft). The survey examines the percentage of power system disturbances accounted by incorrect protection operations and related malfunctions. The conclusive observations state that about 7% of power system disturbances are caused by incorrect operation of protection system. Detailed analysis of survey results subdivides these incorrect operation disturbances further, according to the nature and locality of faults. Compared to this work, [22] consolidates results from a more recent survey on circuit breaker failures for SF6 and minimum-oil CBs in the Swedish and Finnish transmission systems and observes the role of voltage levels, operation frequency etc. Even modern relays used in protection schemes are reported to have reliability insufficiencies due to incorrect operations.

Advanced remedial schemes, which monitor system conditions to provide pre-planned corrective measures in case of contingencies, are generally called System Protection Schemes (SPS). [23] is a project report which studies the background, failure mode taxonomy, modeling ideas and operational consequences for SPS with a framework focusing on both process and system levels. From the above mentioned surveys and the availability of a number of references [1, 24-27], it is evident that comparatively more reliability centered studies have taken place in the field of protection system reliability.

D. More Equipment Specific Reliability Studies

Apart from those mentioned until now, there are power system components and units not discussed in detail here, whose reliability can be associated to either one or more equipment from the previous sections. On-Load Tap Changers (OLTC), Automatic Voltage Control (AVC), Automatic Frequency Control (AFC), Current Transformer (CT), Potential Transformer (PT), sensors, detectors etc. are some of them. Based on the observed scarcity of supporting reliability centered researches, more studies seem to be required to investigate deeper in to the impacts on system reliability from these units. Fig. 2 illustrates the distribution of the influence of some constituent power system units as per authors' opinion based on review of some studies within respective areas [28, 29].

Fig. 2. Distribution of component reliability influence over primary and secondary sides

Most of the component units from previous sections are illustrated in the figure. According to the physical position in the grid and functional connectivity, each unit interacts in different degrees with primary or secondary system. Section V. A further discusses the variations in interaction of such systems.

E. Impact of the Human Operator and Situation Awareness

Monitoring and control of the primary equipment requires human involvement. Investigation of the August 14, 2003 power blackout in North America presented that one of four major reasons, which caused the blackout, was insufficient situational awareness of the system operators [30]. This was due to a lack of training, effective communications and adequate reliability tools. [31] (page 36) defines situation awareness as “perception of the elements in an environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future”. This concept has been studied and implemented by several industries [32]. However, [33] describes the actual need for situation awareness in the power system domain and reviews the current state of research, which was lacking in the past. Based on this work, [34] continues with an assessment of the impact of inadequate situation awareness. The paper identifies factors that influence the formation of situation awareness in the control center and discuss the effect on power system reliability. Furthermore, a model to assess the impact of insufficient situation awareness on the development of power system blackouts has been studied.

IV. TOOLS

As mentioned in Chapter II, the authors work towards bringing the reliability analysis for primary system and secondary system to a unified platform with consideration to their logical and functional relation. To approach this objective some of the available tools for reliability evaluation and modelling were reviewed. This chapter presents a brief overview of some of the tools functional in reliability studies and highlights their features. Some studies which make use of these tools are also mentioned through the body of discussion. A brief overview of the mapping of one of the tools, Archimate's modeling language with Substation Configuration Language (SCL) of IEC 61850, is emphasised.

A. NEPLAN

The simulation tool NEPLAN, developed by BCP Switzerland, could be utilized to analyse, plan, optimize and simulate electrical power networks [35]. Besides optimal power flow and transient stability calculations, it offers an asset management platform for reliability analysis. The addition of failure data to new or existing power system models provides NEPLAN the data to compute reliability indices of individual load points and the overall power system as well as the cost of unreliability. For example, the failure rate, repair time and switching time of components are data for reliability calculations [36, 37]. In [36] approximately $2/3^{\text{rd}}$ of the transmission system area of England were modeled in NEPLAN and used to evaluate outage event's impact on the system for the computation of component importance indices. The Great Britain study presented that the majority of the outage events do not result in interruption on distribution and generation level but in reduction of security margins for transmission system operators. Recently, due to high maintenance costs and uncertainties in operation, the tool was used for reliability analysis studies of on and offshore wind farms to optimize maintenance costs [37-39].

