THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Towards Intelligent Distribution Systems: Solutions for Congestion Forecast and Dynamic State Estimation Based Protection

Ankur Srivastava

CHALMERS
UNIVERSITY OF TECHNOLOGY

Division of Electric Power Engineering
Department of Electrical Engineering
Chalmers University of Technology
Gothenburg, Sweden, 2021

Towards Intelligent Distribution Systems: Solutions for Congestion Forecast and Dynamic State Estimation Based Protection

Ankur Srivastava

This thesis has been prepared using LaTeX.

Department of Electrical Engineering
Chalmers University of Technology
SE-412 96 Gothenburg, Sweden
Phone: +46 (0)31 772 1000
www.chalmers.se

Printed by Chalmers Reproservice
Gothenburg, Sweden, 2021

To the Almighty, my parents and Sweden

Abstract

The electrical distribution systems are undergoing drastic changes such as increasing penetration level of distributed renewable energy sources, energy storage, electrification of energy-efficient loads such as heat pumps and electric vehicles, etc., since the last decade, and more changes are expected in the future. The emergence of the digitalization and advanced communication of the distribution systems to enhance the performance of the electricity infrastructure also adds further complexities. These changes pose challenges for the distribution system operators such as increased level of network congestions, voltage variations, as well as protection settings and coordination, etc. These will require the development of new paradigms to operate distribution systems securely, safely, and economically while hosting a large amount of renewable energy sources. The work presented in this thesis is part of the EU H2020 project UNITED-GRID which develops innovative solutions to support the distribution system operators by addressing some of the major challenges.

- First, the thesis proposed a comprehensive assessment framework to assess the distribution system operator's future-readiness and support them in determining the current status of their network infrastructures, market/business models, and policies and thus to identify areas for required developments. The analysis for the future-readiness of the three distribution system operators (from France, The Netherlands, and Sweden) participating in the project using the proposed assessment framework has shown that presently the distribution system operators have a rather small penetration of renewable energy sources in their grids, however, which is expected to increase in the future. The distribution system operators would need investments in flexibilities, novel forecasting techniques, advanced grid control as well as improved protection schemes. The need for the development of new business models for customers and changes in the policy and regulations are also suggested by the analysis.
- Second, the thesis developed a congestion forecast tool that would support the distribution system operators to forecast and visualize network overloading and voltage variations issues for multiple forecasting horizons ranging from close-to-real time to day-ahead. The tool is based on a probabilistic power flow that incorporates forecasts of production from solar photovoltaic and electricity demand combined with load models

along with the consideration of different operating modes of solar photovoltaic inverters to enhance the accuracy. The congestion forecast tool can be integrated into the existing distribution management systems of distribution system operators via an open cross-platform using Codex Smart Edge technology of Atos Worldgrid. The congestion forecast tool has been used in a case study for two real distribution systems (7-bus feeder and 141-bus system). It was demonstrated in the case study that the tool can predict the congestion in the networks with various prediction horizons. The congestion forecast tool would support distribution system operators by forecasting the network congestion and setting up a congestion management plan which in turn would offer them to host a higher amount of solar photovoltaic, enhanced system resiliency, mitigation of equipment ageing due to overloading, and other economic benefits.

- Finally, the dynamic state estimation based protection scheme supported by advanced measurement technologies developed within EU project UNITED-GRID has been implemented and validated experimentally at Chalmers power system laboratory. This dynamic state estimation based protection scheme has a strong advantage over the traditional protection scheme as it does not require any relay settings and coordination which can overcome the protection challenges arising in distribution grids with a large amount of renewable energy sources. The results from the validation of the dynamic state estimation based protection scheme at Chalmers laboratory have shown that the fault detection using this scheme has worked properly as expected for an application of the line protection.

Keywords: Congestion forecast, distribution system operator, dynamic state estimation, future distribution systems, future-readiness, photovoltaics, probabilistic power flow, distribution systems protection, renewables.

Acknowledgments

This work has been carried out at the Division of Electric Power Engineering, Department of Electrical Engineering, Chalmers University of Technology, Gothenburg, Sweden. The financial support for this work is provided from the UNITED-GRID project which has been funded by the European Community's Horizon 2020 Framework Programme under grant agreement no. 773717, which is gratefully acknowledged.

I want to take this opportunity to express my sincere gratitude towards my examiner, Professor Ola Carlson, for his guidance, support and encouragement during this research work. I am greatly indebted to my supervisor Dr Tuan Le, for his continuous help, motivation and support. His insightful experience, enthusiastic discussions, technical guidance and editorial assistance, have always been immensely helpful. His motivational words and advice during the challenging times will always be remembered. I would also like to acknowledge my co-supervisor Dr David Steen for his support and encouragement. His assistance with the technical work and accomplishing tasks deserves the highest appreciation despite his hectic schedule.

I want to express my gratitude towards Professor Massimo Bongiorno for always being supportive as the head.

My special words of appreciation go to my office mate Ali Fotouhi. He has been a continuous source of motivation and inspiration. His support and help made me felt like home at Chalmers and Sweden. I want to thank my intelligent, smart and busiest previous office mate, Hannes Hagmar for his support and friendship.

I would like to distinctively acknowledge Christos Agathokleous and Rabindra Mohanty for their friendship and always standing by my side. I want to thank Kyriaki Antoniadou-Plytaria for being a nice colleague and friend. Your mention takes me to flashback with all the happy travelling memories across Europe. I hope we could travel together more in future.

I am also obliged to Georgios Mademlis, Michela Diana, Ioannis Bouloumpasis, Annie Grundevik, Anna Wallin, Hanna Youn, Sara Fogelström and all other colleagues at the division for providing a pleasant working environment. I want to note my appreciation to colleagues in E2 PhD Council.

My thankful regards to Dennis Bijwaard and Omar Mansour from Smart State Technology, The Netherlands, for their cooperation in the research work. Also, I express my sincere thanks to Joni Rossi, Jacqueline Plette, Ulrika

Wahlström, Henrik Forsgren, Lucile Lemius and all other colleagues involved in EU project UNITED-GRID.

I would thank my friends Agin Vyas, Shrey Sharma, Tanushree Sahu, Milagros Navarro Navia, and Verena Steub for their affection and companionship.

I would humbly acknowledge my previous mentors Professor Sydulu Maheswarapu and Professor Saikat Chakrabarti for their guidance, encouragement and support.

I want to express my sincere gratitude towards Deepanjali Khare for her love and affection.

Finally, this would not have possible without the support and encouragement of my parents. Thanks for always being by my side.

Ankur Srivastava
Gothenburg, Sweden
March 2021

List of Abbreviations

AMI	Advanced Metering Infrastructure
ANN	Artificial Neural Network
AQCF	Algebraic Quadratic Companion Form
BFS	Backward-forward Sweep
CM	Colour-map
CP	Cumulative Probability
DER	Distributed Energy Resources
DG	Distributed Generation
DMS	Distribution Management Systems
DSE	Dynamic State Estimation
DSEBPS	Dynamic State Estimation based Protection Scheme
DSP	Digital Signal Processing
DSO	Distribution System Operator
ESS	Energy Storage Systems
ETIP	European Technology and Innovation Platforms
EU	European Union
EV	Electric Vehicles
GPS	Global Positioning System
ICT	Information and Communication Technologies
IEA	International Energy Agency
LV	Low Voltage

MV	Medium Voltage
MCS	Monte-Carlo Simulation
NERC	North American Electric Reliability Corporation
OCP	Open-Cross Platform
PDF	Probability Density Function
PEV	Plug-in Electric Vehicles
PMU	Phasor Measurement Unit
PV	Photovoltaics
PVPS	Photovoltaic Power Systems Programme
PPF	Probabilistic Power Flow
REP	Renewable Energy Production
RES	Renewable Energy Sources
SCADA	Supervisory Control and Data Acquisition
SNET	Smart Networks for Energy Transition
SRA	SmartGrids Strategic Research Agenda
TSO	Transmission System Operator
USB	Universal Serial Bus
WLS	Weighted Least Square

List of Nomenclature

${A_r}^{(p)}$	Current injection at node r for p^{th} iteration
br	Total number of branches
χ^2	Chi-squares function
constant-pf	Constant power factor mode of PV-inverter
constant-V	Voltage-reactive power mode of PV-inverter
C, C_1, C_2	Constant matrices
C_A, C_B, C_C, C_N	Capacitances of phase A, B, C, and N
η	Measurement error vector
G_A, G_B, G_C, G_N	Conductance of phase A, B, C, and N
H	Jacobian matrix
h	Component health
${I_q}^{(p)}$	Current in branch q for p^{th} iteration
${I_{rQ}}^{(p)}$	Reactive current injection at node r for p^{th} iteration
i_A, i_B, i_C, i_N	Sending end currents of phase A, B, C, and N
i_a, i_b, i_c, i_n	Receiving end currents of phase A, B, C, and N
i_{dA}, i_{dB}, i_{dC}, i_{dN}	Currents in series branches of phase A, B, C, and N
J	Objective function of state estimation
kWp	Kilowatt peak
k	Integration time step
K_{P_P}	Constant representing P proportion for active power load
K_{Q_P}	Constant representing P proportion for reactive power load

K_{P_I}	Constant representing I proportion for active power load
K_{Q_I}	Constant representing I proportion for reactive power load
K_{P_Z}	Constant representing Z proportion for active power load
K_{Q_Z}	Constant representing Z proportion for reactive power load
L_A, L_B, L_C, L_N	Reactances of phase A, B, C, and N
μ	Mean for PV and load forecast
m	Number of measurements
$m-n$	Degrees of freedom
n	Number of state variables
N	Total number of nodes
p	Probability of estimation confidence
P	Active power
P_0	Rated active power
P_{inj}	Active power injection
P-Q	Load nodes
P-V	Generator nodes
Q	Reactive power
Q_0	Rated reactive power
Q_{inj}	Reactive power injection
Q_{rL}	Total reactive power load at node r
${Q_{rR}}^{(p)}$	Total reactive power requirement at node r for p^{th} iteration
R	Measurement weight matrix
R_A, R_B, R_C, R_N	Resistances of phase A, B, C, and N

R_1, R_2, S_1, S_2	Constant matrices
S_{rated}	Rated apparent power
S_r	Apparent power load at node r
σ	Standard deviation for PV and load forecast
$\sigma_1^2, \sigma_2^2, \ldots, \sigma_m^2$	Error associated with different measurements
t	Total number of branches connected at node n
t, $t-k$	Time instants
V	Voltage
V_0	Rated voltage
${V_r}^{(s)}$	Specified voltage value at node r
$\Delta {V_r}^{(p)}$	Voltage magnitude mismatch at node r for p^{th} iteration
${V_r}^{(p-1)}$	Voltage of node r for $(p-1)^{\text{th}}$ iteration
V_A, V_B, V_C, V_N	Sending end voltages of phase A, B, C, and N
V_a, V_b, V_c, V_n	Receiving end voltages of phase A, B, C, and N
x	Estimation vector
Y_r	Admittance at node r
$y(t)$	Considered function
z	Measurement vector
ZIP load	Combination of Z, I, and P load
Z_q	Impedance of branch q
Z	Real and constant impedance matrix

Contents

Abstract **i**

Acknowledgements **iii**

List of Abbreviations **v**

List of Nomenclature **vii**

Contents **xiii**

1 Introduction **1**
1.1 Background and Motivations 1
1.2 Problem 3
1.3 Aim of Thesis 5
1.4 Main Contributions 6
1.5 Thesis Outline 7
1.6 List of Publications 8

2 Literature Review **9**
2.1 Current Practices in Distribution Systems 9
2.1.1 Network Congestion Solution 9
2.1.2 System Protection Solution 10

2.2 State of the Art Survey 10
2.2.1 Future-Readiness Assessment Framework 10
2.2.2 Congestion Forecast Tool 11
2.2.3 Dynamic State Estimation based Protection Scheme . . 13

3 Future-Readiness Assessment Framework for Distribution Systems 15
3.1 Framework Description for Distribution Systems Assessment . 15
3.1.1 Technical Indicators 16
3.1.2 Market Indicators 17
3.1.3 Policy Indicators 17
3.2 Case Studies 19
3.3 Future Scenarios for Electricity Production in Sweden 22
3.4 Impact of Regulations on Future Intelligent Distribution Systems 23
3.5 Summary 25

4 Congestion Forecast Tool 27
4.1 Congestion Forecast Tool Description 27
4.1.1 Inputs 27
4.1.2 Visualization of Congestion Forecast Results 29
4.1.3 Real Application from Industry Perspective 30
4.2 Modelling 31
4.2.1 Load Modelling 31
4.2.2 Operating Modes of PV-inverter 32
4.2.3 Probabilistic Power Flow Method 34
4.2.4 Results of Congestion Forecast 34
4.3 Case Studies Description 35
4.3.1 7-bus Feeder of Sorea's Distribution System in France . 35
4.3.2 141-bus Distribution System of Caracas Metropolitan Area 36
4.4 Results and Discussions 38
4.4.1 7-bus Feeder of Sorea's Distribution System in France . 38
4.4.2 141-bus Distribution System of Caracas Metropolitan Area 40
4.5 Scalability and Accuracy of Proposed Tool 45
4.6 Integration with UNITED-GRID Toolbox 47
4.6.1 Objectives 47
4.6.2 Toolbox Functional Description 48

4.6.3 Congestion Forecast Use-Case 49
4.7 Summary 50

5 Application of Dynamic State Estimation for Line Protection 51
5.1 Dynamic State Estimation based Protection Scheme 51
5.1.1 Background 51
5.1.2 General Concept 53
5.1.3 Modelling 54
5.2 Validation of Scheme using Simulation 58
5.2.1 Simulation Setup 58
5.2.2 Simulation Results 59
5.3 Validation of Scheme using Laboratory Experiment 61
5.3.1 Laboratory Experimental Setup 61
5.3.2 Advanced Measurement Technologies Developed by SST 63
5.3.3 Experiment Results 64
5.4 Processing Time 68
5.5 Summary 69

6 Concluding Remarks and Future Work 71
6.1 Concluding Remarks 71
6.2 Future Work 74

References 77

A Model Development of Dynamic State Estimation based Protection Scheme 85

B Network Parameters of 7-bus Feeder in Sorea's Distribution System 91

CHAPTER 1

Introduction

This chapter discusses the background and motivations behind the presented research work along with the problem addressed in the thesis. Furthermore, the aim and main contributions of the research work are presented together with the resulting scientific publications.

1.1 Background and Motivations

With the growing concern towards global warming and climate change, the universal focus has been on the transition towards low-carbon energy systems. Among the various trends associated with this transition, the replacement of conventional fossil fuel-based power generation by renewable energy sources (RES) has been the major technological shift since the last decades. The other trends include the use of demand response resources, energy storage systems (ESSs), electric vehicles (EVs), information and communication technologies (ICT) in the distribution systems. The inclusion of these trends and technologies into today's distribution systems leads them towards the *future's intelligent distribution systems.*

Intelligent distribution systems will play a new role as a market facilitator to integrate a large share of RES. They will become more complex as a cyber-physical ecosystem which would require an integrated paradigm for energy management and control systems based on various data resources. With the customers playing a central role in enabling integrated and flexible solutions that contribute significantly to reducing uncertainty from stochastic renewables and distributed energy resources (DERs), distribution system operators (DSOs) are envisioned as a crucial entity to enable a successful energy transition by providing a high-quality service to all customers. This will require a stronger linkage between competitive technologies and services for the distribution systems in a fast-evolving energy market. A synergy between the power technology research and energy market development, if developed properly, will lay a foundation for the intelligent distribution systems.

The European Technology and Innovation Platforms (ETIPs) through Smart Networks for Energy Transition (SNET) had come up with SmartGrids Strategic Research Agenda (SRA) 2035 in March 2012 [1], where they present the following research challenges and priorities in electrical distribution systems which are necessary for their advancement towards intelligent systems by the year 2035:

- Smart, flexible distributed demand and generation response for secure distribution system control
- Integrated distributed energy storage infrastructure planning in distribution systems
- EV integration into distribution systems
- ICT system security for distribution system operation
- Real-time network monitoring, operation, and control to avoid critical situations

The integration of RES into the electric distribution systems increase the complexity in operation, control, and protection of the system. These trends are expected to continue in the future as RES, mainly solar and wind, are becoming the cheapest source of power generation since the last decade in most parts of the world [2], [3]. The International Energy Agency (IEA) through Photovoltaic Power Systems Programme (PVPS) presented in the

2017 annual report that solar photovoltaic (PV) is now the fastest-growing energy technology [4]. According to their 2019 report [5], an estimated 115 GW PV capacity is installed worldwide in 2019, which raises the cumulative installed PV capacity to 620 GW. There have been similar trends in EVs sales, a record number of more than 1 million EVs have been sold in 2017, while the global stock of EVs has now crossed the mark of 3 million vehicles [6].

Sweden has also been instrumental in its efforts, both in RES installation and sales of EVs. Between 2018 and 2019, Sweden saw an approximately 70% increment in the number of grid-connected solar PV systems, which has led to the total installed solar PV capacity in Sweden to 698 MW (which comprises approximately 1.5% to 2% of the total installed electricity generation capacity) [7]. The installed wind power capacity in Sweden has increased from 241 MW to 8984 MW during 2000-2019 [8], [9]. With regard to EVs, Sweden has been the third most advanced market worldwide in terms of sales, while its sales share has been 6.3% in 2017 [6].

These new market actors and technologies in distribution systems bring several problems for the DSOs such as uncertainty associated with renewable energy production which makes it difficult for the operators to balance the real-time generation and demand. Another problem is related to the network congestions and voltage issues due to the high penetration of RES. Further, the large-scale integration of renewables might lead to the failure of various existing protection schemes/methods due to phenomenons such as bi-directional power flow, fault current limitation, etc. The increasing growth rate of EVs could be challenging for the DSOs to flatten the load curve. Also, the increased participation of customers in the intra-day or day-ahead electricity market and the future concept of peer-to-peer transactions would add further complexity to the system. Cyber-security which is associated with the integration of ICT into the systems has also been one of the concerns.

1.2 Problem

All distribution systems are either going through the paradigm shift to become intelligent systems or will go through in the future and thus, would be posed with the following challenges in managing their day-to-day operation:

- DSOs need to prepare for a transition path from today's passive systems to future's intelligent distribution systems by making a strategic investment in network infrastructure, upgrading monitoring and control systems, introducing novel business models, and seeking policy and regulation changes to enable the active participation of market actors in the overall network management. Hence, DSOs need an assessment framework to evaluate their future-readiness and consecutively identify development gaps for plausible future scenarios and eventually make themselves ready.

- The increased penetration of RES in distribution systems brings various environmental and economic benefits, but the intermittency associated with them also brings operational challenges for the utilities and DSOs, e.g., voltage issues and network congestions [10]. Across the globe, multiple such operational issues have been reported, e.g., [11]–[13] due to higher penetration of PV. Simultaneously, electrical loads in the distribution systems are affected by the emergence of new types of loads such as electric vehicles, heat pumps, etc., which might also impact the peak demand in the network. Thus, maintaining a reliable, economic, and efficient operation of distribution systems by the DSOs is a significant challenge, while hosting a large amount of RES and new types of loads. Thus, keeping in mind today's and future need of DSO to address these issues, a congestion forecast tool is required which can support the DSO by forecasting the congestion levels in their network. The tool could also include the DSO preferences such as the types of inputs, selection of forecast horizons, etc.

- The high penetration of RES also affects the protection schemes used in the distribution systems. In intelligent distribution systems, the number of distributed generation (DG) interconnection with the grid is high, which leads to the failure of conventional protection strategies and other phenomenons such as false tripping, protection blinding, re-closer problems, device discrimination, etc. The protection challenges associated with DG interconnection are mainly caused by the bi-directional power flow, change in fault current and short-circuit level, fault current limitation in converter-dominated distribution systems etc. These challenges require the revisiting of the conventional protection strategies and development of new protection schemes that can address these challenges while maintaining high system reliability.

Based on the problems discussed and the motivation of the thesis, the following research questions have been identified and will be examined within this thesis:

- **Research Question 1**: How can the DSOs evaluate their future-readiness in order to prepare themselves for a smoother transition towards the future intelligent systems? Further, the key indicators associated with this transition that would have major impacts on DSOs in the future are to be identified. The process of assessment of the identified key indicators is also required to be explored.

- **Research Question 2**: How can the network congestion be forecasted in distribution systems with high penetration of RES and more uncertain load for maintaining reliable, economical, and efficient operation? The key factors which impact the network congestion and relevant indicators for the evaluation of network congestion are to be explored. How can the congestion forecast results be presented with advanced visualization features and in a user-friendly way to the DSOs?

- **Research Question 3**: How can a reliable and fast protection scheme be introduced to address the challenges such as reverse power flow or bi-directional power flow, change in fault current and short-circuit levels, fault current limitations, false tripping, protection blinding, etc., caused by the high penetration of RES in the distribution systems? Can the novel protection scheme based on advanced measurement technologies and dynamic state estimation, address the protection challenges caused by the RES? How can the practical challenges associated with experimental validation of the novel protection scheme with an laboratory setup be investigated?

1.3 Aim of Thesis

The aim of this thesis is the development and validation of advanced support tools for DSOs in the context of their transition from today's passive distribution systems towards the future's intelligent distribution systems. The development of a future-readiness assessment framework helps DSO in assessing their current status and preparedness for future transition, the development of congestion forecast tool which will support DSOs to forecast the voltage issues and network congestion, and the implementation and validation of the DSE based protection scheme to offer the DSOs a novel protection scheme that can handle the problems caused by RES and support them in operating their network more reliably and securely.

