RELIABILITY STUDIES OF DISTRIBUTION SYSTEMS INTEGRATED WITH ENERGY STORAGE

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ABSTRACT

The integration of distributed generations (DGs) - renewable DGs, in particular- into distribution networks is gradually increasing, driven by environmental concerns and technological advancements. However, the intermittency and the variability of these resources adversely affect the optimal operation and reliability of the power distribution system. Energy storage systems (ESSs) are perceived as potential solutions to address system reliability issues and to enhance renewable energy utilization. The reliability contribution of the ESS depends on the ownership of these resources, market structure, and the regulatory framework. This along with the technical characteristics and the component unavailability of ESS significantly affect the reliability value of ESS to an active distribution system. It is, therefore, necessary to develop methodologies to conduct the reliability assessment of ESS integrated modern distribution systems incorporating above-mentioned factors. This thesis presents a novel reliability model of ESS that incorporates different scenarios of ownership, market/regulatory structures, and the ESS technical and failure characteristics. A new methodology to integrate the developed ESS reliability model with the intermittent DGs and the time-dependent loads is also presented. The reliability value of ESS in distribution grid capacity enhancement, effective utilization of renewable energy, mitigations of outages, and managing the financial risk of utilities under quality regulations are quantified. The methodologies introduced in this thesis will be useful to assess the market mechanism, policy and regulatory implications regarding ESS in future distribution system planning and operation.

Another important aspect of a modern distribution system is the increased reliability needs of customers, especially with the growing use of sensitive process/equipment. The financial losses of customers due to industrial process disruption or malfunction of these equipment because of short duration (voltage sag and momentary interruption) and long duration (sustained interruption) reliability events could be substantial. It is, therefore, necessary to consider these short duration reliability events in the reliability studies. This thesis introduces a novel approach for the integrated modeling of the short and long duration reliability events caused by the random failures. Furthermore, the active management of distribution systems with ESS, DG, and microgrid has the potential to mitigate different reliability events. Appropriate models are needed to explore their contribution and to assist the utilities and system planners in reliability based system upgrades. New probabilistic models are developed in this thesis to assess the role of ESS together with DG and

microgrid in mitigating the adverse impact of different reliability events. The developed methodologies can easily incorporate the complex protection settings, alternate supplies configurations, and the presence of distributed energy resources/microgrids in the context of modern distribution systems.

The ongoing changes in modern distribution systems are creating an enormous paradigm shift in infrastructure planning, grid operations, utility business models, and regulatory policies. In this context, the proposed methodologies and the research findings presented in this thesis should be useful to devise the appropriate market mechanisms and regulatory policies and to carry out the system upgrades considering the reliability needs of customers in modern distribution systems.

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DEDICATION

To my beloved parents, ***Shyam*** *and* ***Subadra****,*
and
To my wonderful sisters, ***Shobha****,* ***Goma*** *and* ***Rama***
Without whom none of my success would have been possible

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LIST OF ABBREVIATIONS

AC	Alternating Current
BESS	Battery Energy Storage System
CAES	Compressed Air Energy Storage
Cust	Customer
CV	Capacity Value
DC	Direct Current
DER	Distribute Energy Resource
DG	Distributed Generation
DOD	Depth of Discharge
DSE	Disruptive Sag Event
DSO	Distribution System Operator
ECOST	Expected Cost of Interruption
EENS	Expected Energy Not Supplied
EICV	Effective Increment in Capacity Value
ERP	Expected Reward/Penalty
ESS	Energy Storage System
FMEA	Failure Mode and Effect Analysis
HLI	Hierarchical Level I
HLII	Hierarchical Level II
HLIII	Hierarchical Level III
Hr	Hour
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated-Gate Bipolar Transistor
kW	Kilowatt
LP	Load Point
MAIFI	Momentary Average Interruption Frequency Index
MCS	Monte Carlo Simulation
MG	Microgrid
MI	Momentary Interruption

MILP	Mixed Integer Linear Programming
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
MW	Megawatt
Occ	Occurrence
PBR	Performance Based Rate-making
PCC	Point of Common Coupling
PCS	Power Conversion System
PHES	Pump Hydro Energy Storage
PV	Photovoltaic
RBTS	Roy Billinton Test System
RE	Reliability Event
RES	Renewable Energy Source
RPS	Reward Penalty Structure
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SI	Sustained Interruption
SMES	Superconducting Magnetic Energy Storage
SOC	State of Charge
Std	Standard
TSO	Transmission System Operator
UPS	Uninterruptible Power Supply

CHAPTER 1: INTRODUCTION

1.1. Power System Reliability

An electric power system should be planned, operated and maintained to supply reliable power to its customers at an acceptable cost. The electric energy produced at the generation facilities is delivered to the customers through the transmission and distribution facilities. The random failures of these components introduce reliability concerns in the power system. The system reliability can be enhanced with reliability centric planning, operation, system upgrades, and maintenance practices, which often requires a significant amount of investment. Any investment made, however, should be justified by the reliability worth to the electricity consumers and the society as a whole. Quantitative power system reliability assessment provides useful insights in system planning and operation in order to maintain the desired level of supply reliability at an acceptable cost.

The reliability assessment of a power system can be divided into two main domains of system adequacy and system security as shown in Figure 1.1 [1]. System adequacy relates to the ability of the system to supply sufficient energy to its customers within the system operating constraints. It ensures that the system has sufficient generation, transmission, and distribution facilities to satisfy customer demand. Whereas, system security deals with the ability of the system to respond to disturbances within the system to maintain the quality and continuity of power supply to its customers.

