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It is certified that the work contained in the thesis titled **"Reliability Assessment of Distribution Systems Integrated with Renewable Energy Sources"** by **"Sachin Kumar"** has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

It is further certified that the student has fulfilled all the requirements of Comprehensive Examination, Candidacy and State-Of-The-Art for the award of Ph.D. Degree.

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DECLARATION

I, **Sachin Kumar**, certify that the work embodied in this thesis is my own bona fide work and has been carried out by us under the supervision of **Professor (Dr.) R.K. Saket** from **July-2018** to **July-2021**, at the Department of **Electrical Engineering**, **Indian Institute of Technology (Banaras Hindu University)**, **Varanasi, Uttar Pradesh, INDIA**. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma. I declare that I have faithfully acknowledged and given credits to the research workers wherever their works have been cited in my work in this thesis. I further declare that I have not wilfully copied any other's work, paragraphs, text, data, results, etc., reported in journals, books, magazines, reports dissertations, theses, etc., or available at websites and have not included them in this thesis and have not cited as my own work.

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To

My Grand Parents

(Late Mr. Babu Nandan Ram & Late Mrs. Dasi Devi)

My Parents

(Mr. Ghurbhari Ram & Mrs. Kamla Devi)

and

My Wife

(Mrs. Nidhi)

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Date: ____________________ Sachin Kumar

Abstract

This thesis provides a thorough examination of the electrical power system's reliability assessment. The investigations include the generation of natural lightning waveforms to evaluate the reliability of the power system by analysing the effects of the Lightning Impulse Voltage (LIV) waveform. Further, the integration of Distributed Energy Resources (DER), such as Conventional Generation (CG) and Renewable Energy Source (RES), including wind, solar, and battery storage systems, has also been accomplished, and the electrical system's reliability has been analyzed.

Incorporating the renewable energy sources into the distribution network offers some benefits with drawbacks. However, the advantages outweigh the disadvantages since it provides limitless, accessible, and cost-effective information in comparison to traditional sources. According to recent studies, the uncertainties of electrical power sources lead to probabilistic and reliability assessments of electrical systems. The system includes components that are prone to failure, such as offshore and onshore wind farms, microgrids, energy storage systems, and other high voltage networks. As a result, it's critical to talk about how to deal with uncertainty factors in the generating, transmission, and distribution systems. As a result, this thesis discusses use of such conventional energy, wind energy, solar energy, and battery storage technologies for reliability assessments.

When uncertainties are taken into account, integrating wind energy into the conventional grid poses a number of significant difficulties. To evaluate the dependability and performance of the Doubly Fed Induction Generator (DFIG)-based Wind Integrated Power System (WIPS), the uncertainties, such as the occurrence of a three-phase failure and lightning fault, are taken into account. As a result, the power system precondition research was conducted, which included Wind Farm (WF), Voltage Source Converter (VSC), and lightning voltage and current phenomena. As a result, this thesis considers the realistic equivalent circuit to generate lightning envelops of impulse voltage and current as well as rectangular pulse current. The resulting

lightning fault impulse voltage is then applied to the 3-phase terminals of grid-connected DFIG-based WIPS. To compare the output responses of the DFIG-based WIPS, a 3-phase short circuit fault is implemented. The controller gain values are used to monitor the system's behaviour under both faults. The gains of a sixth-order transfer function for Wind Turbine Generator (WTG) are calculated using an optimization technique, which included proportional (k_p) and integral (k_i) gains. The Monte-Carlo (MC) simulation technique is used to evaluate the power system's reliability, with the LIV being a major source of VSC failure. The DFIG-based WIPS is discovered to produce significant responses under both kinds of failures by finding the optimum controller settings. It has also been discovered that the decrease in the number of failures in VSC during the lightning strike increases the system's reliability.

The thesis work has been extended further on the reliability assessment of renewable energy interfaced EPDN considering the Electrical Power Loss Minimization (EPLM). EPLM aims at minimizing the detrimental effect of real power and reactive power losses in the distribution system. Some techniques, including integration of RES, network reconfiguration, and expansion planning, have been suggested in the literature for achieving EPLM. The optimal RES integration (also referred to as Distributed Generation (DG)) is one technique to minimize electrical losses. Therefore, the locations to accommodate these RESs are obtained by implementing two indexes, namely $index_1$ for single RES and $index_2$ for multiple RESs. Then, the optimization technique is applied to obtain an optimal sizing(s) of the Distributed Generations for achieving the EPLM. The reliability assessment of the distribution system is performed using the optimal location(s) and sizing(s) of the RESs (i.e., Solar Photovoltaic (SPV) and WTG.