1.4 Main Contributions

The main contribution of this thesis could be outlined as follows:

- **Development of a future-readiness assessment framework** through which DSOs can assess the current status and future-readiness of their network. In the development of the framework, a set of key indicators are identified which would have major impacts on DSOs in the future and then present their assessment based on inputs from DSOs. The output from this framework along with the plausible scenarios description would serve as an input for identifying the policy recommendations, pathways development, and finally a transition plan for the DSO along with the identification of vital areas of development on which they should focus for a smoother transition towards future distribution systems.

- **A congestion forecast tool** based on probabilistic power flow is developed which incorporates a PV production and load forecast combined with load models and different operating modes of PV-inverters. The tool is developed with different functionalities such as the input requirements and visualization features. Node voltages, branches, and transformers loading levels are chosen as indicators for forecasting network congestion. Cumulative probability-based contour plots and colour-map are proposed as part of the tool's visualization functionality to inform DSO of the location and severity of congestion in the network as well as in specific components. The tool could support DSOs in setting up a congestion management plan which in turn could improve the hosting capacity, enhance the system resiliency, mitigate equipment ageing due to overloading as well as other economical benefits.

- **The implementation and validation of a dynamic state estimation based protection scheme** (DSEBPS) which has the potential to address the protection challenges emerged by the increased penetration of RES in the distribution systems. A dynamic model of the distribution line is implemented using the quadratic integration method and AQCF model. Thereafter, a dynamic state estimation algorithm is implemented incorporating the distribution line dynamic model. The DSEBPS is implemented in Python and supported by advanced measurement technologies developed by Smart State Technology (a partner in EU project UNITED-GRID). The experimental validation is done with the test setup at the Chalmers power system laboratory.

1.5 Thesis Outline

The remaining of the thesis is organized as follows:

- **Chapter 2** presents the literature review with details explaining the current practices in the distribution systems and the state of the art survey.
- **Chapter 3** presents a future-readiness assessment framework for DSOs with the identification and evaluation of key indicators associated with the transition. The comparative assessment between the three distribution system operators (from France, The Netherlands, and Sweden) participating in the project is presented. The future scenarios for electricity production in Sweden are presented. Further, the policy barriers which can impact the innovation and implementation of advanced solutions in distribution systems are identified and presented.
- **Chapter 4** explains the congestion forecast tool which would assist DSOs by forecasting congestion in their networks. The PV production and load forecast have been integrated into the tool. The case-study for two real distribution systems i.e, 7-bus feeder and 141-bus system has been performed and their results are presented. Further, the process details of seamless integration of the tool in the existing distribution management systems of DSOs via an IoT platform Codex Smart Edge of Atos Worldgrid is presented.
- **Chapter 5** details the implementation and validation of the dynamic state estimation based protection scheme supported by advanced mea-

surement technologies developed by SST at Chalmers power system laboratory.

- **Chapter 6** concludes the thesis and presents the plan for the future research work.

1.6 List of Publications

The publications originating from this thesis are:

[A] **Ankur Srivastava**, D. Steen, L. A. Tuan, O. Carlson, *et al.*, "A DSO Support Framework for Assessment of Future-readiness of Distribution Systems: Technical, Market, and Policy Perspectives," in *Proc. International Conference on Electricity Distribution (CIRED 2019)*, Madrid, Spain, June 3-6, 2019.

[B] **Ankur Srivastava**, D. Steen, L. A. Tuan, O. Carlson, "A Congestion Forecast Framework for Distribution Systems with High Penetration of PVs and PEVs," in *Proc. IEEE PowerTech 2019*, Milan, Italy, June 23-27, 2019.

[C] K. A. Plytaria, **Ankur Srivastava**, M. A. F. Ghazvini, D. Steen, L. A. Tuan, O. Carlson, "Chalmers Campus as a Testbed for Intelligent Grids and Local Energy Systems," in *Proc. International Conference on Smart Energy Systems and Technologies (SEST 2019)*, Porto, Portugal, September 9-11, 2019.

[D] J. Rossi, **Ankur Srivastava**, D. Steen, L. A. Tuan, "A Study of the European Regulatory Framework for Smart Grid Solutions in Future Distribution Systems," Accepted for *International Conference on Electricity Distribution (CIRED 2020)*, Berlin, Germany, June 4-5, 2020.

[E] **Ankur Srivastava**, D. Steen, L. A. Tuan, O. Carlson, I. Bouloumpasis, "Development of a DSO Support Tool for Congestion Forecast," *to be submitted.*

Other publications by the author, not included in this thesis, are:

[F] **Ankur Srivastava**, R. Mohanty, M. A. F. Ghazvini, L. A. Tuan, D. Steen, O. Carlson, "Protection of Active Distribution Systems and Microgrids: A Review on Challenges and Solutions," submitted to *IEEE PowerTech 2021*, Madrid, Spain.

CHAPTER 2

Literature Review

This chapter gives an overview of the current practices which are followed in the distribution systems. Further, a detailed state of the art survey is presented to highlight the contribution of the work presented in this thesis.

2.1 Current Practices in Distribution Systems

This section presents the details of the network congestion and protection problems within the distribution systems along with the current practices by the involved stakeholders (DSOs).

2.1.1 Network Congestion Solution

Traditionally, the distribution systems e.g., in Sweden, have been relatively well-dimensioned and network congestions have foremost been solved by grid reinforcements. Due to the relatively long process for grid reinforcement as compared to the rapid evolution of distributed generation and load, the problem of network congestion within distribution systems has become a critical and realistic issue in the very near future. This problem is mainly caused due to the gradual penetration of DERs and the increasing number of high energy-consuming loads, such as EVs or heat pumps spreading over wide geographical areas. This results in various problems such as reverse power flows, voltage violations, and network congestion, etc. Some of these problems have been addressed in [14], where the problem formulation and proposed market-based solutions are of the scale of nations and cross-border with the focuses on energy transactions between DSOs and transmission system operators (TSOs). With the same focus on the market aspect of congestion management, flexibility services were investigated in [15] and [16], where competitiveness and local energy monitoring were specifically promoted.

2.1.2 System Protection Solution

Conventionally, the distribution systems are radial in design and common fault detection methods are based on the fault current magnitude which is fed into the fault point. The commonly used protection methods in such distribution systems are overcurrent, over/under voltage, and neutral voltage displacement. Further, the overcurrent relay uses an instantaneous and/or time-delay unit. The time-relay unit can have an inverse, very inverse, or extremely inverse characteristics. For ring systems, overcurrent relay with directional features is also used to prevent the relay to operate for a fault in reverse direction [17]. Now, with the increasing penetration of RES in the distribution systems, the conventional protection methods do not work as intended. The main issues which lead to failures of these schemes are bi-directional power flow, change in fault current level, fault current limitation, false tripping, protection blinding, auto-recloser problem, device discrimination, etc. [18]–[25].

2.2 State of the Art Survey

This section presents the state of the art survey for the advanced DSO support tools which are developed and validated in this work.

2.2.1 Future-Readiness Assessment Framework

The researchers working in various fields have taken up research problems similar to future-readiness assessment framework by proposing different versions of assessment frameworks. For instance, in [26]–[28], a performance indicators-based framework has been proposed for evaluating the performance of engineering faculty, proactive performance monitoring scheme, and, the performance of technological audit at the firm's level, respectively. In [29], a framework is developed for the classification of smart city performance indicators and then identify technologies and actions needed for city management and planning towards urban growth. In [30], a big data framework has been developed for the assessment of electric power data quality. A framework has been used in [31], where DSO controls have been assessed in the non-binding transactive energy market. Although several questions are raised in [32], which relate with market and policy perspective for flexibility use to DSO in order to manage embedded microgrids and islanded power systems, still a well-developed assessment framework for evaluating the future-readiness of DSOs is required.

2.2.2 Congestion Forecast Tool

Due to different uncertainties associated with RES, deterministic power flow methods are unable to incorporate them in the power flow model. Thus, generally, a probabilistic approach is adopted to account for these uncertainties. For PVs uncertainties modelling, different versions of probabilistic algorithms are used in [33]–[35]. A probabilistic approach is used in low-voltage (LV) networks in [36]. Further, a probabilistic algorithm is developed in [33] to evaluate the capacity of power reserve for a system with high PVs penetration. The authors in [37] used a probabilistic approach for the evaluation of the maximum integration limits for distributed generations with voltage constraints. A simplified version of the backward-forward sweep (BFS) method which employs a Gaussian mixture distribution is proposed to solve probabilistic power flow (PPF) more efficiently to be used for planning of LV networks in [36]. Similarly, a new probabilistic method is proposed in [35] which is based on quasi-static time-series analysis in combination with the golden section search algorithm to prevent reverse power flow in distribution systems due to PV integration. The impact of uncertainty associated with DERs is analyzed in [38] and the benefits of installing microgrids to address such challenges are also administrated. Thus, the probabilistic approach is utilized for addressing several research problems in the distribution systems; however, most of the existing works have not addressed the research problem associated with the forecasting of network congestion.

There has also been extensive on-going research for congestion management in distribution systems. For instance, in [39], a real-time congestion management method based on the flexibility service from electric vehicles and heat pumps is proposed. However, this method expects that DSO has the ability to forecast the network congestion. Besides, a report is presented in [40] on DSOs observatory, which mentions that with regard to market-based congestion management models relying on flexibility, the forecasting and categorizing the volume of network congestion is a new topic for DSOs that needs to be further explored. Moreover, a report in [41] explains how the DSO presents the flexibility requirement to the aggregator when the network congestion cannot be avoided. The report further explains that a communication and service platform is used to announce the congestion forecasts which is required for non-discriminatory selection, management, and processing of flexibility choices. However, the method for the forecast and identification of the congestion is not mentioned. The works presented in [42]–[46] have proposed different congestion management methods using dynamic tariff, household demand response, congestion pricing, and dynamic subsidy, which would require the inputs of congestion forecast. Similarly, a congestion management method based on hierarchical and distributed control concept is presented in [47]. From the above description, it is evident that there is an increasing interest in active congestion management in distribution systems, as more frequent and severe congestion incidents are expected in the future. Therefore, there is an emerging interest in a solution for a fast and accurate congestion forecast. Most of these works have mentioned the need for a congestion forecast or simply assumed that DSOs have the capability to forecast the congestion highlighting the importance of the congestion forecast for the DSOs.

Several researches have addressed the congestion forecast issue, e.g. [48], in which a probabilistic method is developed for detecting and ranking the congested lines to help network operators. A congestion forecast framework is proposed in [49] with Chalmers University campus as a testbed [50], which considers only snapshot data of system uncertainties with limited visualization of network congestion. However, what is expected to be primarily needed by the DSOs in the coming years is a compact tool that can forecast network congestion over the desired forecast horizons and has interactive visualization capabilities. Further, the inclusion of other operating conditions such as PV-inverter operating modes and load models within such congestion forecast tool would be an enhancement for the DSOs.

2.2.3 Dynamic State Estimation based Protection Scheme

System protection against undesirable events is one of the important functions of the power system operation. It is also important from the perspective of system reliability, continuity of power supply, and personnel's safety. The North American Electric Reliability Corporation (NERC) has reported that approximately 10% of protection operations are mis-operations which lead to interruptions [51]. From 2012 to 2014, 31% of mis-operations occurred due to incorrect settings, 19% due to relay failures, and 13% due to communication failures which in total accounts for 63% of the total mis-operations [51].

The changing scenario of power generation by RES instead of conventional power sources has also brought new protection challenges, at both transmission and distribution levels. RES-based power generation is highly intermittent and may lead to reverse power flow or bi-directional power flow which causes relay coordination problems, change in fault current level, etc. RES is often accompanied by power-electronics interfaced inverters, which are responsible for fault current limitations [20]. Other phenomenons such as false tripping, protection blinding, auto-recloser problems, device discrimination, single-phase connection problems, etc., could also occur in the distribution systems.

A simple and reliable alternative solution to tackle these problems and challenges in distribution systems could be a dynamic state estimation based protection scheme [52]. DSEBPS has the potential of being an alternative to present-day protection schemes with enhanced simplicity and reliability. The voltage and current measurements from the component under protection are measured and then the dynamic states of the system are estimated which helps to predict the health of the component and in a decision to trip or no-trip. With the growing acceptance and deployment of phasor measurement units (PMUs) in the electrical grids, DSEBPS gains further significance.

The conceptual details of DSEBPS along with the specific examples are presented in [53]. The DSEBPS is used for the detection of the transformer inter-turn faults in [54]. A centralized protection scheme based on dynamic state estimation (DSE) is presented in [55], which is used for hidden failures detection and taking remedial measures to weaken their effects until they are removed. Also, a centralized protection scheme based on the DSE is presented in [19], to tackle the protection challenges in the microgrid system.

CHAPTER 3

Future-Readiness Assessment Framework for Distribution Systems

This chapter presents the work conducted on development of a DSO support framework for assessment of future-readiness of distribution systems. The assessment framework consists of two steps as the identification of the key indicators associated with this transition and assessing the current status by evaluation of these indicators based on inputs from DSOs. Case studies have been carried out for DSOs in three European countries, i.e., Göteborg Energi (Sweden), SOREA (France), and ENEXIS (The Netherlands).

3.1 Framework Description for Distribution Systems Assessment

The framework for distribution systems assessment consists of two steps, i.e., selection of key indicators and their assessment. The overall methodology for assessment framework is shown in Figure 3.1 [56], [57].

The first step is to identify the key indicators which impact this transition. Although, the most relevant advancements are related to technical requirements

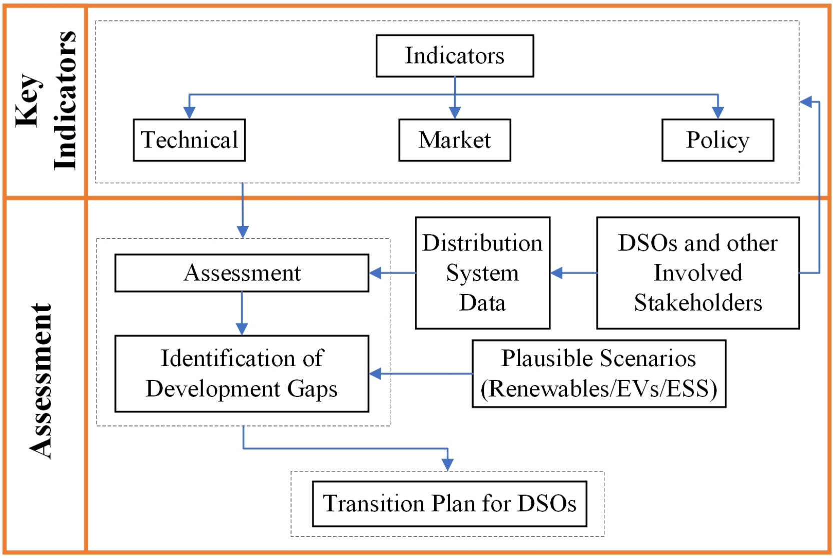


Figure 3.1: Overall methodology for future-readiness assessment framework.

for DSOs, the available market structures, policies, and regulations are also instrumental. The market and policy aspects will have a potential impact on the DSOs but are not directly controlled by them. Thus, all these aspects are interrelated, and their exclusion may limit the possible advancement in one direction or reduce the possible benefit in another. As a result, the indicators are classified as technical, market and policy. The description of these indicators and their sub-indicators is presented as follows:

3.1.1 Technical Indicators

These indicators mainly address the technical aspects associated with production and distribution of electricity. The selection of indicators is motivated from the issues addressed in ETIPs-SNET SRA 2035 [1] and inputs from the partner DSOs involved in EU project UNITED-GRID. The following technical indicators are identified:

(a) Distributed Energy Resources: It covers the aspects such as the amount of distributed renewable energy production (REP) and associated forecasting, EVs integration, heat-pumps, and district heating along with its availability for flexibility, and energy storage systems.

(b) Level of Monitoring and Control: It covers the advancement level of DSOs with respect to monitoring and control, e.g., smart meters, advanced metering infrastructure (AMIs), and supervisory control and data acquisition (SCADA).

(c) System Status: It covers the present infrastructure situation and operational data of the system such as loading profile and levels, existing system capacity, system configuration, quality and reliability of supply and participation in frequency control.

(d) Cyber-physical Description: It covers the cyber-physical characteristics such as systematic architecture, structural framework for fidelity models and systems integration. It has gained importance as ICT system security has been one of the focus areas for the DSOs.

3.1.2 Market Indicators

These indicators mainly address services and markets, tariffs, financial aspects, and business models. In addition to the financial and market context set up by the DSO itself, it is important to consider how external actors/stakeholders could influence the DSOs. To capture the external influences, some indicators are related to available services from external stakeholders such as electricity retailer and service providers. The following market indicators are identified:

(a) Markets and Services: It refers to the available markets organized by the DSO or by other actors where end users could provide their services.

(b) Tariffs: It refers to the evaluation of the electricity charges for the end user. The tariff is divided into grid tariff and retail electricity pricing.

(c) Business Models: It refers to the available business models provided by the DSOs or other actors.

3.1.3 Policy Indicators

These indicators mainly address the regulation and policy aspects. They become a relevant indicator especially in the era of changing role of the

DSOs. Traditionally, DSOs are highly regulated entities driven by national and European authorities because they act as natural monopolies (to have numerous competing structures would make no sense). While new policies are being drafted which will have a significant impact on DSOs, their absence may hinder the possible technology advancements. The following policy indicators are identified:

(a) Level of Unbundling: It refers to the implementation of the unbundling. The most relevant existing European policy in this regard is the third energy package [58], which has been enacted to improve the functioning of the internal energy market and resolve structural problems.

(b) Roll-out of Smart Meters: It refers to a cost-benefit analysis for the roll-out of smart meters and policies supporting them. It is one of the most relevant indicators for the DSOs in the energy transition, as mentioned in the third energy package [58].

(c) Network Codes: It refers to finding the key barriers for DSOs in implementation of existing network codes, which are legally binding European implementing regulations supporting the integration of national and regional electricity markets into a unified internal European market. It gains relevance as it is feared sometimes that current codes do not account for the more diverse, flexible and active role that DSOs need to take up in future.

(d) Impact of Winter Package on DSOs Tasks: It refers to the effect of policy aspects of winter package [59], on different tasks of DSOs. The package includes both non-legislative initiatives as well as legislative proposals. They include new rules on European Union (EU) electricity market design and a proposal for a directive on common rules for the internal electricity market and a proposal for a regulation on the internal electricity market. Many of the new principles focus on empowering consumers and the importance of the internal market.

(e) Impact of New Network Codes and Guidelines: It refers to expected effects of new network codes and guidelines as mentioned in the winter package [58]. The package not just proposes a new set of network codes and guidelines but also specifies the way the DSOs will be involved in their development.

(f) National/Regional Policies on DERs: It refers to identifying other national policies that can have an impact on the distribution systems, for instance, incentives for certain types of renewable energy or legislation/lack of legislation on aggregators.

The second step is to assess the current status, i.e., future-readiness of DSOs. The qualitative assessment is done based on the DSOs response on the proposed indicators. The DSOs along with other involved stakeholders will provide inputs in the form of system data, market/business models, regulatory policies, etc. The output of the proposed assessment framework would serve as an input for identification of the development gaps, i.e., the progress needed, within each area, i.e., technical, market, or policy, for the transition toward a future intelligent distribution systems. Finally, with the identified development gaps and plausible scenarios (Renewables/EVs/ESSs, etc.), a suggestion for DSO transition plan will be delivered.

3.2 Case Studies

The proposed framework has been used to assess the current status of three distribution systems in Sweden, France, and the Netherlands. The presented case studies could be used as an example of how to use the framework and how the results may look like. The DSOs included in the case study are:

(a) Göteborg Energi (Sweden): Göteborg Energi is a Swedish municipality owned energy company. The grid has nearly 262 000 customers and 4.4 TWh of annual energy consumption.

(b) SOREA (France): SOREA is a small distribution network company in France. It is active in electricity production and distribution and operates its grid mainly with hydro- and PV-based production. The grid has nearly 14 000 customers and 140 GWh of annual energy consumption.

(c) ENEXIS (The Netherlands): ENEXIS is a Dutch DSO supplying electricity to around 2.8 million customers. The annual energy consumption is 34.5 TWh. Their distribution system covers both urban and rural areas.

The three involved DSOs have filled the proposed indicators list and the assessment has been done based on their responses. A comparative assessment with the proposed indicators of the three DSOs is presented in Table 3.1. Although, the three DSOs having relatively different sizes and number of customers (hence power demand), as well as different market rules and policies at national level, it would be beneficial for them as well as for other DSOs in Europe to look at the comparative assessment between them. This may also act as a motivation for a transition towards future intelligent distribution systems.

Table 3.1: Comparative Assessment of the three European DSOs

Indicators Name	**Comparative Assessment**
Distributed Energy Resources	Limited local renewable energy production in all DSOs. The EVs demand is not high in all the networks, but the infrastructure is being built. Only ENEXIS has a small amount of energy storage provisions. Although, none of the networks has provision for flexibility today.
Level of Monitoring and Control	The level assessed by AMIs and automation systems varies from high (Göteborg Energi and ENEXIS) to low (SOREA).
System Status	The power distribution is mainly done by underground cables in all DSOs. Also, all have a high level of reliability of supply while frequency control is done at the TSO level.
Cyber-Physical Description	As of today, not much information is available for Göteborg Energi and SOREA. But ENEXIS has implemented some standards for improved risk and security management.
Markets and Services	Currently, not much information is available for SOREA and ENEXIS, whereas Göteborg Energi has some advanced provisions for competitive electricity prices that are available through different market mechanisms.