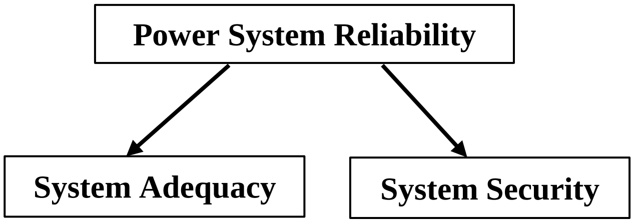

Figure 1.1. Domains of power system reliability.

Generation, transmission and distribution facilities constitute the three main functional zones of a power system. The reliability assessment can be conducted at different hierarchical levels that combines these different functional zones as shown in Figure 1.2 [1]. Reliability evaluation at the hierarchal level I (HLI) assesses the sufficiency of generation facilities to meet the system load. The transmission and distribution facilities are not considered at this level. The adequacy evaluation at this level is termed as "generation capacity reliability evaluation". The reliability analysis at the hierarchal level II (HLII) takes into account both the generation and the transmission facilities. In contrast to reliability assessment at HLI, the impact of transmission line constraints and the locational aspect of generation facilities on the supply reliability at the different transmission nodes and the overall system are assessed at the HLII level. The adequacy assessment at this level is termed as the "bulk system or composite system reliability evaluation". The hierarchical level III (HLIII) includes all three functional zones of the power system to evaluate the reliability at individual load point level. Usually, reliability analysis is performed at the distribution system level with an input from the HLII evaluation, since the complexity of a practical power system due to system size, diversity in composition and ownership issues makes it difficult to conduct the HLIII assessment.

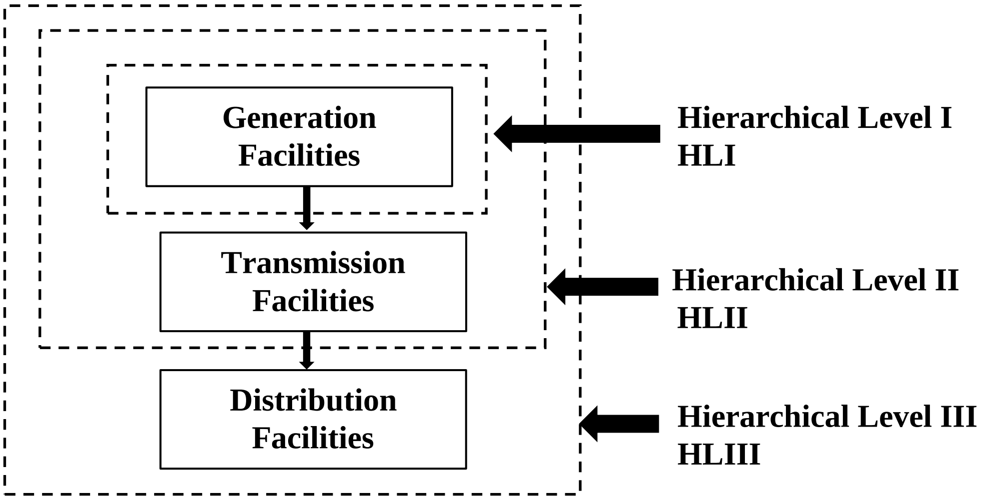

Figure 1.2. Functional zones and hierarchical levels in reliability assessment.

Historically, distribution system reliability has been given considerably less attention than that of generation and bulk system reliability. This is mainly because generation and transmission inadequacy often have larger scale consequences on the overall power system, whereas the impact of unreliability in the distribution network has a localized effect. The studies, however, have shown that distribution systems make the greatest contributions (approximately 80%) to the unavailability statistics in the context of supply to load points [1]. It follows that distribution system reliability indices are an important consideration when evaluating network integrity with regards to load supply capability and infrastructure upgrade priorities. Moreover, the recent trends of deregulation and privatization have put distribution utilities in a completive environment. The distribution utilities are being re-regulated to ensure customer supply reliability and efficient system operation. In addition, the integration of microgrids and distributed energy resources (DERs) - distributed generation and energy storage technologies into distribution networks have changed the way the distribution system operates. It also affects the business model of distribution utilities, customer supply reliability, and tariff structures. The distribution system reliability is thus becoming more relevant and getting increased attention due to such ongoing changes in the modern power systems. The increasing importance of distribution system reliability assessment is also driven by financial reward and penalty imposed on distribution system owners based on reliability performance. This thesis is focused on the reliability assessment of modern distribution systems.

1.2. Modern Distribution Systems and Reliability Concerns

The distribution system links the transmission system to the customer load points. It is composed of sub-transmission lines, feeders, substations, protection systems, and other power switchgear. Distribution grids are usually operated as radial systems. They are equipped with sectionalizing and tie switches that provide the ability to link one circuit to another in order to facilitate maintenance and outage restoration. Electricity customers with high reliability needs are served with a “network” type distribution systems that have multiple feeders linked together.

The distribution network is prone to failures/faults and often covers a large geographical area. Such faults result in different types of reliability events, such as, voltage sag, momentary interruptions, and sustained interruptions. The IEEE Std. 1159 [2] defines a voltage sag as the reduction in the root mean square voltage magnitude below a nominal voltage (between 10% and 90% of a nominal voltage). A momentary interruption, as defined in the IEEE Std. 1366 [3], is a brief loss of continuity of supply resulting from the opening and closing of a protective device for a short interval of time. Generally, service interruptions for one to five minutes are classified under momentary interruptions [3], [4], and the interruptions that last longer are classified as sustained interruptions [1], [3]. A growing number of electricity customers in a modern distribution system employ digital and power electronic equipment such as adjustable speed drives, computers, and automated manufacturing lines that require high reliability and power quality, as they are susceptible to mis-operation even with short duration reliability events (voltage sag and momentary interruptions) [5]. Both short and long duration reliability events are responsible for the financial loss to the modern distribution customers (especially to the industrial/commercial customers) and to the network [6].