Moreover, a Battery Energy Storage Device (BESD) is also incorporated optimally with the RESs to achieve the EPLM further and to improve the system's reliability. The result analysis is performed by considering the power output rating of WTG-GE's V162-5.6MW (IECS), SPV-Sunpower's SPR-P5-545-UPP, and BSS-Freqcon's BESS-3000 (i.e., Battery Energy Storage System (BESS) 3000), which the corresponding manufacturers provide. According to the study outcomes, the results are found to be coherent with those obtained using other techniques that are available in the literature. These results are considered for the reliability assessment of the electrical distribution system. reliability assessment is further analyzed considering the uncertainties in reliability data of WTG and SPV, including the failure rate and the repair time. The reliability assessment of optimally placed Distributed Generations is performed by considering the electrical loss minimization. It is inferred that the reliability of the EPDN improves by contemplating suitable reliability data of optimally integrated RESs.

This thesis thoroughly explores the reliability assessment of DG interfaced Distribution System (DS)s based on power loss minimization. The work has been performed on IEEE 33 bus and IEEE 118 bus Distribution Systems with 1CG, 1CG+1WTGs, and 1CG+2WTGs for several Power Factor (pf), including Unity Power Factor (UPF), 0.9, 0.85, and 0.82. Firstly, the optimal siting(s) and sizing(s) of DG/DGs is/are obtained based on loss of power minimization. An optimization technique is implemented to find the DGs' optimal sizing(s). The locations to accommodate these DGs are obtained by implementing the two indexes, namely, $index_1$, $index_2$, and $index_3$ for single and multiple DGs. The results obtained are coherent with the results obtained by using other techniques available in the literature. Then the reliability assessment of DS is accomplished considering uncertainties in DG reliability data, including failure per year (λ_p) and outage duration or Repair Time (RT). Various types of loads, including commercial, industrial, and residential, have also been considered to analyze the reliability. The reliability assessment of optimally placed DG integrated DS is performed for 1CG, 1CG+1WTGs, and 1CG+2WTGs, and it is observed that the DS's reliability improves with the increasing number of DGs and lower uncertainty in reliability data.

Contents

List of Tables

Chapter 1

Chapter 2

Chapter 3

Chapter 4

Chapter 5

Appendix B

Appendix C

List of Figures

Chapter 4

Chapter 5

Appendix A

List of Abbreviations

AENS	Average Energy Not Supplied
ASAI	Average Service Availability Index
ASUI	Average Service Unavailability Index
BESD	Battery Energy Storage Device
CAIDI	Customer Average Interruption Duration Index
CAIFI	Customer Average Interruption Frequency Index
CG	Conventional Generation
CF-PSO	Constriction Factor-based Particle Swarm Optimization
DER	Distributed Energy Resources
DFIG	Doubly Fed Induction Generator
DG	Distributed Generation
DS	Distribution System
ECOST	Expected Interruption Cost
EDNS	Energy Demand Not Supplied
EENS	Expected Energy Not Supplied
EIR	Energy Index of Reliability
ENS	Energy Not Supplied

EPDN Electrical Power Distribution Network

EPLM Electrical Power Loss Minimization

ESS Energy Storage System

EV Electric Vehicle

IEAR Interrupted Energy Assessment Rate

LIV Lightning Impulse Voltage

LI Lightning Impulse

LOEE Loss of Energy Expectation

LOLE Loss of Load Expectation

LOLF Loss of Load Frequency

LOLP Loss of Load Probability

MC Monte-Carlo

PDF Probability Density Function

pf Power Factor

PI Proportional Integral

PSO Particle Swarm Optimization

RES Renewable Energy Source

RPCG Rectangular Pulse Current Generation

RT Repair Time

RTS Reliability Test Systemm

SPR Surface Plasmon Resonance

SPV Solar Photovoltaic

SG Spark Gap

SAIDI System Average Interruption Duration Index

SAIFI System Average Interruption Frequency Index

UPF Unity Power Factor

VSC Voltage Source Converter

WECS Wind Energy Conversion System

WF Wind Farm

WIPS Wind Integrated Power System

WT Wind Turbine

WTG Wind Turbine Generator