Indicators Name	**Comparative Assessment**
Tariffs	Grid tariffs are mainly based on fixed costs with provisions of subscribed power and energy charge in case of all three DSOs.
Business Models	Currently, not much information is available for Göteborg Energi, while SOREA and ENEXIS have feed-in tariff models available for PV- and hydro-power.
Level of Unbundling	The level of unbundling varies from partial unbundling (SOREA) to total unbundling (Göteborg Energi and ENEXIS).
Roll-out of Smart Meters	Roll-out varied from currently 100% in Göteborg Energi to expected 72% by 2020 in ENEXIS and expected 100% by 2024 in SOREA.
Network Codes	Currently, not much information is available for Göteborg Energi and ENEXIS, while SOREA is aligning themselves to achieve objectives.
Impact of Winter Package on DSO Tasks	Currently, not much information is available for SOREA and ENEXIS, while Göteborg Energi has possibilities of new tariffs being introduced at a local level.
National/Regional Policies on DERs	All DSOs are committed towards the national legislation for the reduction in greenhouse gas emissions, increased renewable generation, energy savings, advanced metering and setup of local energy storage and communities.

The investigated DSOs have shown diversity in terms of technology, policy and market readiness. The DSOs need to be prepared themselves for the following:

- Needs for investments in flexibilities
- Needs for advanced forecasting and monitoring
- Needs for advanced system automation and protection

- Needs for incentives schemes and business models
- Needs for changes in the role of DSOs which can own and/or procure certain resources and services

3.3 Future Scenarios for Electricity Production in Sweden

In the transition towards the future intelligent distribution systems, analysis of well-developed and thought-out future scenarios could be extremely helpful to make this transition smoother and predict the possible challenges before the DSOs. These future scenarios would also provide inputs to future-readiness assessment framework for the identification of development gaps and further assist in the development of transition plan for DSOs as presented in Figure 3.1.

In this context, four future scenarios have been studied from IVA's (Royal Swedish Academy of Engineering Sciences) project Electricity Crossroads for the electricity production in Sweden during 2030-2050, which is based on the gross energy potential available from different energy sources [60]. The economical or environmental aspects are not considered in the gross energy potential. For these four future scenarios, a different combination of fossil-free electricity generation are considered. The details of the electricity production from IVA's Electricity Crossroads scenarios are presented in Table 3.2 [61].

Table 3.2: IVA's Electricity Crossroads scenarios electricity production in Sweden during 2030-2050

Scenarios	**Hydro** (TWh)	**Wind** (TWh)	**Solar** (TWh)	**Bio energy** (TWh)	**Nuclear** (TWh)
More Solar and Wind	65	55	15	25	0
More Bio energy	65	40	5	50	0
New Nuclear Power	65	20	5	20	50
More Hydro Power	85	35	5	35	0

The key observations from these scenarios can be presented as below:

(a) In Scenario 1 - More solar and wind, almost 50% of the total annual energy consumption will come from variable energy resources. But due to higher share of variable energy resources, there must be some technical supplementary measures in place to accommodate the associated uncertainty.

(b) In Scenario 2 - More Bio-energy, it has capability to make Sweden self-sufficient in terms of the need of both power and energy. But this alternative has an associated risk which involves huge investment cost due to absence of biomass competition in large-scale bio-energy solutions.

(c) In Scenario 3 - New Nuclear Power, there is not significant investment need in the development of new systems. Although, the technology development and the experience gained internationally should be taken into consideration to choose the best alternative among the available technologies.

(d) In Scenario 4 - More Hydro Power, the share of hydro power will be increased which has the capability to make Sweden self-sufficient in terms of the need of both power and energy. There is an additional advantage with the hydro power of being a flexible energy source.

The analyzed future scenarios show the challenges associated with the different sources of electricity production in Sweden. These can be further translated to challenges which the DSOs might face in near future.

This work is motivated from these challenges which DSOs will face in near future due to several complexities as discussed above.

3.4 Impact of Regulations on Future Intelligent Distribution Systems

The work presented in this section is done in collaboration with RISE, Sweden [62]. The main results from the work are presented here while the details of the work can be found in [63].

There will be a significant impact on the role of DSOs in Europe due to climate change goals, changing market frameworks and technological innovations.

The nature and scale of these challenges are strongly driven by the European vision and strategies on climate and energy.

An extensive review of new policy priority areas within the energy and climate framework and electricity market design, and subsequent discussions with three partner DSOs (from Sweden, France, and The Netherlands) are done. Based on them, the following five priority barriers are identified which can hinder distribution grid innovation and the implementation of advanced smart grid solutions developed for distribution systems:

(a) Impact of Recent Developments in EU Climate Strategies on the DSOs: The global and European visions and strategies for reaching binding climate goals result in policies and regulations that set up a process for member states to decarbonize the power sector. This requires large investments and a major transition by all stakeholders, particularly at the distribution level. However, not all DSOs have sufficiently explored innovative solutions or developed their own long-term strategies adapting to the expected transformation of the energy sector.

(b) The Future Role Versus the Income Regulation of DSOs: Distribution systems are considered as non-competitive natural monopolies with regulated incomes that are collected via network tariffs, imply low financial risks for the DSOs but also low incentives for innovation. Moreover, recent and expected future regulations on operational cost reduction, might result in a tightening of the authorized income space for the DSOs, who are concerned that with additional flexibility requirements on top of the traditional DSOs tasks, the affordability of the energy supply will be impeded and could be a major economic barrier in the maintenance and development of their grid.

(c) A New Active Role for the DSO in the Electricity Markets: A transformation of the traditional DSO business model is required so that the DSO become a neutral market facilitator that coordinates the impact of flexibility operations on its network, irrespective of the flexibility model and the chosen technology. The core concern is that the necessary regulatory framework for smart management and the incentives towards DSOs for innovation are not in place yet. It is difficult for the DSO to take up the new role as market facilitator since there are no real markets for grid services yet and there are limited opportunities available in terms of differentiated components in the distribution tariffs.

(d) Ownership of Storage Devices and Incentivizing the Use of Storage Services: The storage services should be market-based and competitive which puts strong restrictions on the ownership and management of storage units by DSOs. DSOs can be enabled and incentivized to use services from energy storage and some exceptions are allowed. However, these exemptions could be short-term and if an alternative solution turn up in the market. As long as a real service market does not exist, this is perceived as a regulatory gap with large uncertainties that hamper the needed investments in storage.

(e) Legally Processing and using Personal Data from Intelligent Metering: Smart meters will play an important role in the new market design by facilitating consumers in managing their consumption patterns through flexibility. DSOs can only access personal data from smart meters if that is necessary to perform other legal obligations and they should not go beyond the purpose for which these data have been collected. This implies minimizing processing activities and defining specific monitoring accuracies. In some cases, such data protection challenges have slowed down the roll-out and deployment of smart meters.

3.5 Summary

This chapter has presented a future-readiness assessment framework with a list of technical, market and policy indicators for DSOs, to assess their current status and future-readiness. For the demonstration of the use of the developed framework, case-studies for DSOs in Sweden, France, and the Netherlands have been carried out. A comparative assessment between the DSOs is also presented along with the identification of areas of preparedness required for the transition. The key takeaways from the case-studies are that DSOs currently have a limited amount of renewable energy production in their grids, but the share will be increased. Thus, DSOs need investments in flexibilities, advanced forecasting and monitoring, system automation and protection, incentive schemes and business models, etc. As part of future studies, the assessment results from this framework will serve as input for developing a transition plan for DSOs to facilitate a smoother transition towards the future. The assessment results would also help in identifying plausible scenarios, policy recommendations, and pathways development, all of which also serve inputs for transition plan for DSOs. Most importantly, the proposed framework can be used by other DSOs to assess their future-readiness. Further, some future scenarios for the electricity production in Sweden are presented which provides the insight into the possible challenges for the DSOs in the near future. Additionally, DSOs will be impacted in terms of innovation and applying smart grid solutions such as advanced tools developed in this thesis, by the new regulations for the distribution systems. In this regard, five priority barriers are identified as, impact of recent developments in EU climate strategies on the DSOs, the future role versus the income regulation of DSOs, a new active role for the DSO in the electricity markets, ownership of storage devices and incentivizing the use of storage services, legally processing and using personal data from intelligent metering, after an extensive review of new policy priority areas and discussions with DSOs in Sweden, France, and the Netherlands.

CHAPTER 4

Congestion Forecast Tool

This chapter presents the work conducted on development of a congestion forecast tool which would assist DSOs by forecasting the congestion levels in their networks. The detailed methodology and modelling is presented followed by the case-studies carried out on a part of real distribution network of SOREA in France and 141-bus distribution network of Caracas metropolitan area.

4.1 Congestion Forecast Tool Description

This section presents an overall description and features of the proposed congestion forecast tool including the inputs, visualization of forecast results and discusses the possible applications of the tool from the DSOs perspective. The modelling of the probabilistic power flow framework and other associated elements are discussed in Section 4.2.

4.1.1 Inputs

The various inputs required for the congestion forecast tool are as follows:

4.1.1.1 System Data

It includes the network parameters, branches ampacity, and transformers rated capacity. It can be provided in different data formats as separate input files by the DSO. For the integration of the tool with the distribution management system (DMS) of the DSO, it can be provided through existing SCADA/DMS.

4.1.1.2 Forecast of PV Production and Load Demand

It includes the forecasts of PV production and load demand, load model parameters. The forecast errors are also provided as inputs to the tool and should be made available to the DSO through the PV production and load forecast services.

4.1.1.3 DSO Preferences

It includes the number of Monte-Carlo simulations (MCS), node voltage limits, PV-inverter operating modes, and tolerance limits. These preferences are set as a default value but can be altered by the DSO.

The flow chart of the congestion forecast tool along with the preferences, is presented in Figure 4.1.

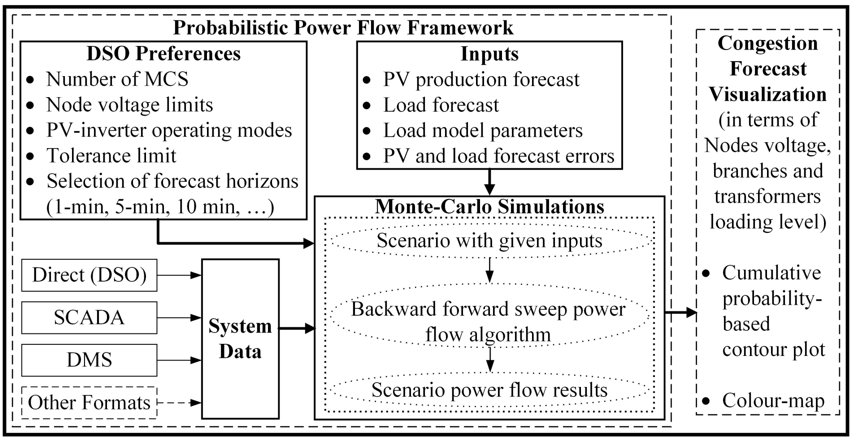


Figure 4.1: Flow chart of the congestion forecast tool.

4.1.2 Visualization of Congestion Forecast Results

The congestion forecast visualization helps the DSO in identifying the exact location and severity of congestion and assists them in taking suitable mitigating actions such as market participation, flexibility procurement, etc. The main features of the congestion forecast visualization are:

4.1.2.1 Congestion Forecast Indicators

The following indicators are proposed for congestion forecast visualization:

- Cumulative Probability-based Contour Plot: Cumulative probability (CP) denotes the probability of a variable reaching a level equal to or greater than a threshold. Here, the CP's are calculated with the desired threshold for all the chosen congestion indicators such as nodes voltage and components overloading. They are used for contour plots, which help the DSO in understanding the congestion severity in a specific node and component.

- Colour-map: Colour-map (CM) is the colour-based representation of the network, indicating the severity and the exact location of the congestion.

4.1.2.2 Congestion Forecast Horizons Selection

With the proposed congestion forecast tool, network congestion forecast can be made with various forecasting horizons depending on the needs and operation strategies of the DSO on how they tackle the possible congestion in their network in different time-frames. The details of the possible forecast horizons, along with the selection reasoning, are presented in Table 4.1. For instance, 5-min ahead forecast horizon value is selected by taking the average of five forecast values between 0^{th} and 5^{th} minute. It should be noted that these time-horizons can be customized by the DSO. Possible congestion management strategies with various time-horizons which can be taken by the DSO are shown in Figure 4.2.

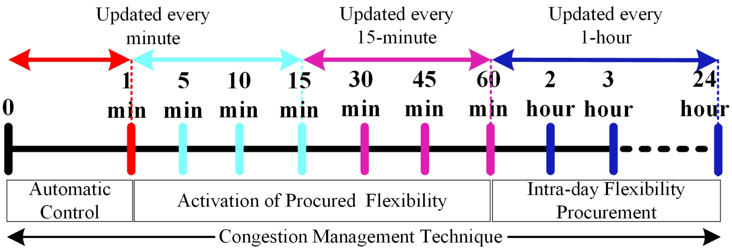


Figure 4.2: Strategic selection of forecast horizons along with the respective congestion management strategies.

Table 4.1: Congestion Forecast Horizons with Selection Reasoning

Sl. No.	Forecast Horizons	Reason for Selection	Forecast Value Selection
1	1-min ahead	Evaluate real-time congestion status	Next minute (0^{th}-1^{st}) forecasted value
2	5-min, 10-min and 15-min ahead	Identify congestion forecast in close to real-time conditions	Average of the forecasted values for 0^{th}-5^{th}, 5^{th}-10^{th}, and 10^{th}-15^{th} minute
3	30-min, 45-min and 60-min ahead	Set up a close to real-time congestion management plan	Average of the forecasted values for 15^{th}-30^{th}, 30^{th}-45^{th}, and 45^{th}-60^{th} minute
4	2-hour, 3-hour, ... 24-hour ahead	Set up an intra-day congestion management plan	Peak value among the average of forecasted values for four 15-min time slots between 1^{st}-2^{nd}, 2^{nd}-3^{rd}, ... and 23^{rd}-24^{th} hour

4.1.3 Real Application from Industry Perspective

The congestion forecast tool will assist DSO in the daily congestion management and network planning, depending on the forecast horizons. In short forecast horizons, the DSO will be enabled with timely congestion management by employing market and tariff-based flexibility solutions [64]. It would result in enhancement of the system's resiliency, mitigation of equipment ageing due to overloading, reducing the high additional congestion cost, and other economic benefits. While, long-term forecast horizons (e.g., several months or years ahead) will allow the DSO to procure flexibility for avoiding costly grid reinforcement.

4.2 Modelling

This section presents the modelling approach associated with the different components in the congestion forecast tool.

4.2.1 Load Modelling

This subsection presents the details of the inclusion of load models into the tool. Usually, the constant power load model is considered where the loads are assumed to remain independent of the system voltage. The active and reactive load characteristics for a combination of constant power (P), constant current (I), and constant impedance (Z), called as *ZIP* load model, can be expressed as a function of voltage:

$$P = P_0\left[k_{P_P} + k_{P_I}\left(\frac{V}{V_0}\right) + k_{P_Z}\left(\frac{V}{V_0}\right)^2\right] \tag{4.1}$$

$$Q = Q_0\left[k_{Q_P} + k_{Q_I}\left(\frac{V}{V_0}\right) + k_{Q_Z}\left(\frac{V}{V_0}\right)^2\right] \tag{4.2}$$

where V_0 represents the nominal voltage, k_{P_P} and k_{Q_P} are constants representing the proportion of P load, k_{P_I} and k_{Q_I} are constants representing the proportion of I load, k_{P_Z} and k_{Q_Z} are constants representing the proportion of Z load, for active and reactive power load, respectively.

The following steps are iterated to include the load models in the probabilistic power flow calculation [65]:

(a) Initial values of voltage at all the system nodes are taken as one p.u.

(b) Calculate load values with the inclusion of load models.

(c) Calculate branch currents and new node voltages.

(d) Update the values of both active and reactive loads with new node voltages.

4.2.2 Operating Modes of PV-inverter

Due to increased DERs penetration, there are stricter requirements for DERs interconnection with the distribution grid when compared previously. Some of these interconnection requirements are mentioned in the recent IEEE standard on the interconnection and interoperability of DERs [66]. The two most common operating modes of PV-inverter are constant power factor and voltage-reactive power. In this work, it is assumed that PV-inverter operates in both modes. These modes are incorporated into the tool to mimic the interconnection requirements as follows:

4.2.2.1 Constant Power Factor Mode (constant-pf)

In this mode, all the nodes except the slack node are modelled as P-Q nodes. The PV production at all the nodes is modelled as a negative load and with a constant power factor. The step-wise formulation of the BFS algorithm in this mode for p^{th} iteration, are as follows:

(a) A flat voltage profile is taken for all nodes except the slack node, which is kept constant.

(b) Calculate current injection at node r, as:

$$A_r{}^{(p)} = \left[\frac{S_r}{V_r{}^{(p-1)}}\right]^* - Y_r V_r{}^{(p-1)} \quad \forall\, r = 1, 2, \ldots, N \tag{4.3}$$

(c) Calculate branch currents (in branch q) in the backward direction starting from the last node, as:

$$I_q{}^{(p)} = A_n{}^{(p)} + \sum_{h=1}^{t} I_h{}^{(p)} \qquad \forall\, q = br, \ldots, 2, 1 \tag{4.4}$$

(d) Update node voltages (at node n) in the forward direction starting from the slack node, as:

$$V_n{}^{(p)} = V_m{}^{(p)} - Z_q I_q{}^{(p)} \qquad \forall\, q = 1, 2, \ldots, br \tag{4.5}$$

where N, br, t, and Z_q represent the total number of nodes, total number of branches, total number of branches connected at node n and the impedance of branch q, respectively.

These steps are iterated until the convergence is reached.

4.2.2.2 Voltage-Reactive Power Mode (constant-V)

In this mode, the PV production nodes are modelled as P-V nodes and load nodes are modelled as P-Q nodes. A compensation method is used for the elimination of voltage mismatches from their specified values at P-V nodes [67]. The step-wise formulation of voltage mismatch compensation in addition to the BFS algorithm for k P-V nodes in the system and p^{th} iteration are as follows:

(a) Calculate voltage magnitude mismatch at r^{th} node, as:

$$\Delta V_r{}^{(p)} = \left|V_r{}^{(s)}\right| - \left|V_r{}^{(p)}\right| \quad \forall\, r = 1, 2, \ldots, k \tag{4.6}$$

(b) Calculate the reactive current injection at r^{th} node, as:

$$I_{rQ}{}^{(p)} = j\left|Z_r{}^{-1} \Delta V_r^{(p)}\right| \quad \forall\, r = 1, 2, \ldots, k \tag{4.7}$$

(c) Calculate the total reactive power requirement Q_{rR} at r^{th} node, as:

$$\begin{aligned} Q_{rR}{}^{(p)} &= Q_r{}^{(p)} + Q_{rL} \\ Q_r{}^{(p)} &= \text{Im}[V_r I_{rQ}^{'}{}^{*}]^{(p)} \quad \forall\, r = 1, 2, \ldots, k \end{aligned} \tag{4.8}$$

(d) Check whether the calculated Q_{rR} $(= Q_{inj})$ satisfies:

$$P_{inj}{}^2 + Q_{inj}{}^2 \leq S_{rated}{}^2 \quad \forall\, r = 1, 2, \ldots, k \tag{4.9}$$

Otherwise, calculate the new value of P_{inj} and Q_{inj} [49].

where ${V_r}^{(s)}$, Z, Q_{kL} and $I^{'}_{kQ}$ represents the specified voltage value at node r, a real and constant impedance matrix, reactive power load at node k, and the sum of the required reactive current and load current injection.

These steps are iterated until the voltage mismatches for all P-V nodes reach within the tolerance limit.

4.2.3 Probabilistic Power Flow Method

The probabilistic approach is used to model the uncertainties in the proposed congestion forecast tool. MCS is employed to run a large number of scenarios to incorporate PV production and load forecast in the system. BFS method is used for solving the power flow algorithm.

This work considers Gaussian probability density function (PDF) for generating MCS values using the values obtained from PV production and load forecast, as described by (4.10):

$$PDF = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\dfrac{(x-\mu)^2}{2\sigma^2}} \tag{4.10}$$

where mean (μ) is the value of PV production and load forecast, while standard deviation (σ) depends on forecast type and horizon.

4.2.4 Results of Congestion Forecast

The congestion results are extracted from the power flow results of MCS presented in Section 4.2.3. To visualize the congestion forecast results, the following indicators are chosen:

Node Voltage

It refers to the node voltage and deviation from its nominal value.

Branch Loading

It refers to the loading of a branch relative to its rated ampacity.

Transformer Loading

It refers to the loading of a transformer relative to its rated capacity.

4.3 Case Studies Description

4.3.1 7-bus Feeder of Sorea's Distribution System in France

The considered system, as shown in Figure 4.3, has the radial structure with seven nodes, which includes both medium- and low-voltage (MV and LV) nodes, five branches, and one MV-LV transformer (20/0.4 kV). The ampacity of all branches is assumed to be 350 *Amperes*, while the rated capacity of the transformer is 250 kVA. Presently, the system has two PV installations at nodes 5 and 7 with the maximum capacity of 74 kWp and 82 kWp (kilowatt peak), respectively. A camera-based acquisition system is installed at node 6 to be used for the PV production forecast. The network parameters are provided by the UNITED-GRID [68] project partner Sorea and presented in Appendix B.

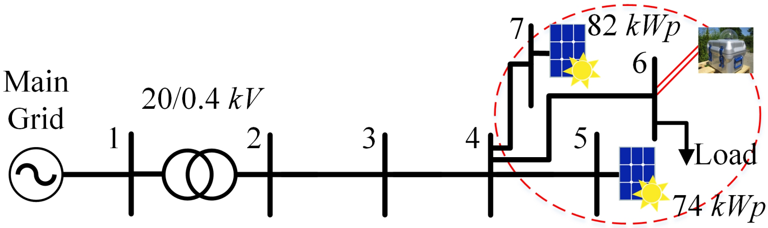


Figure 4.3: Single-line diagram of a part of Sorea's distribution system.

Other input data for the congestion forecast includes:

i) Near-real-time (one minute-ahead) PV production forecast data provided by the UNITED-GRID project partner CEA. The PV production forecast method is based on the sky-images taken by the camera located at node 6 and is described in [69]–[71].

ii) Load forecasting data is also provided by CEA, whose forecasting method is based on an artificial neural network (ANN) [70].