The reliability indices of a distribution system can be assessed both at the system level and at the individual load points. At the load point level, the failure frequency (λ), the average outage duration (r), and the outage probability or unavailability (U) are the basic indices. The unavailability index is usually weighted by the number of hours in a year, and expressed as the average annual outage time in hours per year. These indices can be used to obtain other load and energy based indices, such as the expected energy not supplied $(EENS)$ at each load point of the distribution system. The load point indices are aggregated to obtain the system indices. The system average interruption frequency index (SAIFI), the system average interruption duration index (SAIDI), and the expected energy not supplied (EENS) can be obtained using (1.1) - (1.3) using the basic load point indices and additional information on the number of customers and the load connected at each load point in the system [1].

$$SAIFI = \frac{\sum \lambda_i N_i}{\sum N_i} \tag{1.1}$$

$$SAIDI = \frac{\sum U_i N_i}{\sum N_i} \tag{1.2}$$

$$EENS = \sum L_{a,i} U_i \tag{1.3}$$

Where, λ_i, U_i, $L_{a,i}$, and N_i denote the failure frequency, average annual outage time, average load connected, and the number of customers of load point i, respectively.

The above described indices are based on the sustained interruption of supply. Mostly, the reliability indices used in the utility planning and regulatory compliance structure are based on the frequency and duration of sustained interruptions [6]. However, the impact of short duration reliability events (voltage sags and momentary interruptions) is significant for modern industrial/commercial customers due to the installation of sensitive equipment/processes. The momentary average interruption frequency index (MAIFI) is used to measure the frequency of momentary interruptions in the network [3], [6]. The network performance associated with the voltage sag is reported with the annual frequency as a function of sag magnitude and duration [5].

The electric power utilities strive to optimize their investment in their system to supply energy to the customers at the lowest possible cost with an acceptable level of reliability. The investment should, therefore, be justified the reliability worth to the electricity consumers. The customer outage cost analysis provides valuable input to electric power supply reliability worth assessment. The reliability worth to the customers is evaluated with an expected cost of interruption (ECOST), expressed in dollars per year, both at the load point level as well as at the system level. The cost of interruptions at the customer level depends on the type of customer, the load curtailed, the duration of interruption, and the time of interruption [1]. The public-owned utilities, or vertically integrated utilities often incorporate a value-based reliability approach as it provides a framework to evaluate the investment cost required to achieve a certain level of reliability (reliability cost) and the benefits derived by society (reliability worth) with the improved reliability. The concept of reliability cost/worth can be illustrated using Figure 1.3 [1]. As the utility cost associated with system upgrades increases, the financial losses incurred to the customers due to the interruptions/reliability events decreases. The total societal cost is the sum of reliability cost and the interruption cost. The value-based reliability assessment framework provides a reliability criterion at the optimal point where the societal cost is minimum.

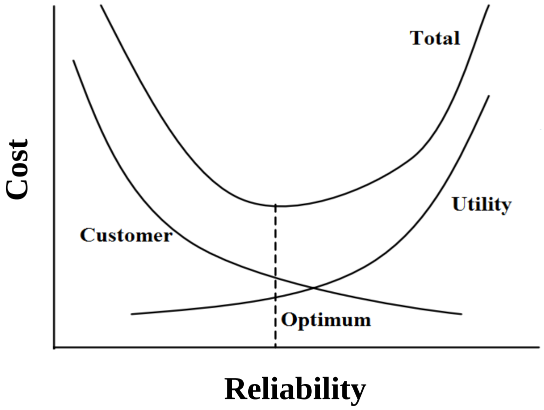

Figure 1.3. Reliability cost worth concept.

Most distribution systems in the past operated as part of a vertically integrated system, where the utility owned all the three functional zones of generation, transmission and distribution. Modern distribution systems today are owned by separate entities and operated by individual distribution system operators (DSO) in a deregulated environment. Many jurisdictions around the world are implementing different forms of incentive/performance-based regulation (PBR) [7] to encourage the DSO to improve economic efficiency in the competitive market environment. In order to ensure that the quality of electric supply does not deteriorate while utilities strive to achieve economic incentives under PBR, regulators set the reliability standards that the utilities are obligated to comply. In this context, a reward/penalty structure (RPS), formulated based on the DSO's reliability performance, is often incorporated in PBR [7] along with other incentive mechanism related to network losses and efficient utilization of network assets. Figure 1.4 shows a general representation of RPS [7]. The DSO is rewarded/penalized if its reliability index is less/greater than the reward/penalty point as shown in Figure 1.4. There is no reward or penalty in the dead zone. The dead zone and the penalty and reward points are set by the regulator considering the mix of customers served, geography, historic performance of the DSO, etc.

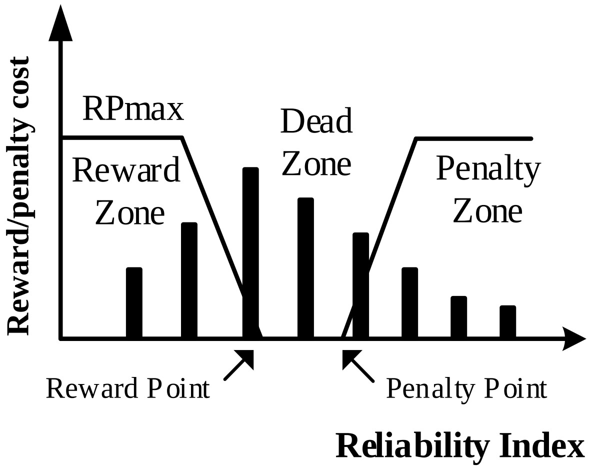

Figure 1.4. General scheme of Reward/Penalty structure.