B. BlockSim

ReliaSoft's BlockSim is a commercial software for reliability analysis. It provides the user with a program for system reliability, availability, maintainability and related analyses [40]. The software offers to model systems and processes with RBD configurations and FTA gates. In [41], the need for a standard tool or a tool set for power system reliability analysis is identified and thus several evaluation methods were compared to the RBD method with BlockSim. The paper concludes RBD with BlockSim as a practical and applicable technique for reliability analysis with advantages such as easy construction, understanding and modification of the model. It also presents some benefits, for example, all reliability indexes are obtainable and that there are no restrictions on the failure, repair, and other time distributions in the systems. On the other hand, the study [42] compared BlockSim with two other software packages: ARNIC Raptor and Relx Reliability Block Diagram, and raise awareness that all results of reliability modelling should be critically analysed through understanding modelling methodology and solution algorithms.

C. Architecture Analysis Tools

Enterprise Architecture Analysis Tool (EAAT) is a software system for modeling and analysis of enterprises and their information systems. The EAAT tool is inspired by graphical decision-theoretic methods, such as Bayesian networks and influence diagrams [43]. In order to support decision making so as to improve enterprise systems, properties such as availability, interoperability etc. need to be analysed [44, 45].

For creating architectural models for information systems and Enterprise Architecture (EA), ArchiMate was developed as an open and independent modeling language. The tool aids in describing construction and operation of business processes, organizational structure, information flow, IT systems and

technical infrastructure for enterprises. In [46] an application of the modeling platform is done, where availability analysis based on Fault Tree is used to perform case studies in the banking and electrical utility industries. Whereas [47] adapts Probabilistic Relational Model (PRM) which consist of a modification ArchiMate model, as an assessment framework for the availability analysis of power systems and illustrates its value as a decision support tool.

Furthermore, a mapping between ArchiMate and the configuration language, SCL, of IEC 61850 is done in [48]. The IEC 61850 is the key international standard for the communication network and systems in substations and those for power utility automation. The standard considers the generation of substation management using communications with Intelligent Electronic Devices (IEDs) [49]. The mapping achieved in [48] relates the structure, functions and components in automated substations to corresponding entities within ArchiMate's model architecture. The work is supposed to assist utilities to understand how to model their respective application cases in to the software platform with the added advantage of keeping up with the IEC standards while doing this.

V. OVERALL RELIABILITY ANALYSIS ON COMBINED PRIMARY AND SECONDARY SYSTEMS

A. Challenges in Investigating on Integrated System

The nature of interactions between control and primary systems might be far complex to be captured entirely from a generalised reliability perspective. For enhanced operational efficiency of automated systems, the ICT needs to have a reasonable degree of access to information and data of and on the status of primary grid components. Due to various timing of erection and technical reasons, practically the level of communication varies widely in quantity and quality. Both automated and manually operated systems might co-exist in certain sections of grid.

Advanced automated grid components like CB relays, OLTCs etc. may be communicating adequately with secondary system compared to many other primary components. The data signals from measuring equipment, sensors, protection and safety equipment etc. may as well be reaching the control systems with sufficient quality. But the manually operated systems in the same grid, should to be considered as equipment with poorer speed and rate of communication. For example, consider a mechanically operated disconnector switch, which needs to be attended by technicians when they receive an alert signal of some sort. Another case may be a conductor line where faults are detected through expert inspections. From an automated system operation perspective, these are certain challenges that introduce communication gaps in data fed in and out of the ICT system.

B. Review of Studies on Integrated System

This section briefly discusses couple of works within the state of the art of combined risk and reliability studies considering both primary and secondary systems. These two works have significantly motivated and contributed towards the

approach adopted by authors, which is mentioned in the next section. [5] approaches reliability evaluation using PRM formalisation of automated substation structures. Here the power system can be framed as per components, applications and logical structure with corresponding reliability factors associated to it. The framework modelling choice on logical or physical structure and the idea of relating the two are the highlight features. When considering the IEDs connected in an automated substation, a physical network explains the modelling hardware and the properties specific to different components. Whereas the logical construct refers to the implemented functionality achieved through the physical network. Features in power system structures like redundancy can be modelled in both function and logic. Hence defining the relations between elements is part of PRM formalisation.