The PV production and load forecast data used in this case study is for 11$^{\text{th}}$ October 2018, as shown in Figure 4.4 and is obtained by the above solution. It can be seen that the PV production for each installation is forecasted to vary between 0 to 40.91 kW, while the load is forecasted to vary between 0 to 7.8 kW.

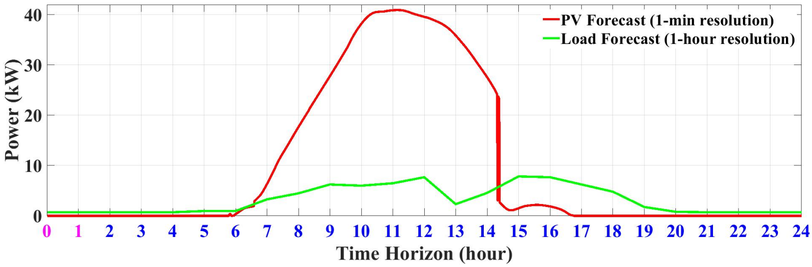


Figure 4.4: The PV production and load forecast profile at 00:00 hours on 11$^{\text{th}}$ October 2018 over the next 24-hours for Sorea's site in France.

4.3.2 141-bus Distribution System of Caracas Metropolitan Area

The considered system is a real distribution system in the metropolitan area of Caracas[72]. The system has a nominal voltage of 12.47 kV with 140 branches and 84 load buses. The system has been modified to include PV installations at all the load buses. The same PV production profile, as shown in Figure 4.4, is considered at all the PV nodes varying between 0 to 409.1 kW in Section 4.4.2.1 and Section 4.4.2.2. While, in Section 4.4.2.3, it varies between 0 to 143.2 kW. For a realistic load scenario, the feeders in the considered system are randomly divided into residential, commercial, and industrial areas. Further, the hourly load profiles at different nodes for these areas are presented in Figure 4.5, which are obtained from the real load data of a local DSO in Sweden. The single-line diagram for the 141-bus distribution system is shown in Figure 4.6. The branches' ampacity is assumed to be 1500 *Amperes*.

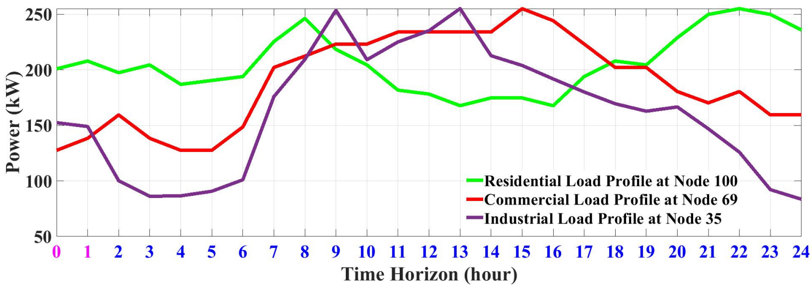


Figure 4.5: Residential, commercial and industrial load profiles used in the 141-bus distribution system.

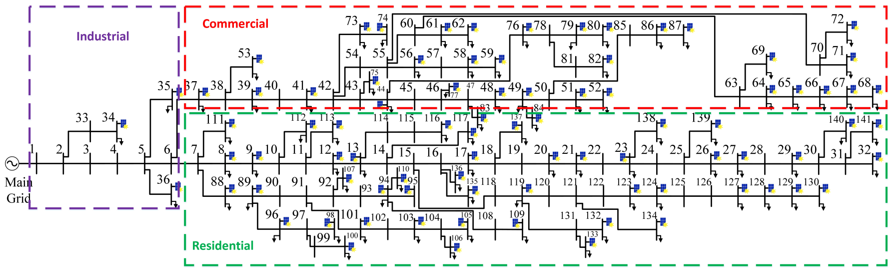


Figure 4.6: Single-line diagram of the 141-bus real distribution system in the metropolitan area of Caracas with PV installations.

Table 4.2: Load Model Parameters for Different Cases

Sl. No.	Load Type	Active Power Coefficients			Reactive Power Coefficients		
		k_{P_P}	k_{P_i}	k_{P_z}	k_{Q_P}	k_{Q_i}	k_{Q_z}
1	Constant Power	1	0	0	1	0	0
2	Residential Feeder	0.10	0.85	0.05	0.00	0.65	0.35
3	Constant Impedance	0	0	1	0	0	1
4	Equal Proportion of ZIP load	0.33	0.33	0.33	0.33	0.33	0.33

To analyze the impact of load models on the congestion forecast accuracy, different cases are studied, which are presented in Table 4.2. These cases include constant P load, constant Z load, an equal proportion of ZIP load, and load model obtained through the measured data of loads provided by a DSO in Sweden for a typical residential feeder [73].

As explained in Section 4.1.2.2, the congestion forecast is performed continuously on a rolling horizon. The PV production and load forecast errors depend on the forecast horizon, and hence different errors are considered, as shown in Table 4.3 [70]. The PV production and forecast errors are considered as zero during the evening and night hours.

Table 4.3: PV Production and Load Forecast Errors over Different Forecast Horizons (in %)

Forecast Error	Forecast Type	Forecast Horizons				
		1-min ahead	5-min, 10-min and 15-min ahead	30-min, 45-min and 60-min ahead	2-hour, 3-hour, ... 6-hour ahead	7-hour, 8-hour, ... 24-hour ahead
Case 1	PV	1.0	3.0	5.0	8.0	10.0
	Load	5.0	5.0	5.0	5.0	8.0
Case 2	PV	1.5	4.0	6.0	9.0	12.0
	Load	6.0	6.0	6.0	6.0	10.0

The proposed congestion forecast tool has been implemented using MATLAB R2019b and Python. The number of MCS is considered 10 000 [38], and the power flow convergence criterion is taken as 0.00001 p.u.

4.4 Results and Discussions

4.4.1 7-bus Feeder of Sorea's Distribution System in France

The visualization of the congestion forecast over a day is presented through both CP-based contour plot and colour-map. The simulation is done with PV production and load forecast data for 00:00 hours of 11th October 2018 under a constant-pf mode of PV-inverter.

4.4.1.1 Cumulative Probability-based Contour Plot

To illustrate the result of the congestion forecast, the CP for the voltage at node 5 is shown in Figure 4.7. The contour plot shows the difference over various forecast horizons. The CP for node voltage deviation remains low (green area) from 1-min to 7-hour ahead and then starts increasing (towards yellow area) until 13-hour ahead and subsequently starts decreasing. For the 13-hour ahead, the CP for node voltage to be above 1.04 p.u. is 0.7 (or 70% of the times). The colour bar in the contour plot represents the severity of congestion.

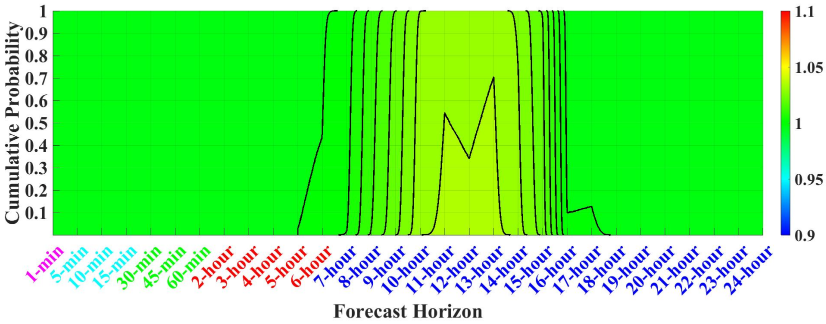


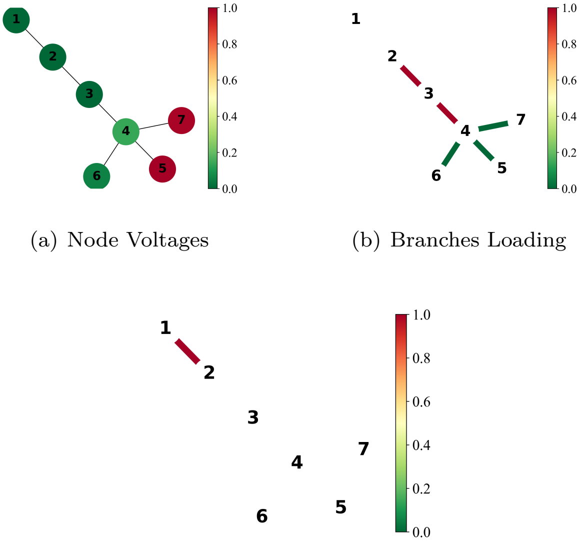
Figure 4.7: CP-based contour plot for visualization of the congestion forecast at node 5, simulated with a constant-pf mode for Sorea's 7-bus system.

It is evident from Figure 4.7 that the network is subjected to different congestion levels over the considered forecast horizons. These changes in the congestion levels occur mainly due to varying PV production and load demand during the day. This simulation uses the forecasted data for an entire day, starting from 00:00 hour. As the sun rises, the PV production increases, reaching its peak value around noon and decreasing after that. Thus, mainly the higher PV production level leads to an increase in the node voltages and vice-versa while the load has a negligible effect due to the small proportion.

4.4.1.2 Colour-map

The colour-map is useful in evaluating the overall picture and the exact locations of the network congestion. The colourbar here represents the CP for congestion. For illustration purposes, the congestion threshold for the node voltage is taken as 1.03 p.u., for branches and transformer loading as 0.5 and 0.3 p.u., respectively. The DSO can specify their thresholds as desired.

It can be seen from Figure 4.8(a) that for 13-hour ahead forecast, nodes 5 and 7 have high CP for voltage deviation; node 4 has medium CP while the rest nodes have low CP for voltage deviation. Similarly, Figure 4.8(b) shows that branches $2-3$ and $3-4$ have high CP for congestion, and the rest of the branches have low CP for congestion. Furthermore, Figure 4.8(c) shows that the transformer has a high CP for overloading. Due to the length limit, the colour-map for only one time horizon is presented here while the animated version of colour-map over different forecast horizons can be found at [74].



(a) Node Voltages

(b) Branches Loading

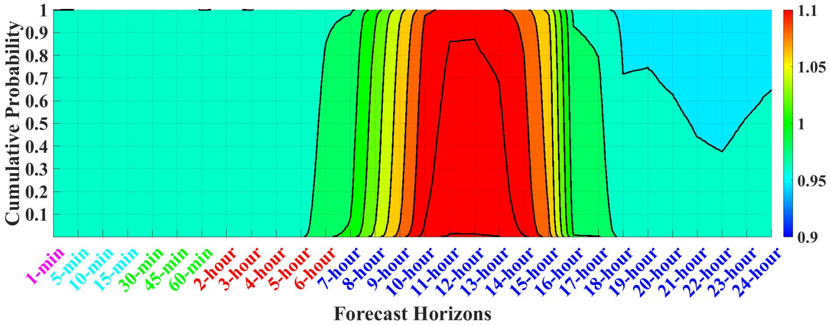
(c) Transformer Loading

Figure 4.8: Colour-map visualizing congestion forecast for 13-hour ahead simulated with a constant-pf mode for Sorea's 7-bus system.

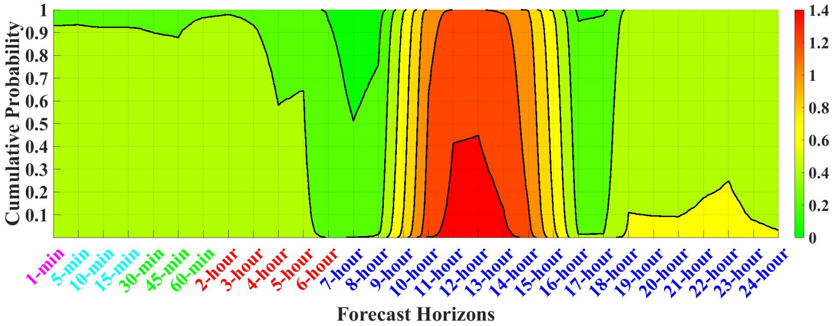
4.4.2 141-bus Distribution System of Caracas Metropolitan Area

4.4.2.1 Visualization of Congestion Forecast over a Day

To visualize the congestion forecast over a day, the simulation is carried out with a constant-pf mode using the PV production and load forecast profile, as shown in Figure 4.4 and Figure 4.5, respectively. With this tool, the node voltage and branches loading can be forecasted at all the system nodes and branches. Although, in this work, node 141 is chosen as it is one of the weakest nodes in terms of voltage variation, and branch $3-4$ is chosen as it is one of the most loaded branches in the network.



(a) The voltage at node 141



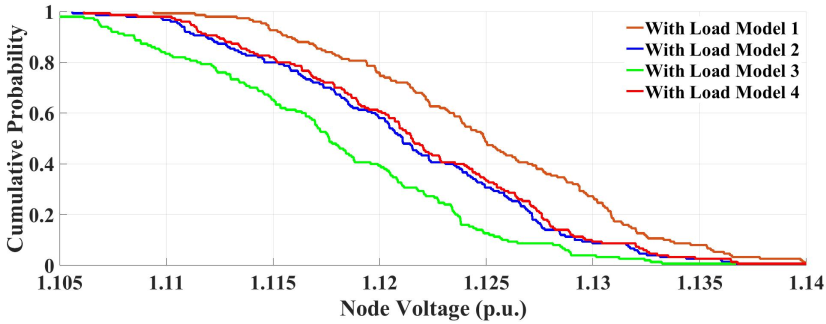
(b) The loading level of branch $3 - 4$

Figure 4.9: CP-based contour plots for visualization of congestion forecast simulated with a constant-pf mode for the 141-bus distribution system.

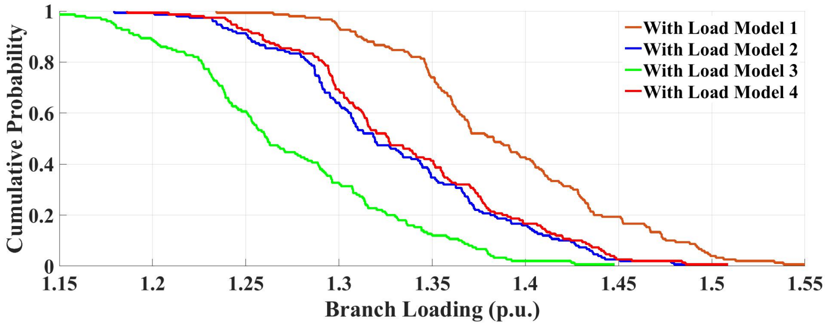
It can be seen from Figure 4.9(a) that for 13-hour ahead, the CP for voltage to be above 1.1 p.u. at node 141 is approximately 0.85. Similarly, from Figure 4.9(b), for 13-hour ahead the CP for loading level of branch $3 - 4$ to be above 1 p.u. is approximately 1. Thus, it is clearly visible from CP-based contour plots (Figure 4.9) that the network is subjected to a different level of congestion over the considered forecast horizons. These changes in the congestion levels occur mainly due to varying PV production and load demand during the day.

4.4.2.2 Impact of Load Models on Congestion Forecast Results

To assess the impact of load models, four simulations with different load model parameters are carried out. The CP for voltage at node 141 and loading level of branch 3 – 4 for 13-hour ahead (maximum PV production) with different load models are shown in Figure 4.10(a) and Figure 4.10(b), respectively.



(a) The node voltage at node 141



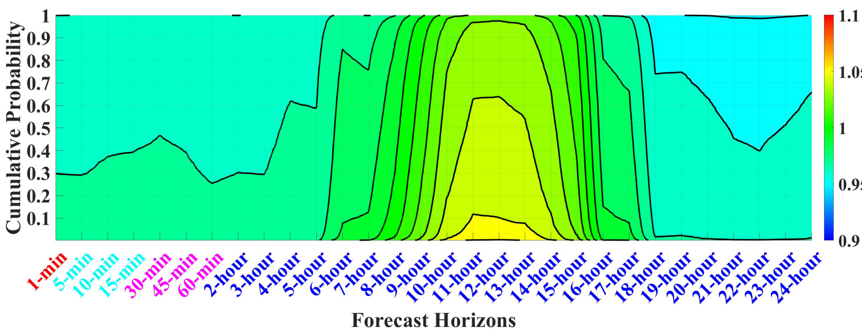
(b) The loading level of branch 3 – 4

Figure 4.10: CP-based congestion indicators showing the impact of load models on congestion forecast for 13-hour ahead for the 141-bus distribution system.

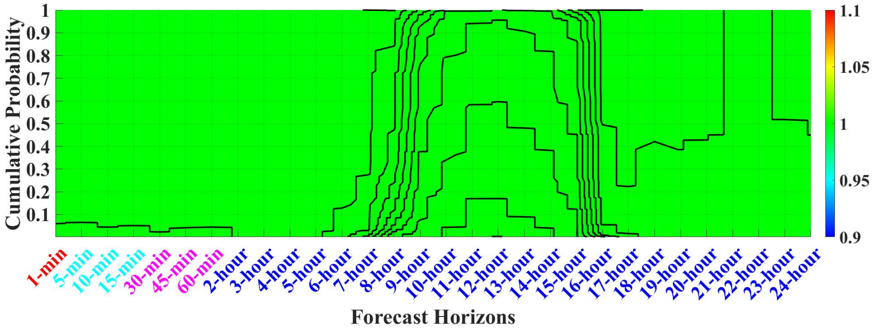
It can be seen from Figure 4.10(a) that the node voltage deviation is highest with load model 1 (P). This can be explained using the "voltage drop" equation of a simple network. Assuming an increase in the PV production at a node, there will be an increase in the node voltage, and this change will not be affected by the constant power load (the consumed power will not change regardless of the change in voltage). While the node voltage deviation is lowest with load model 3 (Z) because the increase in PV production will lead to a rise in voltage initially. As the load is a constant-impedance load, the consumed power will increase with increased voltage, which leads to higher line current and reduced node voltage. Hence, the node voltage deviation is lowest with the load model 3 (Z) and highest with the load model 1 (P). Further, with load models 2 and 3 (residential feeder and constant impedance), the node voltage is higher with the load model 2 because the voltage deviation will be higher in constant current load ($P \propto V$) than in constant impedance load ($P \propto V^2$), as the voltage is proportional to the power in I load while it is proportional to the square root of power in Z load, Similar explanations can be applied for branch loading with the different load models as shown in Figure 4.10(b). The results have shown that it is important to have good load models to have a more accurate congestion forecast, i.e., not over- or under-estimate the network's congestion levels.

4.4.2.3 Influence of Operating Modes of PV-Inverter on Congestion Forecast Results

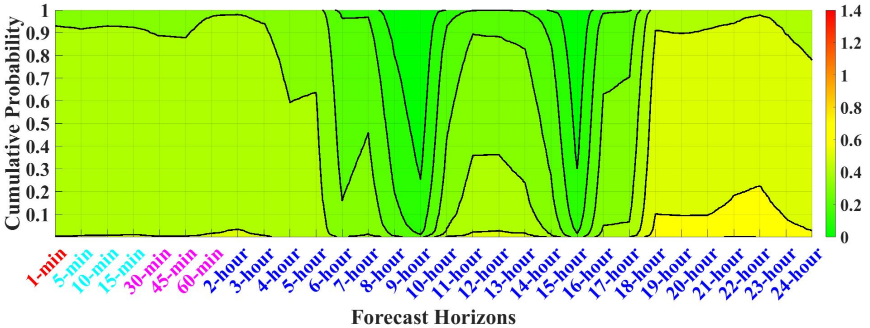
To assess the impact of operating modes of PV-inverter, the simulations are done with constant-pf and constant-V modes of operation. The PV production is considered the same at all the PV locations, varying between 0 and 143.2 kW. The CP for voltage at node 141 and loading level of branch $3-4$ under the two modes of operation are presented in Figure 4.11.



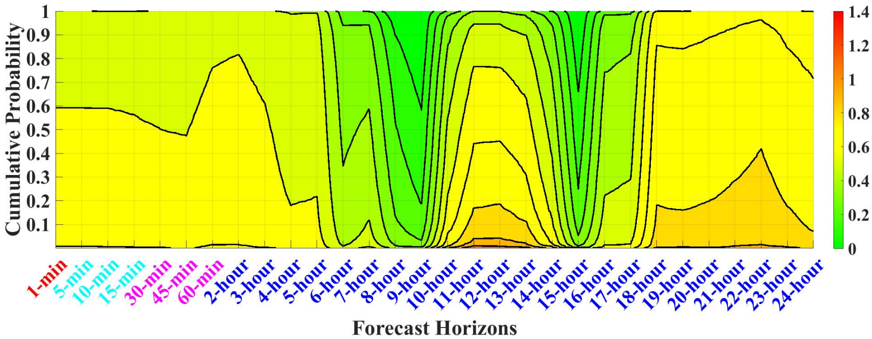
(a) The voltage at node 141 with constant-pf mode



(b) The voltage at node 141 with constant-V mode



(c) The loading level of branch 3 − 4 with constant-pf mode



(d) The loading level of branch 3 − 4 with constant-V mode

Figure 4.11: CP-based contour plots showing the influence of operating modes of PV-inverter on the congestion forecast for the 141-bus distribution system.

For 13-hour ahead, the CP for node voltage to be above 1.04 p.u. in constant-pf mode is 0.6 (Figure 4.11(a)) while in a constant-V mode, it is 0 (Figure 4.11(b)). Similarly, for 13-hour ahead, the CP for branch loading to be above 0.8 p.u. in constant-V mode (Figure 4.11(d)) is approximately 0.2 while it is almost 0 in constant-pf mode (Figure 4.11(c)).