The reliability of supply provided by a distribution system to its customers has a significant impact on the socio-economic development of a modern society. Thus, utilities take the customer reliability concerns into account in distribution system planning and operation. The emergence of new participants/entities and technologies in the distribution system, e.g. distributed generations (DG), energy storage systems (ESS), microgrids, load aggregator, and the market participation of DERs/microgrids, etc. have significantly changed conventional operation and planning practices. The following subsections present a brief discussion on the major changes and the reliability concerns of modern distribution systems.

1.2.1. Integration of Distributed Energy Resources

The integration of renewable energy sources (RES), e.g. solar PV and wind power into the power system is increasing as depicted in Figure 1.5 [8], [9], mainly driven by the environmental concerns. A large share of these resources have been interconnected to the medium and low voltage distribution networks in the form of DG. The cogeneration, solar PV, and wind-based resources are widely used DG technologies. The emission constraints imposed by the regulators in many jurisdictions have favored the significant growth of renewable energy based DGs. However, the intermittency and the variability of renewable resources add more uncertainty to the system, which adversely affects the reliability of the power distribution systems. The active management of the distribution system with DERs, microgrid, and smart technologies is expected to address such challenges shifting the traditional passive distribution network to an active/smart distribution network. The strategic utilization of DGs helps in voltage support, energy-loss reduction, power quality and reliability improvement, deferral of network expansion driven by demand growth, etc. [8]. Figure 1.6 shows a typical active distribution network with DG, ESS, and a microgrid.

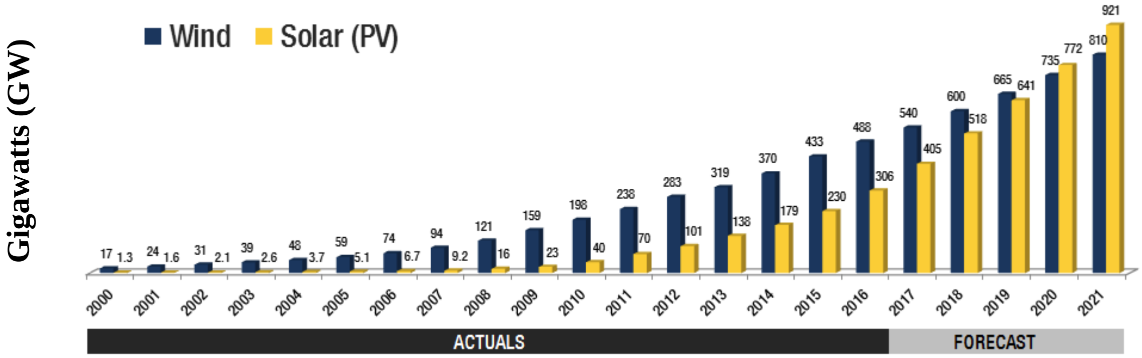

Figure 1.5. Trend of penetration of renewable energy into power systems [9].

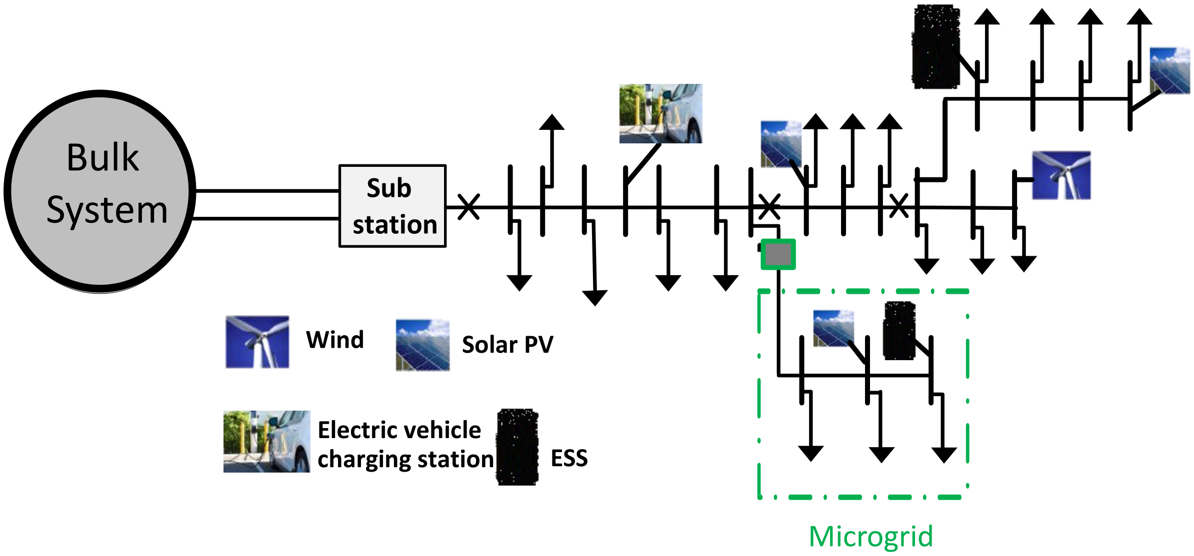

Figure 1.6. Distribution network with DERs and microgrid.

Microgrids are the building blocks of an active distribution system. A microgrid can be defined as a low or medium voltage network containing a cluster of local loads with DGs, energy storage, and controllable loads. A microgrid has a static switch installed at the utility side of the point of common coupling (PCC) as shown in Figure 1.7. Microgrids are capable of either performing in a grid-connected or islanded operation mode. The operation modes depend on system requirements, the output of renewable energy resources, electricity market, etc. A microgrid is also considered to retain a self-healing capability by virtue of autonomous microgrid operation to protect the customer loads from system faults on the utility side. This capability is provided by a static switch installed at the PCC that can isolate such faults in a very short time and allow the DERs to supply power to the load points. The DERs inside the microgrid help maintain the frequency and voltage stability during utility supply interruptions. In addition, the microgrid operator can participate in energy-arbitrage and provide supply capacity and ancillary services to the system operator utilizing its resources.