In [6], the concept of relating the control functions with primary component operations, followed by the reliability evaluation which relates them is discussed. Some sample case studies are presented on this framework. Initially, a set of functions and physical component actions are defined based on understanding of automated control systems and primary grid. How combinations of failure in these functions affect the actions, are represented by event tree and respective status of each action. Having a set of defined functions which are relating to physical actions occurring mainly in primary side aids to recognise and relate the influence of secondary equipment on primary. The concept of using control functions is adopted from [6] and combining it with the theory, data, methods and tools referred in this paper, the authors approach reliability evaluation of practical complex power system sections with hierarchical inter-dependencies, causal factors etc.

C. Control Function Approach

The authors approach the task of collective system reliability analysis, through defining an updated value for reliability indices. Reliability of a component in the primary system that requires some level of controlling from the secondary side is affected by the reliability of respective systems in the secondary side which delivers that control. Hence the traditionally used value of availability need to be updated with a factor reflected from the associating secondary system with better attention to the details and functionality of primary. The appropriate data for both systems should be properly chosen and combined evaluations have to be performed with latest tools developed which handle a sufficient degree of concerns. The updated indices should provide more accurate calculation figures that can hold well and provide better realistic analysis.

As shown in Fig. 3, control function approach for connecting secondary and primary component reliability initially involves proper selection of component availability data of secondary side. Associating the availability of the secondary equipment responsible for each control function, the respective function availability can be modeled. The derivation of range and degree by which each function impacts the corresponding primary system defines the updated system reliability.

Fig. 3. Control function approach for relating secondary component reliability data to corresponding primary component

VI. CLOSURE

This paper conducts a review of reliability studies carried out in power systems and related aspects of it. The nature and features of equipment specific evaluations were initially observed. This suggests that an overall system level analysis may be beneficial over more than one sub-optimal solutions in different constituent sections. Thus the idea of analysing the system reliability with a combined focus on both primary and secondary systems was emphasized and an overview of its state in research was done. It is suggested that analysis of the system in terms of control functions might be an option and this approach was discussed briefly. The total economic aspects and viability of such methods are yet to be determined through future research.

REFERENCE

- [1] G. H. Kjølle, Y. Aabø, and B. T. Hjartsjø, "Fault Statistics as a Basis for Designing Cost-Effective Protection and Control Solutions," Norway, [Online]. Available: http://www.sintef.no/project/Vern_kontroll%20og%20automatisering/cigre_2002.pdf.
- [2] M. Stifter, E. Widl, F. Andren, A. Elsheikh, T. Strasser, and P. Palensky, "Co-simulation of components, controls and power systems based on open source software," in *Power and Energy Society General Meeting (PES), 2013 IEEE*, 2013, pp. 1-5.
- [3] L. Hua, S. Sambamoorthy, S. Shukla, J. Thorp, and L. Mili, "Power system and communication network co-simulation for smart grid applications," in *Innovative Smart Grid Technologies (ISGT), 2011 IEEE PES*, 2011, pp. 1-6.
- [4] M. Armendariz, M. Chenine, A. Al-Hammouri, and L. Nordström, "A Co-Simulation Platform for Medium/Low Voltage Monitoring and Control applications," 2014.
- [5] J. König, L. Nordstrom, and M. Osterlind, "Reliability Analysis of Substation Automation System Functions Using PRMs," *IEEE Transactions on Smart Grid*, vol. 4, pp. 206-213, Mar 2013.
- [6] H. Hajian-Hoseinabadi, "Impacts of Automated Control Systems on Substation Reliability," *IEEE Transactions on Power Delivery*, vol. 26, pp. 1681-1691, Jul 2011.
- [7] B. G. Kim, H. G. Kang, H. E. Kim, S. J. Lee, and P. H. Seong, "Reliability modeling of digital component in plant protection system with various fault-tolerant techniques," *Nuclear Engineering and Design*, vol. 265, pp. 1005-1015, 2013.
- [8] R. Billinton and R. N. Allan, *Reliability evaluation of power systems* vol. 2: Plenum press New York, 1984.
- [9] L. Pottonen, U. Pulkkinen, and M. Koskinen, "A Method for Analysing the Effect of Substation Failures on Power System Reliability," *15th PSCC, Liege*, pp. 22-26, 2005.
- [10] M. Al-Muhaini and G. T. Heydt, "Evaluating Future Power Distribution System Reliability Including Distributed Generation," *IEEE Transactions on Power Delivery*, vol. 28, pp. 2264-2272, Oct 2013.