It is evident from the results that in a constant-V mode, the CP for nodes voltage has decreased but simultaneously the loading level of branches has increased. The reason for the reduced voltage deviation is due to the consideration of $P - V$ nodes. In a constant-V mode, the voltage is maintained at a specified value through reactive power compensation by injection of higher reactive current, which leads to higher current and MVA loading in associated branches and transformers. Thus, the PV-inverter operating mode is an important aspect to be considered in the congestion forecast tool.

4.5 Scalability and Accuracy of Proposed Tool

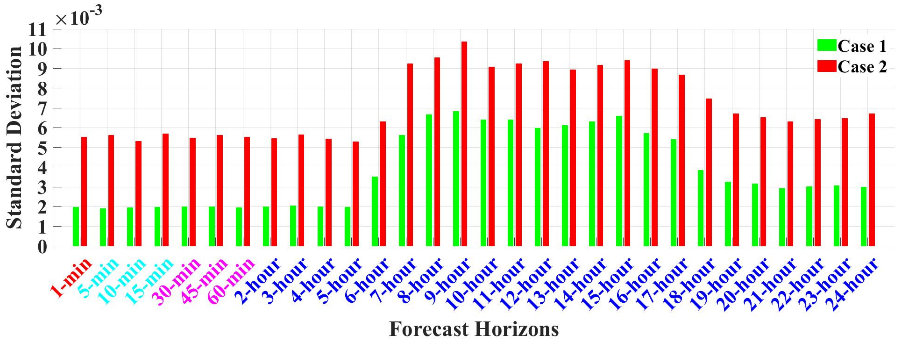
The scalability of the proposed tool when applied to a large distribution system, is an important feature, which is considered during tool development. The tool is applied to a 7-bus feeder of Sorea due to the availability of the physical solution for PV production and load forecast. Further, the tool is applied to the 141-bus real distribution system to evaluate the scalability. The computational time (for all time horizons) for the two case studies in a constant-pf mode of operation is presented in Table 4.4. These results are obtained with MATLAB (R2019b version) and the computer configuration as Intel(R) Core(TM) i7-7700K CPU @4.20-GHz processor and 48 GB RAM.

Table 4.4: Computational Time For Congestion Forecast Tool with Different Test Systems (in seconds)

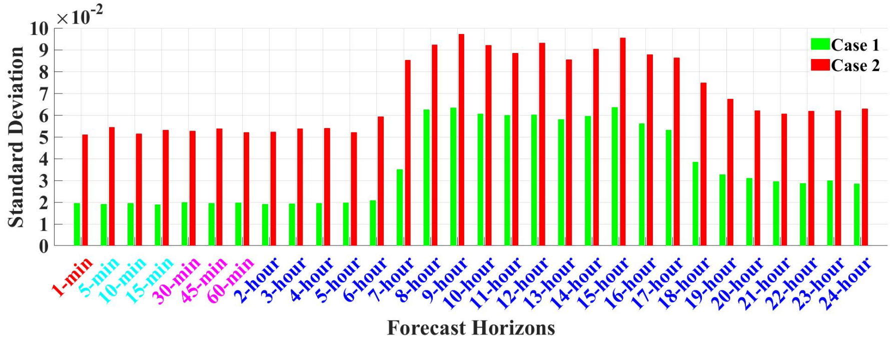
Sl. No.	**Number of MCS**	**Sorea's 7-bus system**		141-**bus system**	
		Tolerance Limit		Tolerance Limit	
		0.001 p.u.	0.00001 p.u.	0.001 p.u.	0.00001 p.u.
1	100	0.93	1.01	5.98	7.60
2	1000	3.89	4.50	58.34	75.04
3	10000	39.81	46.23	1239.13	1411.29

The computational time of the algorithm depends on the number of the MCS and the tolerance limit. The higher number of MCS and stricter tolerance limits would lead to more accurate determination of the CP for congestion indicators which is the backbone for contour plots and colour-map. It can be seen from Table 4.4 that the computational time increases with the increase in the number of MCS and stricter tolerance limits. Thus, it is a trade-off situation between computational time and accuracy for the DSO. Like in the 141-bus system, with the given computer configuration, the most optimal solution appears as 1000 MCS and 0.001 p.u. tolerance limit.

Another important aspect is the accuracy of the congestion forecast, which mainly depends on the PV production and load forecast accuracy. The lesser PV production and load forecast error would lead to more accurate scenarios generation through MCS, and thus, the results of the congestion forecast will be more accurate. To validate this aspect, two congestion forecast simulations are performed with different forecast errors of PV production and load. The PV production and load forecast errors used in these two simulations are shown in Table 4.3. For each congestion forecast, the mean and standard deviation for the normal distribution is calculated for node voltages and branch loading levels. The standard deviation for the voltage at node 141 and the loading level of branch $3-4$, are presented in Figure 4.12(a) and Figure 4.12(b).



(a) The node voltage at node 141



(b) The loading level of branch $3-4$

Figure 4.12: Standard deviations of congestion indicators simulated with different forecast errors for the 141-bus distribution system.

It can be seen from Figure 4.12 that higher PV production and load forecast errors lead to a higher standard deviation of node voltages (Figure 4.12(a)) and branch loading (Figure 4.12(b)) as the forecast errors considered in case 1 are lower as compared to case 2. However, there is no substantial difference in the mean value of node voltages and branch loading in the two simulations as the same mean (μ) obtained from PV production and load forecast is used in the Gaussian PDF for generating MCS in the two simulations.

4.6 Integration with UNITED-GRID Toolbox

4.6.1 Objectives

The main objectives of the tools integration are as follows:

- Validation of the developed tools on the demonstrator sites
- Development of tools using open-platform technologies for seamless integration with the industrial standards
- Reduce the launch time to market for the developed tools by doing the early-stage integration with the existing DMS of DSOs

4.6.2 Toolbox Functional Description

The different functionalities and architecture of the toolbox are explained here. The list of the actors involved in this architecture are as follows:

- DSO
- DSO SCADA platform
- MV nodes
- LV nodes
- External service provider

The functional diagram of overall solution for tools integration with the involved actors is presented in Figure 4.13. The functional diagram has two parts where the first part presents the integration of the congestion forecast tool along with the involved actors while the second part presents the integration of the dynamic state estimation based protection scheme along with the advanced measurement technologies developed by SST, with the overall solution.

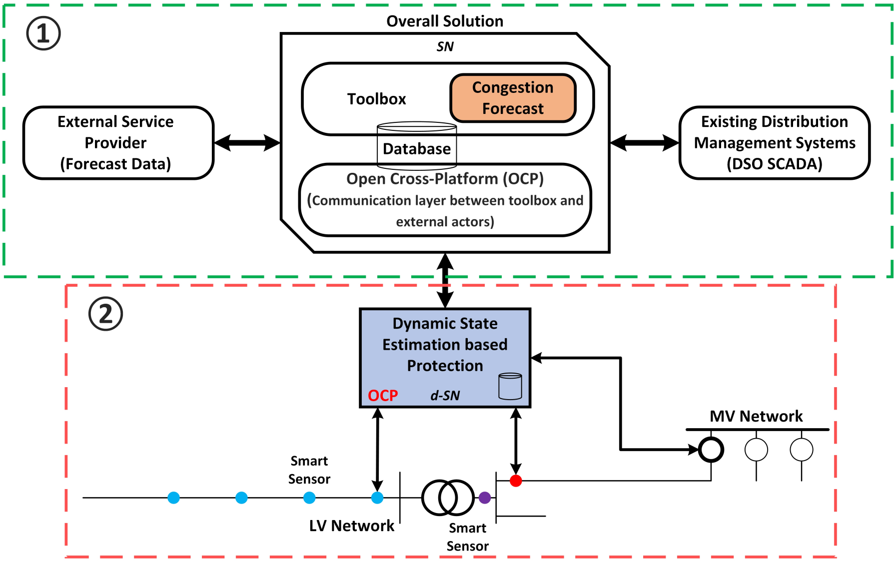


Figure 4.13: Functional diagram of overall solution for tools integration with DSO SCADA.

Overall Solution

The overall solution consists of two parts:

- Toolbox: It consists of the advanced functionalities such as congestion forecast tool.
- Open cross-platform (OCP): It ensures the proper connectivity between the different involved actors and the collection of the data by external service providers.

The overall solution would control the management of the tools developed in the toolbox. This centralized instantiation is referred as smart node and abbreviated as *SN*. While, there is also distributed instantiation which will be directly installed in the field for the protection tool. This distributed instantiation is referred as distributed smart node and abbreviated as *d-SN*.

External Actors

There are the following three types of external actors:

- DSO SCADA platform: It refers to the existing SCADA system of the DSO.
- MV/LV nodes: It refers to the medium/low voltage nodes where the different physical devices or assets are connected for the purpose of data acquisition, communication, control etc.
- External service provider: It refers to the external data sources whose information is not coming from the field. It could include the PV production and load forecast data used for the congestion forecast tool.

4.6.3 Congestion Forecast Use-Case

The use-case methodology is an important tool which is useful in describing the different usage scenarios for implementation of smart grid tools with a standard procedure. There are some standard definitions of use-case, one such by EPRI is given as a valuable method of documenting applications and processes for purposes of defining requirements [75].

The details of the congestion forecast use-case considered in this work are given in Table 4.5.

Table 4.5: Overview of Congestion Forecast Use-case

Use-case	Name	Congestion forecast
	Main Objectives	• To forecast network congestion in distribution systems • To develop an advanced interactive visualization for network congestion
	Short Description	The future distribution systems will face the risk of having network congestion due to high penetration of RES and load. The congestion forecast tool will forecast congestion levels in terms of voltage deviation and components overloading.

4.7 Summary

This chapter presents a tool to assist the DSO to forecast the congestion levels in their networks as per the preferences specified by the DSO. The tool can present the cumulative probability-based contour plots and colour-map of the network which visualize the network loading conditions for the DSO and make it easy for the DSO to take necessary preventive or corrective actions. The tool has performed adequately with the test systems. Various factors such as forecast accuracy, load models, and PV-inverter operating modes, which can impact network congestion are incorporated in the tool. Within the EU project UNITED-GRID, the proposed tool is planned to be integrated to the existing distribution management system via an IoT platform Codex Smart Edge of Atos Worldgrid. The tool will be used by DSO to support their daily congestion management tasks and better utilize their grids and thus reduce the need for expensive network reinforcement. The electricity consumers will also be benefitted from the tool as the distribution network will be operated more securely.

CHAPTER 5

Application of Dynamic State Estimation for Line Protection

This chapter presents the work conducted on the implementation and validation of a dynamic state estimation based protection scheme using advanced measurement technologies developed by SST at Chalmers power system laboratory.

5.1 Dynamic State Estimation based Protection Scheme

5.1.1 Background

Power system protection has evolved from the era of electromechanical relays to the present era of sophisticated microprocessor-based relays. There are various types of protection schemes such as over-current, distance, differential, etc., which are proposed over time and offer their advantages and disadvantages. The main factors contributing towards the mis-operations of the present protection schemes are:

(a) Higher complexity and sophistication of protection schemes

(b) Protection based on limited system information

(c) Failure to operate properly during the occurrence of hidden failures in system

The NERC presented the performance statistics in the protection systems as shown in Figure 5.1. The figure presents that almost 50% of mis-operations are caused either due to incorrect setting errors or relay failures.

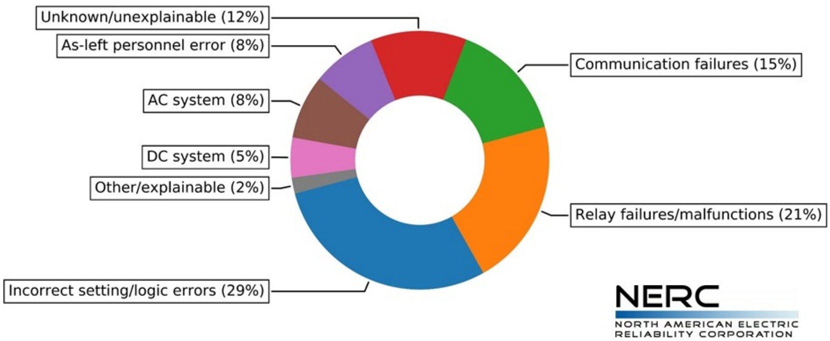


Figure 5.1: Performance Statistics in Protection Systems from NERC [51]

Further, key examples such as downed conductors in distribution systems, faults occurring close to the neutral of solidly grounding systems, high impedance fault, etc., show the existence of various other protection gaps in the system as the conventional protection schemes are unable to detect these kinds of faults. Also, increasing penetration of DERs into the distribution systems leads to failure of conventional protection schemes and other phenomenons such as false tripping, protection blinding, re-closer problems, device discrimination, etc. These challenges are mainly caused by the bi-directional power flow, change in fault current and short-circuit level, fault current limitation in converter-dominated distribution systems, etc.

All these protection gaps require either revisiting of the existing protection schemes or the development of novel protection schemes. One such novel protection scheme based on the DSE has the potential to address these protection gaps. The main advantage associated with DSEBPS is the simplification of the protection as it does not requires setting with additional capabilities to detect hidden failures and cyber-attacks on the system [52].

5.1.2 General Concept

DSEBPS is a novel concept which is motivated from one of the most accurate protection scheme i.e., differential protection [52]. The concept of DSEBPS is a further generalization of the original Kirchhoff's law to the extent of validation of component's all physical laws. Some examples of such physical laws could be Kirchhoff's voltage and Faraday's laws [53]. Thus, the component under protection should satisfy all the physical laws. DSE models all physical laws that the device is supposed to satisfy in the form of a dynamic model. The component's dynamic model is constantly observed by DSE and any violations of laws (abnormality) are apprehended and subsequently, a corrective action can be taken to protect the component. Based on the dynamic model, DSE calculates the operating condition of the component and thus generates the protection decision i.e., trip or no-trip signal. The important aspect here is the protection decision from dynamic state estimation is purely based on the component's operating condition and no dependence on other system components operating condition, giving it an edge over the other conventional protection schemes. The overall concept of the DSEBPS is shown in Figure 5.2.

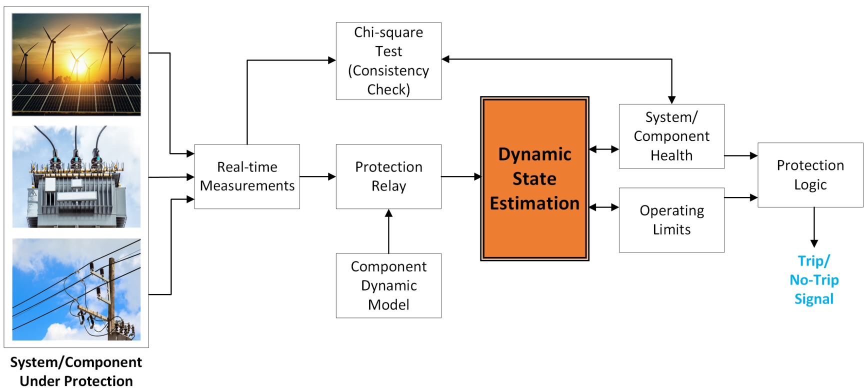


Figure 5.2: Generalized concept figure of DSEBPS.

DSEBPS requires real-time voltage, current, and frequency measurements from the component under protection. These measurements are utilized by the DSE block which along with the component dynamic model and outputs the operating conditions of the component. In order to check the consistency of the estimated states with the measurements, a well-acclaimed Chi-square test is performed. The Chi-square test provides the confidence level in the estimated variables which can be used to predict the health of the component. Therefore, under normal or steady-state conditions, the confidence level should be high i.e., the component is in good health, while during the abnormal or fault conditions the confidence level should be low i.e., the component is in bad health. Finally, the results of operating conditions from DSE along with the component's health conditions from the Chi-square test can be used to decide the protection logic whether to trip or no-trip. Additionally, this concept helps to improve the selectivity for the fault detection, meaning that the DSE will keep predicting good health for the component even if the fault has occurred just outside the component as it will be seen as an external fault and not as an internal fault [55], [76].

The application of the DSE in the protection of various components and systems is quite wide. However, this chapter focuses on the line protection along with the simulation and laboratory experimental validation results. The DSE based protection scheme is validated for both simulations (underground distribution cable) and laboratory experiment (overhead transmission line).

5.1.3 Modelling

5.1.3.1 Algebraic Quadratic Companion Form (AQCF) Model of Distribution Line

This section presents the basics of the AQCF model for the distribution line which is based on the quadratic integration method. The presented model is for a three-phase line and represents one π-section [77]. The schematics of the π-representation of the three-phase distribution line is presented in Figure 5.3. In the presented schematics, the line has three phases as A, B, and C and neutral N. The resistances and reactances of each phase are represented as R_A, R_B, R_C, R_N and L_A, L_B, L_C, L_N, respectively. The shunt capacitances for each phase are represented as C_A, C_B, C_C, C_N. Also, G_A, G_B, G_C, G_N are considered for the numerical stabilization purpose and may not be essentially part of the actual system. The sending end voltages and currents are represented as V_A, V_B, V_C, V_N, and i_A, i_B, i_C, i_N, respectively. While the receiving end voltages and currents are represented as V_a, V_b, V_c, V_n and i_a, i_b, i_c, i_n, respectively. Also, i_{dA}, i_{dB}, i_{dC}, i_{dN} are the currents in the series branch of the three phases of the distribution line.

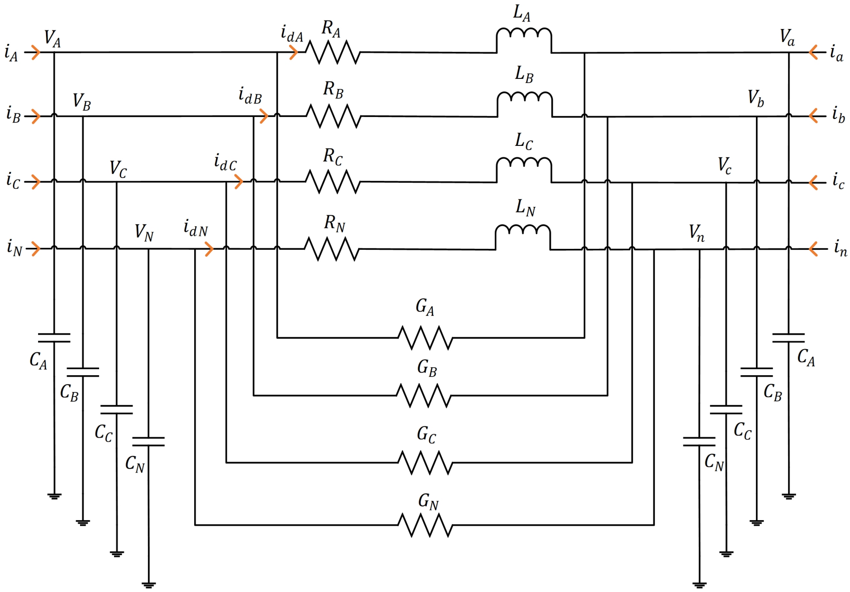


Figure 5.3: Three-phase line diagram for the electric distribution line.

The following equation is obtained from the AQCF Model of distribution line [77], as derived in (A.20):

$$H_1 \begin{bmatrix} z(t) \\ z\left(t - \frac{k}{2}\right) \end{bmatrix} = H_2 \begin{bmatrix} x(t) \\ x\left(t - \frac{k}{2}\right) \end{bmatrix} - H_3 \left[z(t-k) \right] - H_4 \left[x(t-k) \right] \quad (5.1)$$

where,

$$H_1 = \begin{bmatrix} \frac{k}{6}R_1 + R_2 & \frac{2k}{3}R_1 \\ -\frac{k}{24}R_1 & \frac{k}{3}R_1 + R_2 \end{bmatrix}, H_2 = \begin{bmatrix} \frac{k}{6}S_1 + S_2 & \frac{2k}{3}S_1 \\ -\frac{k}{24}S_1 & \frac{k}{3}S_1 + S_2 \end{bmatrix}$$

$$H_3 = \begin{bmatrix} \frac{k}{6}R_1 - R_2 \\ \frac{5k}{24}R_1 - R_2 \end{bmatrix}, H_4 = \begin{bmatrix} -\frac{k}{6}S_1 + S_2 \\ -\frac{5k}{24}S_1 + S_2 \end{bmatrix}$$

Restructuring (5.1), we obtain the new equation in the standard form of state estimator:

$$\begin{bmatrix} z\left(t\right) \\ z\left(t-\dfrac{k}{2}\right) \end{bmatrix} = H \begin{bmatrix} x\left(t\right) \\ x\left(t-\dfrac{k}{2}\right) \end{bmatrix} - C_1\left[z\left(t-k\right)\right] - C_2\left[x\left(t-k\right)\right] \tag{5.2}$$

$$\begin{bmatrix} z\left(t\right) \\ z\left(t-\dfrac{k}{2}\right) \end{bmatrix} = H \begin{bmatrix} x\left(t\right) \\ x\left(t-\dfrac{k}{2}\right) \end{bmatrix} + C \tag{5.3}$$

where,

$$H = H_1^{-1}H_2, C_1 = H_1^{-1}H_3, C_2 = H_1^{-1}H_4, C = -C_1\left[z\left(t-k\right)\right] - C_2\left[x\left(t-k\right)\right]$$

The details of the quadratic integration method and AQCF model of distribution line are presented in Appendix A.

5.1.3.2 State Estimation Algorithm

The most common approach for the solution of the state estimation i.e., the weighted least square (WLS) algorithm is used to solve the state estimation problem. The linear version of the WLS algorithm is presented:

$$z = Hx + \eta \tag{5.4}$$

where z represents the measurement vector, H represents the Jacobian matrix, x represents the state estimator vector and η represents the measurement error vector.