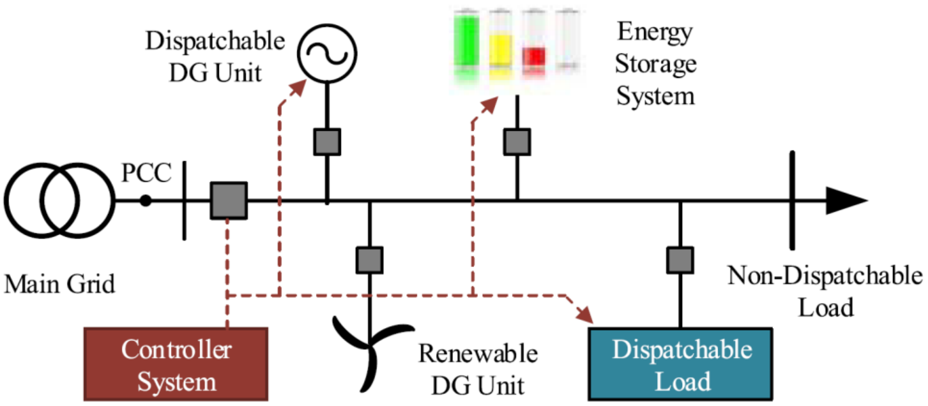

Figure 1.7. Schematic of a typical microgrid [10].

1.2.2. Different Energy Storage Technologies

ESSs have the potential to facilitate the integration of high penetration of RESs and enhance/maintain the system reliability. Although ESS is a relatively expensive technology, the prices for these technologies have been steadily decreasing [11]. ESS technologies present attractive business cases in many power system applications [12], [13], and therefore, the integration of ESS is expected to increase substantially in the near future. Figure 1.8 presents a comparison of different storage technologies in terms of the rated power, the discharge duration, and major applications.

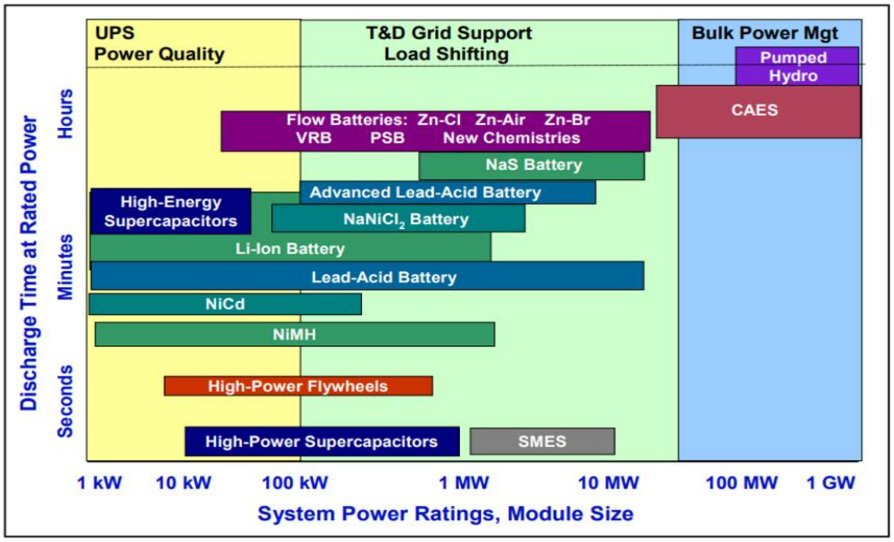

Figure 1.8. Comparison of energy storage technologies [13].

The compressed air energy storage (CAES) and pumped hydro energy storage (PHES) are capital intensive and are limited to certain geographic locations [14]. These technologies can attain their rated power in order of minutes. Given the high power rating and discharge duration, these technologies are more suitable to bulk power system applications as they can handle high power and energy requirements. They can be utilized for output smoothing and capacity firming of RES, black start, spinning reserve, and supply capacity applications.

Flywheels, supercapacitors, and superconducting magnetic energy storage (SMES) are mainly utilized for high-power applications that require short discharge durations. These technologies can respond at their rated power in order of milliseconds. These technologies can be utilized in frequency and voltage regulation, renewable energy smoothing, etc. [14], [15].

Recent advancements in different battery technologies such as Sodium-based battery, Lithium-ion battery, Lead acid, Nickel-based battery, and the flow batteries have accelerated their deployment in distribution system applications, making them widely used storage technologies in distribution networks [14], [16].

1.2.2.1. Battery Energy Storage Systems

Batteries consist of electrochemical cells, with solid negative and positive electrodes, and aqueous electrolyte [14]. The positive ions flow from the positive to the negative electrode while electrons flow in the opposite direction during the charging process, and vice-versa for the discharging process. The studies have shown the efficacy of battery technologies, such as Nickel-based, Lithium-ion, Sodium-based, Lead acid batteries, etc. in various power system applications [14]. Nickel-based batteries possess high energy density, however, they have relatively low cycle life. Lithium-ion batteries possess high efficiency and energy density. Sodium-based battery is a mature technology, and it is characterized by long cycle life and high discharge duration. Lead acid batteries, although being one of the oldest technologies, have limited grid-scale deployment due to its relatively low cycle life and energy density [17].

Flow batteries have been deployed to support the grid-scale applications, in addition to the above-mentioned battery technologies [17]. The flow batteries have an ionic solution stored outside of the cell and can be fed into the cell in order to generate electricity [17]. The flow batteries possess a longer life cycle in comparison to traditional battery systems and the discharge duration can be increased by adding more electrolyte [17]. Redox Flow batteries, Zinc-bromide (Zn-Br), etc. are examples of flow batteries. The battery technologies have fast response time (in order of milliseconds), and can be utilized in a range of power system applications, such as peak shaving, electric energy time shift, renewable capacity firming, renewable energy smoothing, spinning reserve, frequency/voltage regulation, power quality, and outage mitigation.