- [11] L. Andersson, K. P. Brand, C. Brunner, and W. Wimmer, "Reliability investigations for SA communication architectures based on IEC 61850," in *Power Tech, 2005 IEEE Russia*, 2005, pp. 1-7.
- [12] F. Roos and S. Lindahl, "Distribution system component failure rates and repair times—an overview," in *Conf. Rec. the Nordic Distribution and Asset Management Conference*, 2004.
- [13] C. J. Wallnerström, L. Bertling, and L. A. Tuan, "Risk and reliability assessment for electrical distribution systems and impacts of regulations with examples from Sweden," *International Journal of Systems Assurance Engineering and Management*, vol. 1, pp. 87-95, 2010.
- [14] C. J. Wallnerström and P. Hilber, "Vulnerability Analysis of Power Distribution Systems for Cost-effective Resource Allocation," *IEEE Transactions on Power Systems*, vol. 27, pp. 224-232, 2012.
- [15] V. C. Gungor and F. C. Lambert, "A survey on communication networks for electric system automation," *Computer Networks*, vol. 50, pp. 877-897, May 15 2006.
- [16] B. Yunus, A. Musa, H. S. Ong, A. R. Khalid, and H. Hashim, "Reliability and availability study on substation automation system based on IEC 61850," in *Power and Energy Conference, 2008. PECon 2008. IEEE 2nd International*, 2008, pp. 148-152.
- [17] L. Andersson, C. Brunner, and F. Engler, "Substation Automation based on IEC 61850 with new process-close Technologies," in *Power Tech Conference Proceedings, 2003 IEEE Bologna*, 2003, p. 6 pp. Vol. 2.
- [18] L. Castro Ferreira, P. A. Crossley, and R. N. Allan, "The impact of functional integration on the reliability of substation protection and control systems," *Power Delivery, IEEE Transactions on*, vol. 16, pp. 83-88, 2001.
- [19] H. Hajian-Hoseinabadi, "Reliability and component importance analysis of substation automation systems," *International Journal of Electrical Power & Energy Systems*, vol. 49, pp. 455-463, Jul 2013.
- [20] M. Berg and J. Stamp, "A reference model for control and automation systems in electric power," *Sandia National Laboratories report SAND2005-1000C*, 2005.
- [21] T. Johansson, F. Roos, and S. Lindahl, "Reliability of protection systems - operational experience 1976-2002," in *Developments in Power System Protection, 2004. Eighth IEE International Conference on*, 2004, pp. 303-306 Vol.1.
- [22] T. M. Lindquist, L. Bertling, and R. Eriksson, "Circuit breaker failure data and reliability modelling," *IET Generation Transmission & Distribution*, vol. 2, pp. 813-820, Nov 2008.
- [23] J. McCalley, O. Oluwaseyi, V. Krishnan, R. Dai, C. Singh, and K. Jiang, "System protection schemes: limitations, risks, and management," *Final Report to the Power Systems Engineering Research Center (PSERC)*, 2010.
- [24] M. I. Ridwan, K. L. Yen, I. A. Musa, and B. Yunus, "Reliability and availability assessment of transmission overhead line protection system using reliability block diagram," in *2010 IEEE International Conference on Power and Energy (PECon)*, 2010, pp. 964-969.
- [25] A. H. Etemadi and M. Fotuhi-Firuzabad, "New Considerations in Modern Protection System Quantitative Reliability Assessment," *IEEE Transactions on Power Delivery*, vol. 25, pp. 2213-2222, 2010.
- [26] Y. Fang, A. P. S. Meliopoulos, G. J. Cokkinides, and Q. Binh Dam, "Effects of Protection System Hidden Failures on Bulk Power System Reliability," in *Power Symposium, 2006. NAPS 2006. 38th North American*, 2006, pp. 517-523.
- [27] W. Fengli, B. W. Tuinema, M. Gibescu, and M. A. M. van der Meijden, "Reliability evaluation of substations subject to protection system failures," in *PowerTech, 2013 IEEE Grenoble*, 2013, pp. 1-6.
- [28] M. Bahadomejad, G. Xinbo, and N. C. Nair, "IEC 61850 based smart load-shifting through on-load tap changer control," in *Innovative Smart Grid Technologies Asia (ISGT), 2011 IEEE PES*, 2011, pp. 1-7.
- [29] X. Ding, J. Shi, and L. Zhou, "The Research of the Smart Automatic Voltage Control(Smart AVC)," *AASRI Procedia*, vol. 4, pp. 85-89, 2013.