The objective function for the state estimation is the minimization of the sum of the weighted squares of measurement residual function, given as:

$$\begin{aligned} J &= \left(z - H\hat{x}\right)^T R^{-1}\left(z - H\hat{x}\right) \\ J &= \eta^T R^{-1} \eta \end{aligned} \tag{5.5}$$

where $\hat{x}$ is the state estimation solution vector and R is the measurement weight matrix and defined as $diag\left(\sigma_1^2, \sigma_2^2, \sigma_3^2, \ldots.., \sigma_m^2\right)$.

The solution for the state estimation comes out as:

$$\hat{x} = \left(H^T R^{-1} H\right)^{-1} \left(H^T R^{-1} z\right) \tag{5.6}$$

5.1.3.3 Chi-squares Test for Estimation Confidence Level

The following steps are performed for the Chi-squares test using the WLS state estimation algorithm [54]:

1. Calculate the state estimation objective function J from (5.5)

2. Checkup with the Chi-squares distribution table for the probability of estimation confidence:

   $$p = \chi^2_{[J,(m-n)]}$$

   where χ^2 represents the Chi-squares function, J is the objective function, $(m-n)$ is the degrees of freedom, m is the number of measurements and n is the number of state variables.

5.1.3.4 Component Health and Protection Logic

The component health (h) can be evaluated based on the probability of estimation confidence from the Chi-squares test as:

$$h = 1 - p = 1 - \chi^2_{[J,(m-n)]} \tag{5.7}$$

The logical diagram for the objective function of the Chi-squares test, confidence level, and trip signal are shown in Figure 5.4. It can be seen from Figure 5.4 that during the instants when the Chi-squares test objective function (χ^2) results in low values, then the corresponding value of confidence level remains high and thus the scheme does not send the trip signal. Conversely, when the Chi-squares test objective function (χ^2) results in high values, then the corresponding value of confidence level goes low, and thus the trip signal is sent.

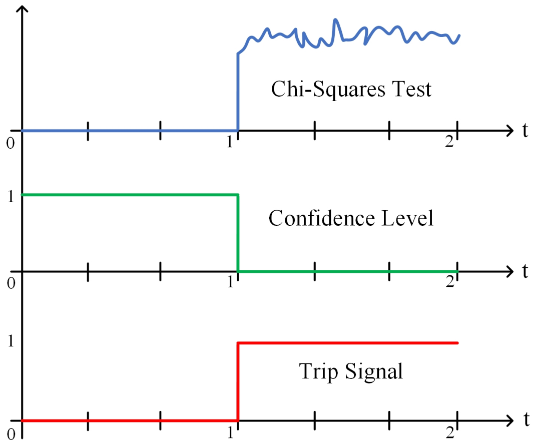


Figure 5.4: Objective function of the Chi-squares test, Confidence level and Trip signal logical diagram.

5.2 Validation of Scheme using Simulation

5.2.1 Simulation Setup

The DSEBPS is simulated for an underground distribution cable in MATLAB Simulink. The three-phase modelling of the underground distribution cable is done using the π-model. The model parameters used for the underground distribution cable are presented in Table 5.1. The considered cable parameters are for an LV armoured XLPE cable with aluminium make 240 mm^2 conductor size for a 3-core configuration [78].

Table 5.1: Underground distribution cable parameters [78]

Cable Parameters	Values
Resistance	0.124 Ω/km
Reactance	0.085 Ω/km
Inductance	0.270 mH/km
Capacitance	0.325 $\mu F/km$

The sending end current (i_A, i_B, i_C), receiving end current (i_a, i_b, i_c) and receiving end voltage (V_a, V_b, V_c) are taken as the measurements as shown in Figure 5.3 and explained in Appendix A. While, the sending end voltage (V_A, V_B, V_C) and series branch current (i_{dA}, i_{dB}, i_{dC}) are the estimated variables, as shown in Figure 5.3 and explained in Appendix A.

The simulation time is set as 2 seconds and the measurements have a sampling rate of 1e-4. In this simulation, a fault is created at 1.4 and cleared at 1.6 seconds. The measurements are recorded and then brought from the MATLAB workspace to the MATLAB script where the code is written for the DSE-based protection scheme. These measurements are fed as the input to this code which further estimates the two variables. These estimated variables are compared with their measured values from the MATLAB simulation.

It is important to emphasize that only the simulation of the DSE is tested here, not the simulation of the relay and other hardware components (CTs, VTs, sensors, breakers, etc.).

5.2.2 Simulation Results

The simulation results for the considered system are presented here. It can be seen from Figure 5.5 and Figure 5.6, that during the normal operating conditions the measured and estimated values of the (V_A, V_B, V_C) and (i_{dA}, i_{dB}, i_{dC}) are pretty close and their difference is not substantial. While, when the fault occurs (between 1.4 and 1.6 seconds), the measured and estimated values are not close and substantial differences can be seen. The previous state is reached as soon as the fault is cleared (for a time greater than 1.6 seconds).

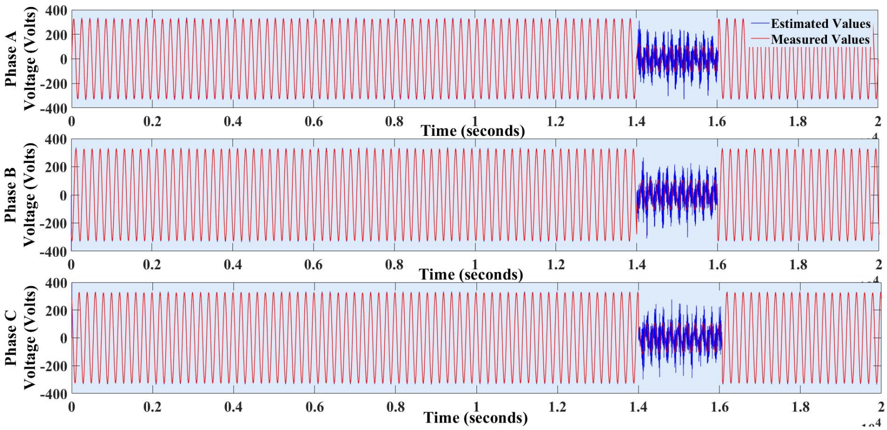


Figure 5.5: The measured and estimated values of V_A, V_B, and V_C for the underground distribution cable in MATLAB simulation.

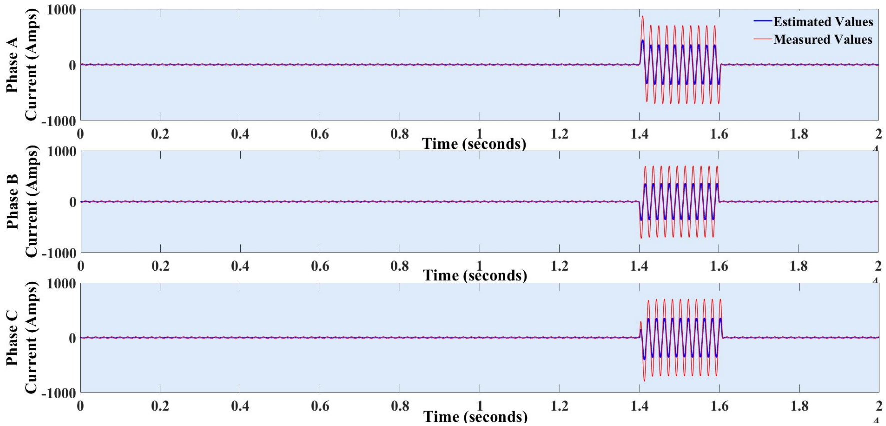


Figure 5.6: The measured and estimated values of V_A, V_B, and V_C for the underground distribution cable in MATLAB simulation.

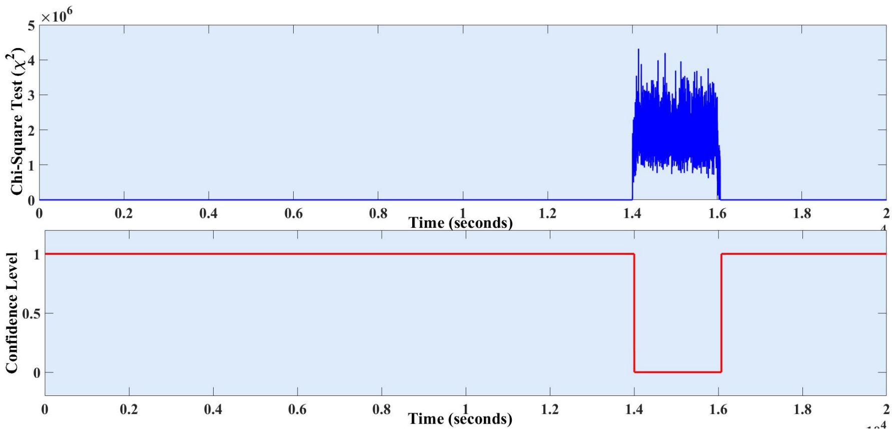


Figure 5.7: χ^2 values and confidence level for the underground distribution cable in MATLAB simulation.

Further, it is evident from Figure 5.7, that χ^2 values (from Chi-square test) are low during the normal conditions (i.e., from 0 to 1.4 and 1.6 to 2 seconds) while the χ^2 values increase substantially during the fault conditions (i.e., during 1.4 to 1.6 seconds). Based on the low χ^2 values, the high confidence level is obtained during 0 to 1.4 and 1.6 to 2 seconds which is also the normal operating conditions. Conversely, high χ^2 values and low value of confidence level are obtained during 1.4 and 1.6 seconds which clearly identifies the fault condition in the cable and thus generates a trip signal.

5.3 Validation of Scheme using Laboratory Experiment

5.3.1 Laboratory Experimental Setup

The Chalmers power system laboratory setup is an accurate scale-down model based on the large Harsprånget hydro-power plant, situated in northern Sweden which consists of a synchronous generator, transformers, transmission lines, and loads. The nominal operating voltage of the model is 400 V. The setup can also be connected with the Chalmers distribution grid. The laboratory setup along with the installation of the LV-sensors is shown in Figure 5.8.

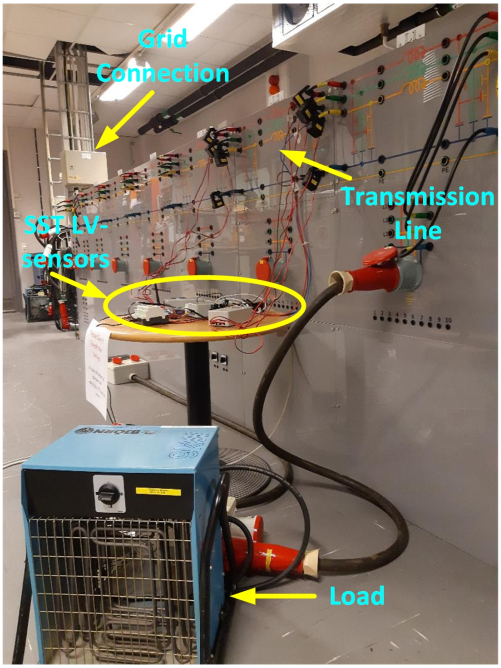


Figure 5.8: Chalmers power system laboratory setup with LV-sensors.

The DSEBPS for the overhead transmission line is validated at Chalmers power system laboratory using the LV-sensors developed by SST, as shown in Figure 5.9. The LV-sensors are installed at Chalmers power system laboratory providing the time-stamped real-time measurements. These measurements are received in a smart node (laptop) where the component dynamic model along with DSE is executed to estimate the states. Thereafter, the Chi-square test is performed using the measurements and estimated states. The health (fault or no-fault) conditions are determined based on the results of the Chi-square test objective function and thus whether to issue a trip or no-trip signal to the breaker.

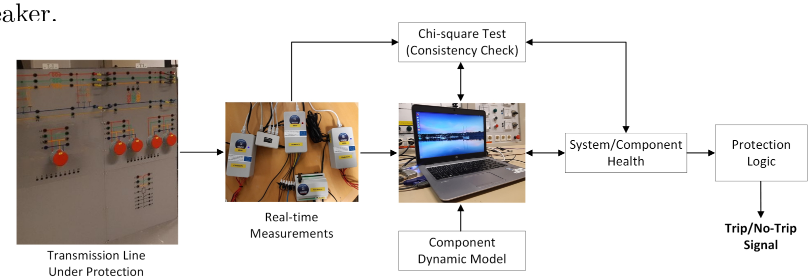


Figure 5.9: Experimental setup diagram for the Chalmers power system laboratory.

The single-line diagram for the power system network at Chalmers power system laboratory is presented in Figure 5.10. The transmission line is modelled using the π-model as shown in the single-line diagram. The parameters for this π-model are presented in Table 5.2. Figure 5.10 also shows the fault point which is the sending end of the 5^{th} π-section of the transmission line.

The LV-sensors measure the sending end current (i_A, i_B, i_C), receiving end current (i_a, i_b, i_c), and receiving end voltage (V_a, V_b, V_c), and bring into the smart node where the python code is written for the DSE-based protection scheme. These measurements are fed as the input to this python code which estimates the sending end voltage (V_A, V_B, V_C) and series branch current (i_{dA}, i_{dB}, i_{dC}) variables.

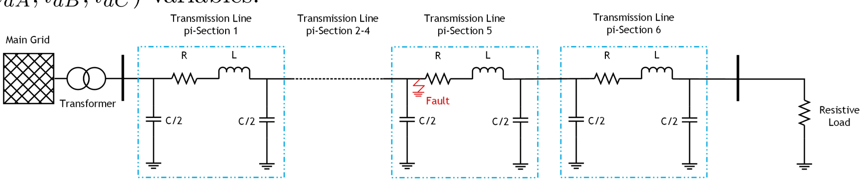


Figure 5.10: Single-line diagram of the Chalmers power system laboratory setup.

Table 5.2: Transmission line parameters for one π-section

Transmission Line Parameters	Values
Resistance	0.052 Ω
Inductance	3.033 mH
Capacitance	46 μF
Grid Frequency	50 Hz
Grid Voltage	400 V

5.3.2 Advanced Measurement Technologies Developed by SST

The LV-sensors developed by SST provide an affordable and reliable real-time measurement solution [79]. To realize the open-platform concept, SST chose embedded Linux (Armbian distribution) as an operating system and developed a real-time digital signal processing (DSP) framework that utilizes the open-source messaging system ZeroMQ [80]. The LV-sensors have the following capabilities:

- Measurement sampling frequencies of at least 4-KHz for voltage and current signals synchronized to global positioning system (GPS)
- Optional synchrophasor output compliant with the IEEE C37.118.1 PMU standard
- Provide real-time streaming data and measurements
- Intelligent data recording mechanism with event-based triggering to enable offline analysis
- Reliable and accurate measurements
- Tamper proof configuration and secure communication

In total, three LV-sensors are installed in this setup at Chalmers power system laboratory, out of which two are current sensors and one is a voltage sensor.

5.3.3 Experiment Results

5.3.3.1 Normal Operating Conditions

The results during the normal operating conditions for the considered system are presented here. It can be seen from Figure 5.11, that during the normal operating conditions, the measured and estimated values of the sending end phase current (CT1 primary current), receiving end phase current (CT2 primary current), and receiving end voltage (VT primary voltage), are in conform with each other. This confirms that during the normal operating conditions, the measured and estimated values should be in accordance with each other, thanks to the correct modelling of the system.

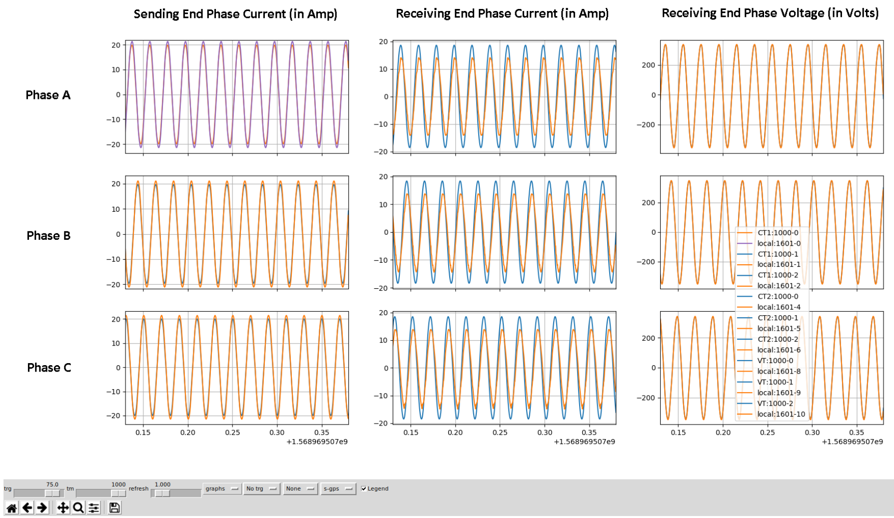
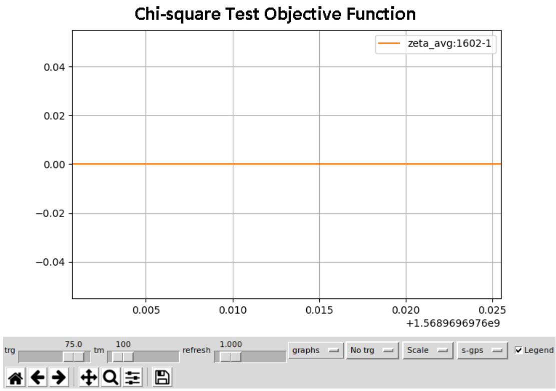
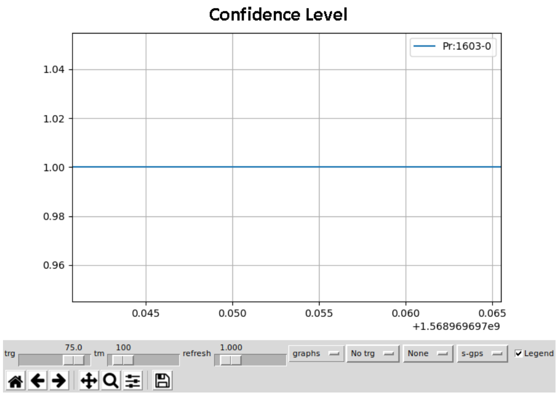


Figure 5.11: The measured and estimated values of sending end phase current, receiving end phase current and voltage during normal operating conditions.

Furthermore, during the normal operating conditions, the χ^2 values (from Chi-squares test) is low due to conformity between the measured and estimated values as shown in Figure 5.12(a) (A threshold value is set for χ^2 values). Based on the χ^2 values, the confidence level is calculated. It can be seen from Figure 5.12(b) that the confidence level remains one during the normal operating conditions.



(a) Chi-square test objective function (χ^2)



(b) Confidence level

Figure 5.12: Chi-square test objective function (χ^2) and confidence level during normal operating conditions.

5.3.3.2 Fault Conditions

A three-phase short circuit fault is created in the transmission line as indicated in Figure 5.10. It can be seen from Figure 5.13, that during the fault conditions, the sending end phase current (CT1 primary current) goes high while receiving end phase current (CT2 primary current), and receiving end voltage (VT primary voltage) tends towards zero due to short-circuit fault.

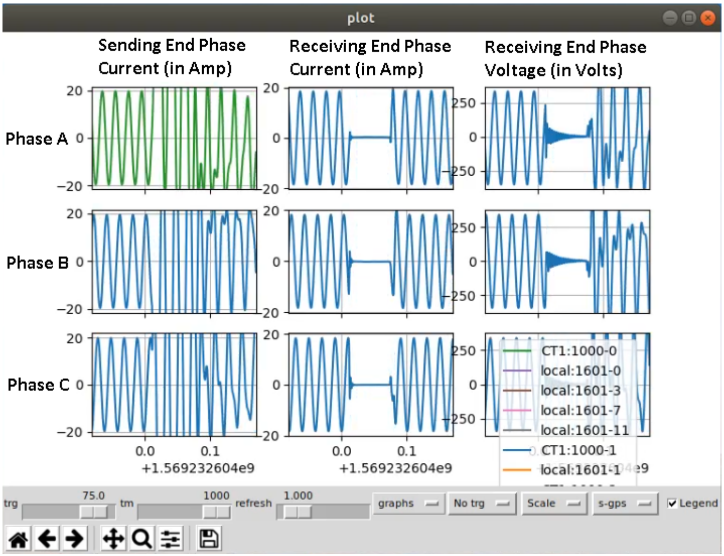


Figure 5.13: The measured values of sending end phase current, receiving end phase current and voltage during fault condition.

For the proper explanation of measured and estimated values of different signals in the system, Figure 5.14 and Figure 5.15 (created with gnuplot [81]) are presented. Further, Figure 5.14 and Figure 5.15 presents the normal and zoomed version plots of measured and estimated values of receiving end voltages (VT primary voltage) for phases A, B, and C, respectively.

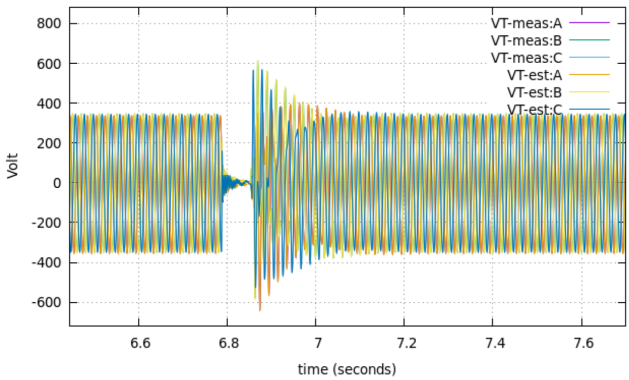


Figure 5.14: The measured and estimated values of receiving end phase voltages of phase A, B, and C, during fault conditions.