Figure 1.9 shows a configuration of a grid-scale battery technology. A battery energy storage system (BESS) mainly consists of a number of battery energy storage (BES) units managed by a battery management & control system. A transformer connects the BESS to the utility grid. Each BES unit consists of a battery string composed of a number of battery modules and a power conversion system (PCS) that consists of dc-link capacitor, DC-DC converter, and AC/DC converter comprised of diodes and IGBTs/MOSFETs [18].

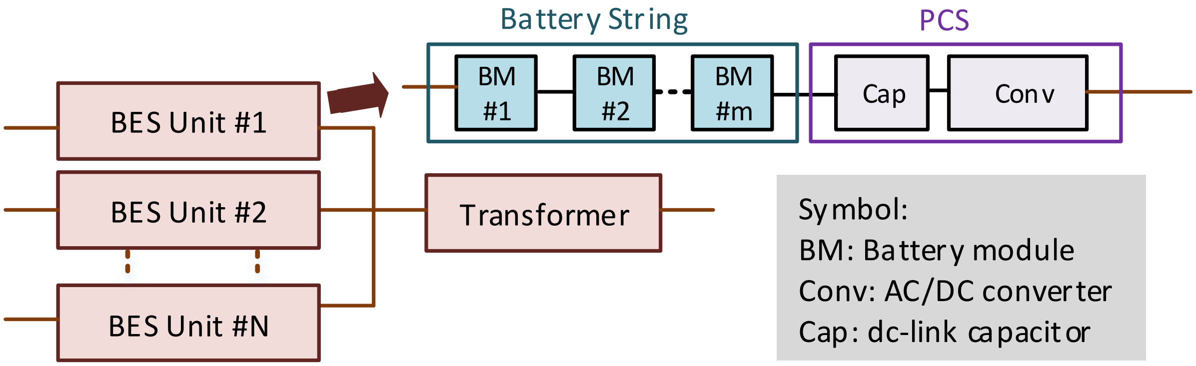

Figure 1.9. Grid-scale reconfigurable BESS.

It should be noted that the degradation is an important aspect associated with the battery storage [19], [20]. The battery degradation can be divided into calendar and cycling degradation. Calendar ageing relates to the battery's inherent degradation over time, during which its capacity rating is affected by the variation in temperature and the state of charge (SOC). [19]. The cycling degradation, on the other hand, is associated with the life lost each time the battery cycles between charging and discharging. It is a function of depth of discharge (DOD), charge/discharge rate, number of frequent charging and discharging, etc. [19]. The appropriate management of battery storage, such as avoiding a high rate of charge/discharge, maintaining an optimal depth of discharge level and limiting the discharge cycles while scheduling, etc. can enhance the battery life [19], [20].

1.2.3. Value of Energy Storage to Distribution Systems

Energy storage systems offer a range of benefits to the various stakeholders of a modern distribution system, including the ESS owner, the DSO, the microgrid operator, and the end-user. The DSO has the responsibility of managing the interconnected and available resources and operating the grid to provide customers with power supply. Some recognizable benefits of ESS deployment in the distribution network are listed below [12], [16], [19]:

- System expansion deferral: The continuous load growth and its uncertainty in a distribution system often lead to situations where the delay in transmission and distribution system expansion creates serious reliability concerns. The option for new capacity addition may not be feasible due to emission constraints imposed in response to environmental concerns, or due to economic reasons as the added capacity will be unused during off-peak hours. The ESS could be a feasible alternative in such scenarios by supplying capacity during network constraints, thus deferring the system upgrades to later years.
- Energy arbitrage benefit: the DSO can utilize the ESS in the completive market to purchase and store the energy when the electricity price is low and to discharge it to make profit when the price is high.
- Renewable energy time shifting: The power output of renewable energy resources is intermittent in nature, therefore, may not significantly contribute to the peak carrying capacity of the system. The ESS can be operated to store renewable energy during off-peak hours of the day and to discharge the energy during the peak hours, thus increasing the contribution of renewable resources to the peak load.
- Improvement in supply reliability: The ESS together with other distributed energy resources can supply a certain portion of the distribution network in the form of a microgrid during planned or unplanned utility supply interruptions, thus improving the reliability.
- The ESS installed at the customer-premise can be utilized in time-of-use energy management and demand charge management. In addition, the ESS protects critical load against interruptions, voltage sag, and other power quality issues.
- Apart from the above-mentioned benefits, the ESS helps in smoothing the output from the renewable resources, network losses reduction, and provides frequency and voltage support.

As discussed in previous sections, the transition of distribution network from a passive to an active management with the integration of renewable DG, ESS, microgrid, and smart distribution technologies is creating a paradigm shift in infrastructure planning, grid operations, utility business models, regulatory policies, and quality/reliability of supply to customers. In a competitive electricity market, it is important that the appropriate market mechanisms and regulations be set in order to promote the effective coordination among different participants of a distribution system and the transmission system operator (TSO). The recognition of the services provided by the distributed resources such as supply recovery during outages, grid capacity enhancement, network losses reduction, voltage support, etc. is an important step toward it. In addition, the regulatory policies offering incentives to the DSO for promoting the use of DERs and microgrids within its jurisdiction ensure the efficient distribution system operation. Furthermore, electric customers in today’s deregulated environment are increasingly expecting better reliability and power quality, especially with the widespread use of the sensitive equipment/processes, thus establishing the customer reliability as a vital concern in the planning and regulation of distribution systems.