- [30] B. Liscouski and W. Elliot, "Final report on the august 14, 2003 blackout in the united states and canada: Causes and recommendations," *A report to US Department of Energy*, vol. 40, p. 4, 2004.
- [31] M. R. Endsley, "Toward a theory of situation awareness in dynamic systems," *Human Factors: The Journal of the Human Factors and Ergonomics Society*, vol. 37, pp. 32-64, 1995.
- [32] M. R. Endsley, *Designing for situation awareness: An approach to user-centered design*: CRC Press, 2012.
- [33] M. R. Endsley and E. S. Connors, "Situation awareness: State of the art," in *Power and Energy Society General Meeting-Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE*, 2008, pp. 1-4.
- [34] M. Panteli, P. A. Crossley, D. S. Kirschen, and D. J. Sobajic, "Assessing the Impact of Insufficient Situation Awareness on Power System Operation," 2013.
- [35] (08-12-2013). *Neplan by BCP Switzerland web page* Available: http://www.neplan.ch/html/e/e_asset_management_new.html
- [36] J. Setréus, "Identifying critical components for system reliability in power transmission systems," PhD Thesis, Electromagnetic Engineering, KTH Royal Institute of Technology, Stockholm, 2011.
- [37] B. Frankén, "Reliability Study: Analysis of Electrical Systems within Offshore Wind Parks," *Elforsk report 07:65*, November 2007.
- [38] E. Spahic, A. Underbrink, V. Buchert, J. Hanson, I. Jeromin, and G. Balzer, "Reliability model of large offshore wind farms," in *PowerTech, 2009 IEEE Bucharest*, 2009, pp. 1-6.
- [39] N. B. Negra, O. Holmstrom, B. Bak-Jensen, and P. Sorensen, "Aspects of relevance in offshore wind farm reliability assessment," *IEEE Transactions on Energy Conversion*, vol. 22, pp. 159-166, Mar 2007.
- [40] (08-12-2013). *ReliaSoft Corporation*. Available: <http://www.reliasoft.com/BlockSim/index.html>
- [41] W. Wang, J. M. Loman, R. G. Arno, P. Vassiliou, E. R. Furlong, and D. Ogden, "Reliability block diagram simulation techniques applied to the IEEE Std. 493 standard network," *Ieee Transactions on Industry Applications*, vol. 40, pp. 887-895, May-Jun 2004.
- [42] A. Brall, W. Hagen, and H. Tran, "Reliability Block Diagram Modeling - Comparisons of Three Software Packages," in *Reliability and Maintainability Symposium, 2007. RAMS '07. Annual*, 2007, pp. 119-124.
- [43] (14-04-2014). *Department of Industrial Information and Control Systems*, KTH Royal Institute of Technology. Available: <http://www.kth.se/ees/omskolan/organisation/avdelningar/ics/research/sa/p/eaat/welcome-1.387299>
- [44] M. Buschle, P. Johnson, and K. Shahzad, "The Enterprise Architecture Analysis Tool-Support for the Predictive, Probabilistic Architecture Modeling Framework," 2013.
- [45] M. Ekstedt, U. Franke, P. Johnson, R. Lagerstrom, T. Sommestad, J. Ullberg, *et al.*, "A Tool for Enterprise Architecture Analysis of Maintainability," in *Software Maintenance and Reengineering, 2009. CSMR '09. 13th European Conference on*, 2009, pp. 327-328.
- [46] P. Närman, U. Franke, J. König, M. Buschle, and M. Ekstedt, "Enterprise Architecture Availability Analysis Using Fault Trees and Stakeholder Interviews," *Enterprise Information Systems*, 2012.
- [47] J. König, U. Franke, and L. Nordström, "Probabilistic availability analysis of control and automation systems for active distribution networks," in *Transmission and Distribution Conference and Exposition, 2010 IEEE PES*, 2010, pp. 1-8.
- [48] J. König, Z. Kun, L. Nordstrom, M. Ekstedt, and R. Lagerstrom, "Mapping the Substation Configuration Language of IEC 61850 to ArchiMate," in *Enterprise Distributed Object Computing Conference Workshops (EDOCW), 2010 14th IEEE International*, 2010, pp. 60-68.
- [49] I. E. Commission, "IEC-TC57-WG10/11/12, Communication networks and systems Part 1: Introduction and overview, International Standard IEC 61850-1," ed. Geneva, Switzerland, 2003.