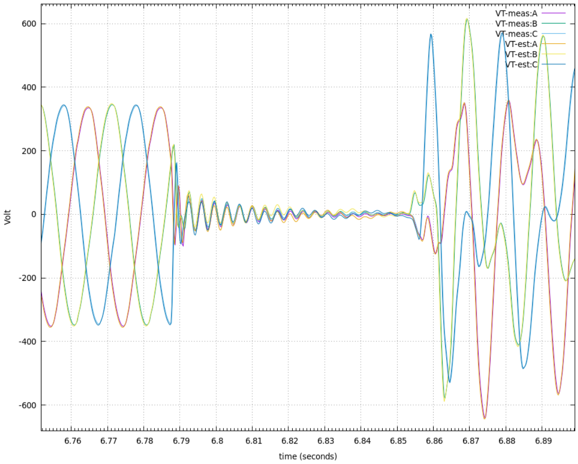
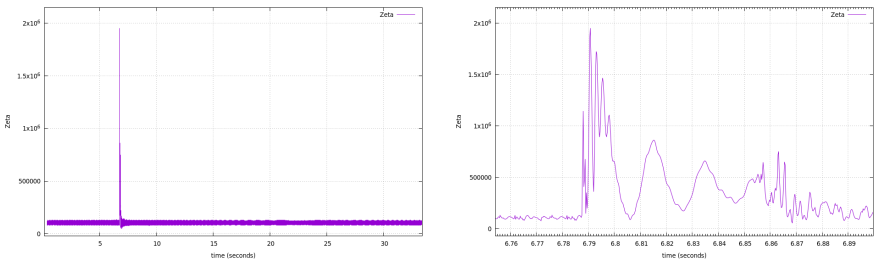


Figure 5.15: Zoomed version of the measured and estimated values of receiving end phase voltages of phase A, B, and C, during fault conditions.

It can be seen from Figure 5.16(a) and Figure 5.16(b), that during the fault condition it leads to higher χ^2 values as the measured and estimated values are not in conformity. During the fault conditions when the χ^2 values go high then the confidence level reaches zero, as shown in Figure 5.17. It can be also be seen that the confidence level goes back to one as the fault is cleared. Thus, based on the confidence level the trip command is sent to the breaker and hence the fault is cleared.



(a) χ^2 values

(b) Zoomed version of χ^2 values

Figure 5.16: Chi-square test objective function (χ^2) during fault conditions.

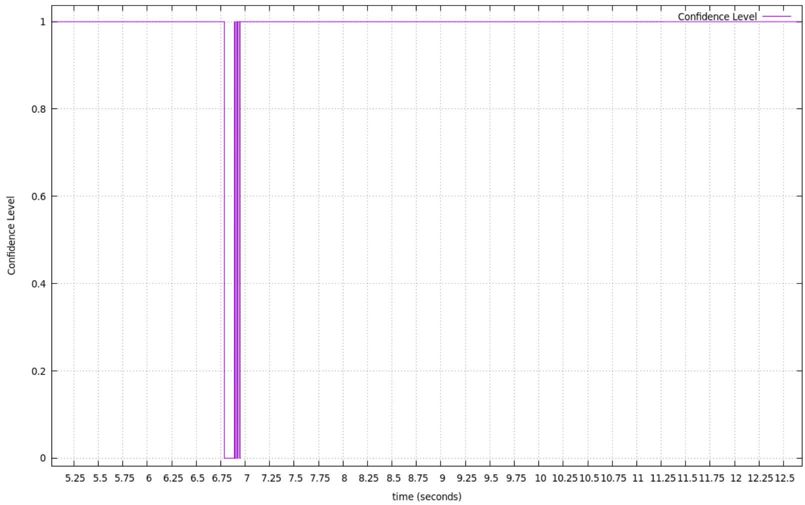


Figure 5.17: Confidence level during fault conditions.

5.4 Processing Time

The processing time is one of the most important features of a protection scheme as like other features such as selectivity, reliability, etc. The general standard for fault clearing time in the transmission systems is 100 milliseconds. Although, in some recent wide-area based protection approaches, the fault clearing time comes out to be more than 100 milliseconds due to latencies issues [82].

To calculate the processing time of the DSEBPS, a performance analysis is done with the setup. The processing time of the algorithm was recorded over a large number of instants. The processing time for a particular sample (with a time tag) is calculated by recording the time difference between the instant when it arrives in the smart node to the instant when it produces the confidence level. The average time is calculated over a large number of instants and it comes out as 12.5 milliseconds. Since the performance of any protection scheme depends on the processing time, so the worst-case scenario (the maximum recorded time over these instants) is also considered which comes out as 34 milliseconds. The mean and standard deviation are estimated with these samples using the *normfit* function in MATLAB and are presented in Table 5.3.

Table 5.3: Estimated parameters and their values for normal distribution of average processing time

Estimated Parameters	Values	
Mean (in *seconds*)	0.0125	
Standard deviation estimate	0.0027	
Lower and upper bounds of the 95% confidence interval for mean (in *seconds*)	0.0125 (Lower Bound)	0.0125 (Upper Bound)
Lower and upper bounds of the 95% confidence interval for standard deviation	0.0027 (Lower Bound)	0.0028 (Upper Bound)

The total fault clearing time is usually composed of different components such as processing time, latencies delay, and circuit breaker operating time. For processing time, the consistency of confidence level is checked for three consecutive samples in this setup which means that if the confidence level remains zero for three consecutive samples, then a trip signal is given to the breaker for operation [83]. The reason behind the checking of three consecutive values is to increase the reliability of the protection scheme. The current setup uses the measurements locally, so the communication and latency delays are not significant. The operating time of the circuit breaker is widely considered to be 2-3 cycles which means 40-60 milliseconds in a 50-Hz system. Thus, DSEBPS takes an average processing time of around 37.5 milliseconds with consideration of three consecutive instants, no latency delay, and circuit breaker operating time around 50 milliseconds, which means that the DSEBPS can clear the fault around 87.5 milliseconds with the current setup.

5.5 Summary

This chapter has presented the details of the novel DSEBPS along with simulation results for an underground distribution cable and the laboratory experimental validation for an overhead transmission line. Firstly, the general concept of DSEBPS is presented followed by the modelling of the distribution line using the quadratic integration method and AQCF model. Then, the state estimation algorithm, Chi-squares test, component health, and protection logic are presented. The Chalmers power system laboratory setup is explained along with some of the advanced features of the LV-sensors developed by SST and used in this setup. The DSEBPS simulation results for an underground distribution cable and the laboratory experimental validation results for the transmission line are presented.

The simulation results have shown that DSEBPS is successfully able to detect the fault conditions and produce a trip signal for underground distribution cable. Further, the results from laboratory experimental validation have shown that the scheme can detect the fault conditions and a trip signal can be generated within 100 milliseconds. The results from both simulation and laboratory experimental validation have shown that the scheme does not require any relay settings except the threshold value required for the objective function (χ^2) of the Chi-square test. In fact, the setup used in this work does not require any relay and the trip signal is directly communicated to the circuit breaker through the smart node via a latching relay USB module. Generally, tens of relays may be present in a modern substation and each relay has an average of 12 protection functions. The coordination of all these relay protection functions is quite complex and might lead to mis-operations [84].

The DSEBPS with its inherent setting-less protection can also be an alternative to different conventional protection schemes used in distribution systems such as overcurrent, under/over-voltage, etc. Presently, distribution systems are going through the transition to becoming intelligent distribution systems and are facing several new protection challenges leading to the failure of conventional protection strategies and other phenomenons such as false tripping, protection blinding, re-closer problems, device discrimination, etc. Due to these challenges, it requires the revisiting of the conventional protection schemes and develop novel protection schemes such as DSEBPS.

CHAPTER 6

Concluding Remarks and Future Work

This chapter presents the concluding remarks from this thesis. Further, the plausible ideas for future work in continuation to the work done in this thesis are presented.

6.1 Concluding Remarks

This thesis presents the development and validation of advanced support tools for DSOs contextual to future intelligent distribution systems. First, the thesis proposed a future-readiness assessment framework which is developed based on the identification of key technical, market, and policy indicators, to help DSOs in evaluating their current status and preparedness for a future transition. Second, the thesis developed a congestion forecast tool that is based on a probabilistic approach and employs the BFS power flow method. This tool will assist DSOs by forecasting congestion levels in their network through interactive visualization of different congestion indicators. Finally, a dynamic state estimation based protection scheme is implemented and validated for the line protection in the thesis.

In Section 1.2 of this thesis, three different research questions were formulated based on the problems identified in distribution systems.

With regards to research question 1, a future-readiness assessment framework with a list of technical, market, and policy indicators for DSOs was developed in the thesis. From the assessment of three DSOs (from France, The Netherlands, and Sweden) using this proposed framework, the following points are observed:

- Generally, the key focus for evaluating the future-readiness remains on the technical aspects such as level of DERs, monitoring and control, etc., while the policy and market aspects are not much emphasized, which might not provide the correct evaluation of future-readiness. In this framework, policy aspects such as level of unbundling, network codes etc. and market aspects such as business models, tariffs, etc. have been considered and evaluated, since they would have great impacts on the actions required by the DSOs in the future.

- The proposed indicators have played a central role in scenario description of intelligent distribution systems, policy recommendation, end-user acceptance, and the development of the pathways.

- The assessment results from the three DSOs have shown that the current level of connected DERs is limited in their networks but DSOs need to be prepared for the increased level of DERs.

- The increased level of DERs would require investment in flexibilities, advanced forecasting and monitoring, advanced system automation and protection schemes, incentives schemes, and business models to promote end-user engagement, and changes in the roles of DSO in which it can own and/or procure certain resources and services to support distribution grid operations.

With regards to research question 2, a congestion forecast tool was developed in the thesis which would support DSOs by forecasting the network congestion and voltage issues for multiple forecasting horizons ranging from close-to-real time to day-ahead in an interactive visualization manner. The developed tool has the PV production and load forecast, load models, and operating modes of PV-inverter, as the main factors in the congestion forecast tool. The node voltage, branches, and transformers loading levels were recognized as the most relevant congestion indicators. The tool also has advanced visualization features such as contour plots and colour-map, in order to help DSOs to visualize congestion in an interactive manner. From the case-studies carried out with the congestion forecast tool, the following observations were made:

- The results from the case-study for visualization of congestion forecast over a day have shown that the network congestion varies considerably due to the different PV production level and load consumption during a day. The network has higher congestion problems especially during the noon hours when the PV production is quite high and the load consumption is small.
- The case-study showing the impact of load models on congestion forecast results has shown that the different load compositions have an impact on the congestion forecast. For a 141-bus distribution system, the constant power load leads to the highest network congestion while the constant impedance leads to the lowest.
- The case-study to examine the impact of operating modes of PV-inverters on congestion forecast results shows that operating modes too have a substantial impact on the network congestion. In constant-V mode, the CP for node voltage reduces drastically as compared to constant-pf mode but this reduction occurs at the cost of increased branches and transformers loading level.

With regards to research question 3, the implementation and validation of a reliable and fast protection scheme that can address the protection challenges that arose in the distribution systems were done in this thesis. This has been achieved by implementing and validating a dynamic state estimation based protection scheme in the Chalmers power system laboratory. The setup for the validation includes the LV-sensors developed by SST which provide GPS-synchronized raw voltage and current measurements. The algorithm for this scheme including the reception of measurement from LV-sensors has been developed in Python and other open-platform software. The scheme has been successfully validated with an experimental setup at Chalmers power system laboratory and the following inferences could be made from validation of the protection scheme:

- The experimental validation of the DSEBPS shows that the three-phase fault can be successfully detected and a trip signal could be sent to the breaker within 100 milliseconds.

- The novel DSEBPS has the potential to address the line protection issues in the distribution systems. Its significance has grown further with the advent of PMU devices which can provide GPS-synchronized voltage and current measurements at very high frequency.

6.2 Future Work

The following ideas concerning the future-readiness assessment framework are identified for future work:

- Evaluate Development Gaps: The assessment results from the framework about the current status and future-readiness will provide the DSOs with specific details for the scope of development in terms of technical, market, and policy indicators. These details in conjunction with the plausible future scenarios would help the DSOs to evaluate the development gaps in the network.

In the context of the congestion forecast tool, the following ideas could be considered for future work:

- Integration with Existing DMS of DSOs: The congestion forecast tool developed in this work will be integrated into the existing distribution management systems of DSOs via an IoT platform Codex Smart Edge of ATOS Worldgrid. This tool will be directly connected to the output of the PV production and load forecast within the UNITED-GRID toolbox. Further, some of the visualization features presented here will be included in the tool integration.

- Linkage with Flexibility Market: The congestion forecast tool can be expanded to be linked with local flexibility market structures. The output of the congestion forecast tool concerning the location, severity, and probability of the congestion incidents could be provided to the DSO which can then initiate the local flexibility market to procure the required flexibility for mitigation of these incidents. Depending on the time horizon of the congestion forecast i.e., long-term or real-time, the DSO can procure the required reservation or activate flexibility, respectively.

Concerning protection challenges in the distribution network, the following could be addressed as an extension of this thesis:

- Investigate DSEBPS Robustness: In order to validate the robustness of the DSEBPS, more case-studies are required to be performed. There are several protection gaps such as hidden faults, high-impedance faults, etc. which are difficult to be detected. These case-studies could be carried out with the experimental setup at Chalmers power system laboratory and the performance of DSEBPS can be further validated.
- Improved Performance of Dynamic State Estimation Algorithm: Recently, there has been quite a lot of research in enhancing the performance of DSE algorithms. The DSEBPS employed in this work uses the linear version of the WLS algorithm which can be replaced with several other DSE algorithms with an objective to enhance the estimation speed and accuracy and hence the performance of the protection scheme.

References

[1] SmartGrids SRA 2035, "Smartgrids strategic research agenda for RD&D needs towards 2035", *European Technology & Innovation Platform*,

[2] IRENA, "Renewable power generation costs in 2018", *International Renewable Energy Agency, Abu Dhabi, Tech. Rep.*, 2019.

[3] GWEC, *Global wind report 2018*, [Online] Available: `https://gwec.net/global-wind-report-2018/`, Apr. 2018.

[4] International Energy Agency, *Photovoltaic Power Systems Programme Annual Report 2017*, [Online] Available: `https://www.iea-pvps.org/index.php?id=6`.

[5] International Energy Agency, *Photovoltaic Power Systems Programme Annual Report 2019*, [Online] Available: `https://iea-pvps.org/wp-content/uploads/2020/05/IEA-PVPS-AR-2019-1.pdf`.

[6] International Energy Agency, *Global EV Outlook 2018*, [Online] Available: `https://www.iea.org/gevo2018`.

[7] Swedish Energy Agency, *Energy in Sweden 2020 – An overview*, [Online] Available: `https://energimyndigheten.a-w2m.se/Home.mvc?ResourceId=174155`.

[8] S. Vindenergi, *Statistics and forecast*, [Online] Available: `https://svenskvindenergi.org/statistik/2017-3`.

[9] *Systemutvecklingsplan 2020–2029*, Statnett, Fingrid, Energinet, Svenska Kraftnät, Tech. Rep. Dec. 2019. [Online]. Available: `www.svk.se/om-oss/rapporter-och-remissvar`.

[10] J. Widén, M. Shepero, and J. Munkhammar, “Probabilistic load flow for power grids with high PV penetrations using copula-based modeling of spatially correlated solar irradiance”, *IEEE Journal of Photovoltaics*, vol. 7, no. 6, pp. 1740–1745, 2017.

[11] Peter Fairley, *Hawaii’s solar push strains the grid*, Jan. 2015. [Online]. Available: `https://www.technologyreview.com/s/534266/hawaiis-solar-push-strains-the-grid/.`.

[12] Liz Hobday, *Electricity distributors warn excess solar power in network could cause blackouts, damage infrastructure*, Australian Broadcasting Corporation, Oct. 2018. [Online]. Available: `https://www.abc.net.au/news/2018-10-11/electricity-distributors-warn-excess-solar-could-damage-grid/10365622`.

[13] Pamela M. Prah, *Utility companies have a solar power problem*, Governing, Feb. 2014. [Online]. Available: `https://www.governing.com/news/headlines/utility-companies-have-a-.html`.

[14] C. Madina, J. Jimeno, J. Merino, M. Pardo, M. Marroquin, E. Estrade, *et al.*, “Exploiting flexibility of radio base stations in local DSO markets for congestion management with shared balancing responsibility between TSO and DSO”, 2018.

[15] FLEXICIENCY, *Energy services demonstrations of demand response, flexibility and energy efficiency based on metering data.* [Online]. Available: `https://cordis.europa.eu/project/id/646482`.

[16] NobelGrid, *New cost-efficient business models for flexible smart grids.* [Online]. Available: `https://nobelgrid.eu/`.

[17] J. M. Gers and E. J. Holmes, *Protection of electricity distribution networks.* IET, 2004, vol. 47.

[18] S. M. Brahma *et al.*, “Development of adaptive protection scheme for distribution systems with high penetration of distributed generation”, *IEEE Trans. Power Delivery*, vol. 19, no. 1, pp. 56–63, Jan. 2004, ISSN: 0885-8977.

[19] O. Vasios, S. Kampezidou, and A. S. Meliopoulos, “A dynamic state estimation based centralized scheme for microgrid protection”, in *Proc. 2018 North American Power Symposium (NAPS)*, pp. 1–6.

[20] V. Telukunta, J. Pradhan, A. Agrawal, M. Singh, and S. G. Srivani, “Protection challenges under bulk penetration of renewable energy resources in power systems: A review”, *CSEE Journal of Power and Energy Systems*, vol. 3, no. 4, pp. 365–379, 2017.

[21] I. Almutairy, “A review of coordination strategies and techniques for overcoming challenges to microgrid protection”, in *Proc. Saudi Arabia Smart Grid (SASG)*, 2016, pp. 1–4.

[22] P. Naveen and P. Jena, “A review on issues and coordination strategies for over current protection in microgrid”, in *Proc. 14th IEEE India Council International Conference (INDICON)*, 2017, pp. 1–6.

[23] A. Khademlahashy *et al.*, “A review on protection issues in micro-grids embedded with distribution generations”, in *Proc. 12th IEEE Conference on Industrial Electronics and Applications (ICIEA)*, 2017, pp. 913–918.

[24] S. M. Brahma *et al.*, “Insight into microgrid protection”, in *Proc. IEEE PES Innovative Smart Grid Technologies Europe*, 2014, pp. 1–6.

[25] V. A. Papaspiliotopoulos *et al.*, “Hardware-in-the-loop design and optimal setting of adaptive protection schemes for distribution systems with distributed generation”, *IEEE Transactions on Power Delivery*, vol. 32, no. 1, pp. 393–400, Feb. 2017, ISSN: 1937-4208.

[26] S. M. Joshi, S. B. Bhattacharjee, V. C. Deshpande, and M. Tadvalkar, “Developing key performance indicators framework for evaluating performance of engineering faculty”, in *Proc. 2016 IEEE Eighth International Conference on Technology for Education (T4E)*, pp. 220–223.

[27] F. Folino, M. Guarascio, and L. Pontieri, “A prediction framework for proactively monitoring aggregate process-performance indicators”, in *Proc. 2015 IEEE 19th International Enterprise Distributed Object Computing Conference*, pp. 128–133.

[28] H. A. Zheng *et al.*, “Designing a key performance indicator system for technological innovation audit at firm’s level: A framework and an empirical study”, in *Proc. 2009 IEEE International Conference on Industrial Engineering and Engineering Management*, pp. 1–5.

[29] R. Carli, M. Dotoli, R. Pellegrino, and L. Ranieri, "Measuring and managing the smartness of cities: A framework for classifying performance indicators", in *Proc. 2013 IEEE International Conference on Systems, Man, and Cybernetics*, pp. 1288–1293.

[30] H. Liu, F. Huang, H. Li, W. Liu, and T. Wang, "A big data framework for electric power data quality assessment", in *Proc. 2017 14th Web Information Systems and Applications Conference (WISA)*, pp. 289–292.

[31] S. Moazeni and B. Defourny, "Distribution system controls assessment in a nonbinding transactive energy market", in *Proc. 2017 North American Power Symposium (NAPS)*, pp. 1–6.

[32] C. Dumbs, G. Jarry, D. Laffaille, S. Hes, D. Panic, I. Leisse, and J. Bruschi, "Flexibility for DSOs on a local scale: Business models and associated regulatory questions raised in the Interflex project", 2018.

[33] M. Fan and L. Huang, "Probabilistic power reserve evaluation algorithm for power systems considering high solar energy penetration", in *Proc. 2018 IEEE Power and Energy Society General Meeting*, pp. 1–5.

[34] Z. Ren, W. Yan, X. Zhao, Y. Li, and Y. Juan, "Probabilistic power flow for distribution networks with photovoltaic generators", in *Proc. 2013 IEEE Power and Energy Society General Meeting*, pp. 1–5.

[35] J. M. Lujano-Rojas, R. Dufo-Lopez, J. L. Bernal-Agustin, J. A. Dominguez-Navarro, and J. P. Catalao, "Probabilistic methodology for estimating the optimal photovoltaic capacity in distribution systems to avoid power flow reversals", *IET Renewable Power Generation*, vol. 12, no. 9, pp. 1045–1064, 2018.

[36] M. Nijhuis, M. Gibescu, and S. Cobben, "Gaussian mixture based probabilistic load flow for LV-network planning", *IEEE Transactions on Power Systems*, vol. 32, no. 4, pp. 2878–2886, 2016.

[37] M. S. S. Abad, J. Ma, D. Zhang, A. S. Ahmadyar, and H. Marzooghi, "Probabilistic assessment of hosting capacity in radial distribution systems", *IEEE Transactions on Sustainable Energy*, vol. 9, no. 4, pp. 1935–1947, 2018.

[38] G. E. Constante-Flores and M. S. Illindala, "Data-driven probabilistic power flow analysis for a distribution system with renewable energy sources using Monte Carlo simulation", *IEEE Transactions on Industry Applications*, vol. 55, no. 1, pp. 174–181, 2018.

[39] S. Huang and Q. Wu, "Real-time congestion management in distribution networks by flexible demand swap", *IEEE Transactions on Smart Grid*, vol. 9, no. 5, pp. 4346–4355, 2017.