1.3. Research Motivations and Objectives

Ongoing changes in power system structure and operational requirements due to the rapid increase of intermittent renewable energy are causing increasing challenges in system planning and operation while maintaining acceptable service reliability. Energy storage systems are perceived as potential solutions to address system reliability issues and to enhance renewable energy utilization. ESS brings different flexibilities to the DSO. The DSO can utilize the ESSs to provide supply capacity during network constraints, which can provide significant economic benefits due to the deferral of network expansion. The ESS located alongside the renewable energy resources helps enhance the capacity value of RES. Utilizing the smart control and communication facilities, ESS together with other DGs can supply a certain portion of the network with islanding operation during the utility supply interruptions.

The regulatory frameworks and market structures largely influence the intention of investor or the DSO in the deployment of ESSs and DGs. Moreover, the benefits to DSO and the end-users by the integration of ESS (and DERs) into its network depend on the ownership of these resources, market structure, and the regulatory framework. This along with the technical characteristics and the component unavailability of ESS significantly affect the reliability value of ESS to an active distribution system. For the DSO-owned DERs, the benefits from utilization of renewable energy, reduced energy purchase cost, and enhanced supply reliability are well recognized. Electric power utilities in some jurisdictions are not allowed to own DERs. The lack of appropriate market structure, regulations, and the effective coordination between DSO and the private investors, in such a scenario, can result in inefficient system planning and operation [21].

Several works [10], [16], [19], [20], [22]-[26] have been done in the past to assess the reliability contribution of ESS to active distribution systems. However, these works do not address the impact of different scenarios of ownership and markets, which significantly affect the reliability contribution of ESS. There is a need to develop methodologies that systematically derive quantitative indicators to assess market mechanism, policy and regulatory implications on the reliability contribution of ESS in future distribution system operation and planning. The primary objective of this research work is to assess the reliability value of ESS to active distribution systems incorporating market structures, regulatory frameworks, and ESS characteristics. In order to achieve this objective, it is necessary to develop appropriate models to carry out the analysis. Development of component reliability models for BESS, modeling of operating strategies of BESS regarding the market participation and other system applications, and the development of reliability evaluation framework to integrate the BESS model, intermittent DGs, and the time-dependent loads are other objectives of the research work presented in this thesis.

With the widespread use of sensitive equipment and industrial processes, the quality of supply is getting increased attention. These devices/processes are susceptible to mis-operation even with short duration reliability events, which include voltage sag and momentary interruptions [5]. For an industrial/commercial customer, the financial losses due to short duration reliability events are significant. To address the customers’ concerns on power quality/reliability in today’s deregulated environment, the regulators and utilities are increasingly recognizing the voltage sag and momentary interruptions in addition to sustained interruptions in the policy-making and reliability planning [27]. Literature survey of related past works [5], [6], [28]-[34] suggest that the new models should be developed to study the impact of both short and long duration reliability events on the quality of supply in the context of active distribution systems. There is also a need to explore the potential of ESS, microgrids and other distributed resources in mitigating the adverse impact of different reliability events. An objective of this research work is to quantify the load point and system reliability profile of active distribution systems incorporating short and long duration reliability events. Appropriate models to systematically incorporate different reliability events are needed in order to meet this objective. Development of aggregated reliability event models, modeling of complex protection settings and alternate supplies, and probabilistic modeling of ESS, DGs and microgrids to assess their role in mitigating the adverse impact of different reliability events on customer supply quality are other objectives of this thesis.

The objectives of the work reported in this thesis are summarized below:

- To develop a component reliability model of BESS considering the failure characteristics of major system components.
- To model the operating strategies of BESS incorporating market structures, regulatory frameworks, and the technical characteristics of storage.
- To develop a methodology to integrate the above BESS model, intermittent DGs, and the time-dependent loads to quantify the reliability value to active distribution systems.
- To develop an aggregated reliability event model incorporating voltage sag, momentary interruptions, and sustained interruptions.
- To incorporate the complex protection settings and the alternate supply configurations of modern distribution systems in the above model.
- To develop models to quantify the contribution of ESS, DGs and the microgrids in mitigating the adverse impact of reliability events on quality of supply.

1.4. Thesis Organization

This manuscript-style thesis is organized into 6 chapters. All the chapters, except the first and the last, are papers submitted to technical publications. This section briefly describes the different chapters within the organization of this thesis.

Chapter 1 provides an overview of power system reliability and the major changes in the modern distribution system. The reliability needs of customers and the incorporation of customer reliability in the system planning and regulatory compliance structures are discussed. Different aspects of energy storage, distributed generation, and microgrid their impact on the supply reliability and system efficiency is briefly described. Preliminary work was done on the reliability assessment of a microgrid in the paper titled "Impact of the Penetration Levels of PV and Synchronous Machine based DG sources on the Reliability of a Microgrid" published in the proceedings of *IEEE Electrical Power and Energy Conference (EPEC*), Saskatoon, 2017 [35]. The main focus of this work was to investigate the effect of varying photovoltaic and synchronous machine based distributed generation source type penetrations on the reliability of a microgrid. The complexities of energy storage and renewable distributed resources were not considered in this work. This work, however, provided the basis to develop new methodologies presented in this thesis to incorporate microgrids in the reliability assessment of active distribution systems. The motivation for the research work and the objectives set in the thesis are also presented in Chapter 1.

Chapter 2 is extracted from the paper titled "Quantifying Reliability Contribution of Energy Storage System to a Distribution System" [36]. This paper has been accepted for publication in the proceedings of *IEEE PES General Meeting*, Portland, OR, USA, August 2018. This chapter presents a methodology to quantify the reliability benefits of DSO-owned ESS. A reliability model of BESS is developed and integrated into a Monte Carlo simulation (MCS) based framework to assess the reliability contribution of ESS that is owned and operated by the DSO. The benefits associated with ESS integration, such as reliability improvement at the load point and the system level, the deferral of immediate distribution system expansion, and better utilization of renewable distributed generation resources are quantified.