[40] G. Prettico, M. Flammini, N. Andreadou, S. Vitello, G. Fulli, and M. Masera, "Distribution system operators observatory 2018", *Publications Office of the European Union*, 2019.

[41] H. Bontius and J. Hodemaekers, "An introduction to EU market-based congestion management models", *USEF Workstream*, 2018.

[42] W. Liu, Q. Wu, F. Wen, and J. Østergaard, "Day-ahead congestion management in distribution systems through household demand response and distribution congestion prices", *IEEE Transactions on Smart Grid*, vol. 5, no. 6, pp. 2739–2747, 2014.

[43] S. Huang, Q. Wu, H. Zhao, and C. Li, "Distributed optimization-based dynamic tariff for congestion management in distribution networks", *IEEE Transactions on Smart Grid*, vol. 10, no. 1, pp. 184–192, 2017.

[44] S. Huang, Q. Wu, L. Cheng, and Z. Liu, "Optimal reconfiguration-based dynamic tariff for congestion management and line loss reduction in distribution networks", *IEEE Transactions on Smart Grid*, vol. 7, no. 3, pp. 1295–1303, 2015.

[45] S. Huang, Q. Wu, L. Cheng, Z. Liu, and H. Zhao, "Uncertainty management of dynamic tariff method for congestion management in distribution networks", *IEEE Transactions on Power Systems*, vol. 31, no. 6, pp. 4340–4347, 2016.

[46] S. Huang and Q. Wu, "Dynamic subsidy method for congestion management in distribution networks", *IEEE Transactions on Smart Grid*, vol. 9, no. 3, pp. 2140–2151, 2016.

[47] A. Kulmala *et al.*, "Hierarchical and distributed control concept for distribution network congestion management", *IET Generation, Transmission & Distribution*, vol. 11, no. 3, pp. 665–675, 2017.

[48] T. M. Masaud, R. D. Mistry, and P. K. Sen, "Placement of large-scale utility-owned wind distributed generation based on probabilistic forecasting of line congestion", *IET Renewable Power Generation*, vol. 11, no. 7, pp. 979–986, 2017.

[49] A. Srivastava, D. Steen, L. A. Tuan, and O. Carlson, "A congestion forecast framework for distribution systems with high penetration of PVs and PEVs", in *Proc. 2019 IEEE PowerTech Milano*, pp. 1–6.

[50] K. Antoniadou-Plytaria, A. Srivastava, M. A. F. Ghazvini, D. Steen, L. A. Tuan, and O. Carlson, "Chalmers campus as a testbed for intelligent grids and local energy systems", in *Proc. 2019 IEEE International Conference on Smart Energy Systems and Technologies (SEST)*, pp. 1–6.

[51] North American Electric Reliability Corporation, [Online] Available: `https://www.nerc.com/Pages/default.aspx`.

[52] A. S. Meliopoulos, G. J. Cokkinides, Z. Tan, S. Choi, Y. Lee, and P. Myrda, "Setting-less protection: Feasibility study", in *Proc. 2013 46th IEEE Hawaii International Conference on System Sciences*, pp. 2345–2353.

[53] A. S. Meliopoulos, G. J. Cokkinides, *et al.*, "Dynamic state estimation-based protection: Status and promise", *IEEE Transactions on Power Delivery*, vol. 32, no. 1, pp. 320–330, 2016.

[54] R. Fan, A. S. Meliopoulos, L. Sun, Z. Tan, and Y. Liu, "Transformer inter-turn faults detection by dynamic state estimation method", in *Proc. 2016 North American Power Symposium (NAPS)*, pp. 1–6.

[55] H. F. Albinali, A. Meliopoulos, and C. Vournas, "Dynamic state estimation-based centralized protection scheme", in *Proc. 2017 IEEE Manchester PowerTech*, pp. 1–6.

[56] A. Srivastava, D. Steen, L. A. Tuan, *et al.*, "A DSO support framework for assessment of future-readiness of distribution systems: Technical, market, and policy perspectives", in *Proc. 2019 25th International Conference and Exhibition on Electricity Distribution (CIRED)*, AIM.

[57] D. Steen, A. Srivastava, L. A. Tuan, *et al.*, "D2.1 baseline description of distribution grid management", 2018.

[58] Energy-European Commission, *Market legislation.* [Online]. Available: https://ec.europa.eu/energy/en/topics/markets-and-consumers/marketlegislation.

[59] Energy European Commission, *Clean energy for all Europeans.* [Online]. Available: https://ec.europa.eu/energy/en/news/clean-energy-package-topagenda-eu-energy-council.

[60] IVA, "Sweden's future electricity production – a project report", 2017.

[61] T. Tran, M. Damaj, M. Guemri, *et al.*, "D2.2 scenario descriptions for active distribution grid developments", 2019.

[62] Research Institutes of Sweden (RISE), [Online] Available: https://www.ri.se/en.

[63] J. Rossi, A. Srivastava, D. Steen, and L. A. Tuan, "A study of the European regulatory framework for smart grid solutions in future distribution systems", in *Proc. 2020 CIRED Berlin Workshop*, AIM.

[64] C. Zhang *et al.*, "FLECH: A Danish market solution for DSO congestion management through DER flexibility services", *Journal of Modern Power Systems and Clean Energy*, vol. 2, no. 2, pp. 126–133, 2014.

[65] M. Haque, "Load flow solution of distribution systems with voltage dependent load models", *Electric Power Systems Research*, vol. 36, no. 3, pp. 151–156, 1996.

[66] *IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces*, IEEE Standard 1547-2018, Feb. 2018.

[67] C. S. Cheng and D. Shirmohammadi, "A three-phase power flow method for real-time distribution system analysis", *IEEE Transactions on Power Systems*, vol. 10, no. 2, pp. 671–679, 1995.

[68] UNITED-GRID, [Online] Available: https://united-grid.eu/.

[69] The French Alternative Energies and Atomic Energy Commission (CEA), [Online] Available: http://www.cea.fr/english.

[70] T. Tran *et al.*, "Development of short-term forecasting tools for load and renewable generation (UNITED-GRID)", Nov. 2018.

[71] SORÉA, [Online] Available: https://www.sorea-maurienne.fr/.

[72] H. Khodr *et al.*, "Maximum savings approach for location and sizing of capacitors in distribution systems", *Electric Power Systems Research*, vol. 78, no. 7, pp. 1192–1203, 2008.

[73] P. Balram, L. A. Tuan, and O. Carlson, "Predictive voltage control of batteries and tap changers in distribution system with photovoltaics", in *Proc. 2016 IEEE Power Systems Computation Conference*, pp. 1–7.

[74] Animated Colour-map. [Online]. Available: `http://publications.lib.chalmers.se/img/srivastava/`.

[75] *About the use case repository.* [Online]. Available: `https://smartgrid.epri.com/Repository/About.aspx`.

[76] S. A. Meliopoulos, "Legacy SE to distributed dynamic state estimators: Evolution and experience", in *Proc. 2015 IEEE Power & Energy Society General Meeting*, pp. 1–5.

[77] Y. H. Lee, "A comprehensive protection scheme for distribution systems", PhD thesis, Georgia Institute of Technology, 2014.

[78] *XLPE insulated power cables catalogue - universal cable (M) berhad.* [Online]. Available: `http://www.ucable.com.my/images/products/UC%20XLPE%20Catalogue.pdf`.

[79] Smart State Technology, The Netherlands, [Online] Available: `https://www.smartstatetechnology.nl/`.

[80] P. Hintjens, *ZeroMQ: Messaging for Many Applications.* "O'Reilly Media, Inc.", 2013.

[81] GnuPlot, [Online] Available: `http://www.gnuplot.info/`.

[82] J. G. Rao and A. K. Pradhan, "Supervising distance relay during power swing using synchrophasor measurements", *IET Generation, Transmission & Distribution*, vol. 11, no. 17, pp. 4136–4145, 2017.

[83] R. Mohanty and A. K. Pradhan, "Protection of smart DC microgrid with ring configuration using parameter estimation approach", *IEEE Transactions on Smart Grid*, vol. 9, no. 6, pp. 6328–6337, 2017.

[84] A. P. S. Meliopoulos and G. J. Cokkinides, *Power System Relaying.* Draft Book, 1996-2018.

[85] A. Meliopoulos *et al.*, "Quadratic integration method", in *Proc. Citeseer 2005 Intl. Power System Transients Conference (IPST)*, pp. 19–23.

APPENDIX A

Model Development of Dynamic State Estimation based Protection Scheme

The model development of DSEBPS for distribution line is explained as follows:

Quadratic Integration Method

The quadratic integration method is used to reduce the complexity of component's dynamic model by the simplification of the involved differential equations. In this method, the considered function is treated to vary as a quadratic function in comparison to the trapezoidal method where it is considered to vary as a linear function. This method helps in increasing the accuracy of the integration technique [85].

The concept of quadratic integration method is shown in Figure A.1. Here, an integration time step is taken of length k, between two-time instants $(t-k)$ and t. The corresponding function values are $y(t-k)$ and $y(t)$. Additionally, a time instant $(t-k/2)$ is taken between the above two instants and corresponding function is $y(t-k/2)$. These three-time instants defines the quadratic function in the time step of $[t-k, t]$.

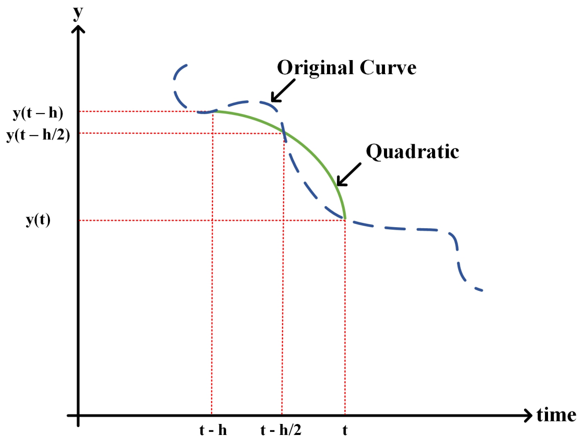


Figure A.1: Quadratic integration method.

The following example will be useful for better understanding of the quadratic integration method:

$$\frac{dy\,(t)}{dx} = Fy\,(t) \tag{A.1}$$

when the quadratic integration method is applied to (A.1), over the time interval $[t-k,t]$, it yields the following equation:

$$\begin{bmatrix} \frac{k}{24}F & I-\frac{k}{3}F \\ I-\frac{k}{6}F & -\frac{2k}{3}F \end{bmatrix} \begin{bmatrix} y\,(t) \\ y\,(t-k/2) \end{bmatrix} = \begin{bmatrix} I+\frac{5k}{24}F \\ I-\frac{k}{3}F \end{bmatrix} [y\,(t-k)] \tag{A.2}$$

Algebraic Quadratic Companion Form Model of Distribution line

Distribution lines are one the most important components in the electrical distribution systems. This section presents the basics of the AQCF model for the distribution line which is based on the quadratic integration method. The presented model is for a three-phase line and represents one π-section [77].

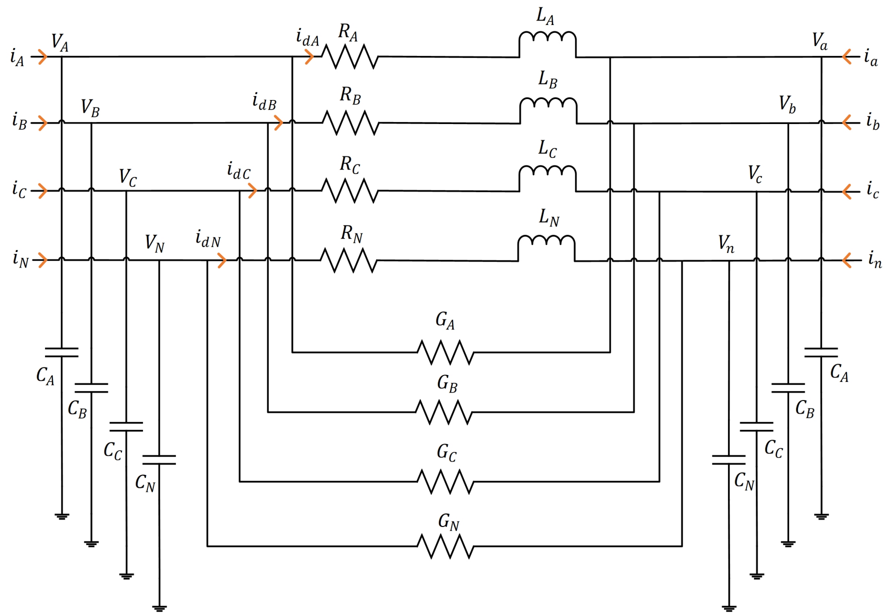


Figure A.2: Three-phase line diagram for the electric distribution line.

The schematics of the π-representation of the three-phase distribution line is presented in Figure 5.3. In the presented schematics, the line has three phases as A, B, and C and neutral N. The resistances and reactances of each phase are represented as R_A, R_B, R_C, R_N and L_A, L_B, L_C, L_N, respectively. The shunt capacitances for each phase are represented as C_A, C_B, C_C, C_N. Also, G_A, G_B, G_C, G_N are considered for the numerical stabilization purpose and may not be essentially part of actual system. The sending end voltages and currents are represented as V_A, V_B, V_C, V_N and i_A, i_B, i_C, i_N, respectively. While the receiving end voltages and currents are represented as V_a, V_b, V_c, V_n and i_a, i_b, i_c, i_n, respectively. Also, i_{dA}, i_{dB}, i_{dC}, i_{dN} are the currents in the series branch of the three phases of distribution line. The model equations using the KVL and KCL for the network diagram shown above can be written as:

$$i_A + G_A V_a = i_{dA} + G_A V_A + C_A \frac{dV_A}{dt} \tag{A.3}$$

$$i_B + G_B V_b = i_{dB} + G_B V_B + C_B \frac{dV_B}{dt} \tag{A.4}$$

$$i_C + G_C V_c = i_{dC} + G_C V_C + C_C \frac{dV_C}{dt} \tag{A.5}$$

$$i_N + G_N V_n = i_{dN} + G_N V_N + C_N \frac{dV_N}{dt} \tag{A.6}$$

$$i_a - G_A V_a - C_A \frac{dV_a}{dt} = -i_{dA} - G_A V_A \tag{A.7}$$

$$i_b - G_B V_b - C_B \frac{dV_b}{dt} = -i_{dB} - G_B V_B \tag{A.8}$$

$$i_c - G_C V_c - C_C \frac{dV_c}{dt} = -i_{dC} - G_C V_C \tag{A.9}$$

$$i_n - G_N V_n - C_N \frac{dV_n}{dt} = -i_{dN} - G_N V_N \tag{A.10}$$

$$V_a = V_A - R_A i_{dA} - L_A \frac{di_{dA}}{dt} \tag{A.11}$$

$$V_b = V_B - R_B i_{dB} - L_B \frac{di_{dB}}{dt} \tag{A.12}$$

$$V_c = V_C - R_C i_{dC} - L_C \frac{di_{dC}}{dt} \tag{A.13}$$

$$V_n = V_N - R_N i_{dN} - L_N \frac{di_{dN}}{dt} \tag{A.14}$$

The above equations (A.3)−(A.14), can be further written as:

$$R_1 z + R_2 \frac{dz}{dt} = S_1 x + S_2 \frac{dx}{dt} \tag{A.15}$$

where, z is the measurement vector which is a function of time and can be expressed as:

$$z = [i_A \quad i_B \quad i_C \quad i_N \quad i_a \quad i_b \quad i_c \quad i_n \quad V_a \quad V_b \quad V_c \quad V_n] \tag{A.16}$$

x is the estimation vector which is a function of time and can be expressed as:

$$x = [V_A \quad V_B \quad V_C \quad V_N \quad i_{dA} \quad i_{dB} \quad i_{dC} \quad i_{dN}] \tag{A.17}$$

and matrices R_1, R_2, S_1 and S_2 can be expressed as:

$$R_1 = \begin{bmatrix} 1&0&0&0&0&0&0&0&G_A&0&0&0\\ 0&1&0&0&0&0&0&0&0&G_B&0&0\\ 0&0&1&0&0&0&0&0&0&0&G_C&0\\ 0&0&0&1&0&0&0&0&0&0&0&G_N\\ 0&0&0&0&1&0&0&0&-G_A&0&0&0\\ 0&0&0&0&0&1&0&0&0&-G_B&0&0\\ 0&0&0&0&0&0&1&0&0&0&-G_C&0\\ 0&0&0&0&0&0&0&1&0&0&0&-G_N\\ 0&0&0&0&0&0&0&0&1&0&0&0\\ 0&0&0&0&0&0&0&0&0&1&0&0\\ 0&0&0&0&0&0&0&0&0&0&1&0\\ 0&0&0&0&0&0&0&0&0&0&0&1 \end{bmatrix}$$

$$R_2 = \begin{bmatrix} 0&0&0&0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&-C_A&0&0&0\\ 0&0&0&0&0&0&0&0&0&-C_B&0&0\\ 0&0&0&0&0&0&0&0&0&0&-C_C&0\\ 0&0&0&0&0&0&0&0&0&0&0&-C_N\\ 0&0&0&0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&0&0&0&0 \end{bmatrix}$$

$$S_1 = \begin{bmatrix} G_A&0&0&0&1&0&0&0\\ 0&G_B&0&0&0&1&0&0\\ 0&0&G_C&0&0&0&1&0\\ 0&0&0&G_N&0&0&0&1\\ -G_A&0&0&0&-1&0&0&0\\ 0&-G_B&0&0&0&-1&0&0\\ 0&0&-G_C&0&0&0&-1&0\\ 0&0&0&-G_N&0&0&0&-1\\ 1&0&0&0&-R_A&0&0&0\\ 0&1&0&0&0&-R_B&0&0\\ 0&0&1&0&0&0&-R_C&0\\ 0&0&0&1&0&0&0&-R_N \end{bmatrix}$$

$$S_2 = \begin{bmatrix} C_A&0&0&0&0&0&0&0\\ 0&C_B&0&0&0&0&0&0\\ 0&0&C_C&0&0&0&0&0\\ 0&0&0&C_N&0&0&0&0\\ 0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0\\ 0&0&0&0&-L_A&0&0&0\\ 0&0&0&0&0&-L_B&0&0\\ 0&0&0&0&0&0&-L_C&0\\ 0&0&0&0&0&0&0&-L_N \end{bmatrix}$$

Subsequently, quadratic integration method as derived in (A.1) and (A.2) is used for the equation derived in (A.15), which results in the following equations:

Over the time interval $[t-k, t]$

$$R_1\left[\frac{k}{6}z\left(t-k\right)+\frac{2k}{3}z\left(t-\frac{k}{2}\right)+\frac{k}{6}z\left(t\right)\right]+R_2\left[z\left(t\right)-z\left(t-k\right)\right]$$
$$=S_1\left[\frac{k}{6}x\left(t-k\right)+\frac{2k}{3}x\left(t-\frac{k}{2}\right)+\frac{k}{6}x\left(t\right)\right]+S_2\left[x\left(t\right)-x\left(t-k\right)\right] \quad \text{(A.18)}$$

Over the time interval $[t-k, t-k/2]$

$$R_1\left[\frac{5k}{24}z\left(t-k\right)+\frac{k}{3}z\left(t-\frac{k}{2}\right)-\frac{k}{24}z\left(t\right)\right]+R_2\left[z\left(t-\frac{k}{2}\right)-z\left(t-k\right)\right]$$
$$=S_1\left[\frac{5k}{24}x\left(t-k\right)+\frac{k}{3}x\left(t-\frac{k}{2}\right)-\frac{k}{24}x\left(t\right)\right]+S_2\left[x\left(t-\frac{k}{2}\right)-x\left(t-k\right)\right] \tag{A.19}$$

The above equations (A.18) and (A.19) can be written down in condensed form as follows:

$$\begin{bmatrix}\frac{k}{6}R_1+R_2 & \frac{2k}{3}R_1\\ -\frac{k}{24}R_1 & \frac{k}{3}R_1+R_2\end{bmatrix}\begin{bmatrix}z\left(t\right)\\ z\left(t-\frac{k}{2}\right)\end{bmatrix}$$
$$=\begin{bmatrix}\frac{k}{6}S_1+S_2 & \frac{2k}{3}S_1\\ -\frac{k}{24}S_1 & \frac{k}{3}S_1+S_2\end{bmatrix}\begin{bmatrix}x\left(t\right)\\ x\left(t-\frac{k}{2}\right)\end{bmatrix}-\begin{bmatrix}\frac{k}{6}R_1-R_2\\ \frac{5k}{24}R_1-R_2\end{bmatrix}\left[z\left(t-k\right)\right]$$
$$-\begin{bmatrix}-\frac{k}{6}S_1+S_2\\ -\frac{5k}{24}S_1+S_2\end{bmatrix}\left[x\left(t-k\right)\right] \tag{A.20}$$

APPENDIX B

Network Parameters of 7-bus Feeder in Sorea's Distribution System

The branches and transformers data for the part of Sorea's system are presented in Table B.1. The branches have different lengths with the same per unit-length parameters. The branches' ampacity and the transformer rating are also given.

Table B.1: Branches and Transformer Parameters for Sorea's Grid

Sl. No.	**Location**	**Resistance** ($m\Omega$)	**Reactance** ($m\Omega$)	**Suscep-tance** (μS)	**Capacity** (kVA/Amp)
		Transformer (LV-side)			
1	1-2	3.0637	14.9269	-	250
		Branches			
2	2-3	9.4350	13.2418	0.1319	350
3	3-4	21.6376	30.3679	0.3026	350
4	4-5	23.2679	5.0894	0.1847	350
5	4-6	27.2495	4.4271	0	350
6	4-7	7.5420	4.1469	0.1150	350