Chapter 3 is a paper titled "Probabilistic Modeling of Energy Storage to Quantify Market Constrained Reliability Value to Active Distribution Systems" submitted to the *IEEE Transactions on Sustainable Energy*. This chapter extends the work presented in Chapter 2 to assess the reliability contribution of BESS considering different scenarios of market structures, and regulatory frameworks. A new probabilistic reliability model of BESS is developed in this chapter. It consists of the Markov based component model and the mixed integer linear programming based formulation of operating strategies incorporating different scenarios of ownership, market structures, and the ESS characteristics. An MCS framework is developed to integrate the ESS reliability model, along with the intermittent DGs and time-dependent loads to conduct the analysis. The reliability/financial risk performance of the DSO with ESS under quality regulations are quantified. Furthermore, the prospect of investor-owned ESS providing supply recovery and distribution grid capacity services to the DSO are explored in this chapter.

Chapter 4 is a paper titled “Graph Theory Embedded Aggregated Reliability Event Modeling for Modern Distribution Systems” submitted to the *IEEE Transactions on Power Systems*. Chapter 2 and 3 of this thesis deal with the reliability issues associated with sustained interruptions. Thus, the developed models do not consider the short duration reliability events. This chapter presents a novel approach to consider voltage sag and momentary interruptions in the reliability studies of modern distribution systems. A graph theory embedded aggregated reliability event model is developed that integrates protection settings, alternate supplies, and DERs/microgrids while assessing the reliability at the load point level and the system level. The case studies were conducted to show the impact of short duration reliability events on quality of supply and the customers’ financial loss. The impact of protection system settings and presence of DERs/microgrids on the reliability is also assessed.

Chapter 5 is a paper titled “Utilizing Energy Storage for Reliability Solutions in Active Distribution Systems” submitted to *International Journal of System Assurance Engineering and Management*. This chapter extends the work presented in Chapter 4 and focuses on assessing the role of ESS to mitigate the impact of different reliability events on the quality of supply. A scenario-based probabilistic model is introduced in this chapter that takes into account the storage technology type, the power/energy rating, hardware availability, the presence of other distributed energy resources in detail. A range of case studies was conducted to provide valuable insights regarding the utilization of ESS and other distributed resources to provide reliability solutions.

Chapter 6 summarizes the overall research work.

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CHAPTER 2: QUANTIFYING RELIABILITY CONTRIBUTION OF AN ENERGY STORAGE SYSTEM TO A DISTRIBUTION SYSTEM [1]

2.1. Abstract

This paper presents a Monte-Carlo simulation based framework to quantify the reliability benefit brought by the integration of an Energy Storage System (ESS) to an active distribution system. The benefits associated with ESS integration, such as reliability improvement at load point and system level, the reliability worth, deferral of immediate distribution system expansion, and better utilization of renewable distributed generation resources are quantified using a suitable reliability model of ESS. Assessments are conducted on a radial distribution test network with photovoltaic arrays and ESS. A range of case studies are performed to assess the reliability contribution of ESS, and conclusions are drawn based on the results obtained.

2.2. Introduction

Integration of renewable energy based distributed generation (DG) sources to a distribution network has increased in the recent years due to legislated Renewable Portfolio Standards, environmental concerns and decreasing installation cost. However, the inherent intermittency and uncertainty with these resources can adversely impact the power quality and system reliability. The security constraint of a network, sometimes, dictates the renewable energy to be curtailed. Energy storage systems (ESS) are deemed to help mitigate the aforementioned problems enhancing the reliability, and utilization of renewable energy while achieving the economic benefits [1].

Studies have shown that distribution systems contribute most to the unavailability of power systems in the context of supply to load points [2]. It follows that distribution system reliability

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[1] **P. Gautam and R. Karki, "Quantifying Reliability Contribution of an Energy Storage System to a Distribution System," in 2018 *IEEE Power and Energy Society General Meeting*, Oregon, USA (Accepted for publication).**

indices should be given important consideration while planning distribution system upgrade and expansion [3].

Many literatures can be found that are centered on assessing the economics, reliability, and other aspects associated with deployment of ESS and DG in distribution systems. Reference [4] discuss the possible multiple usage of ESS at different levels of a power system, and their economic aspects, whereas authors in [5], [6] have investigated the appropriate sizing of ESS in a distribution system for various applications. A Monte-Carlo simulation (MCS) method is presented in [7] to evaluate the reliability of a distribution system with ESS incorporating real-time energy pricing. A model predictive control based ESS scheduling strategy for a distribution system load aggregator is presented in [8] to assess the effect of such operation of ESS in reliability and economics of the system. Reference [9] presents the stochastic optimization framework for ESS operation in a microgrid context. Authors in [10] have proposed the optimal planning framework for a distribution system expansion considering different technologies of Battery Energy Storage System (BESS). A MCS based methodology is used in [11] to quantify the combined benefits of ESS and real time thermal rating of feeders in a distribution system.

Although abundant literature is available that investigate different aspects of distribution systems with DG and ESS, further research is needed to fully comprehend the contribution of ESS in meeting its primary objectives of integrating renewable energy, enhancing the efficiency of the energy system, and maintaining an acceptable level of reliability at reasonable costs. Detailed reliability cost and worth analysis considering operational strategy and constraints of ESS will be important for future distribution system planning. The reliability value to the end customer in terms of load point and worse performing sections should be further investigated. The reliability/environmental contribution associated with the use of ESS in distribution system can provide valuable inputs to distribution system operation and planning.

This work presents a comprehensive MCS based framework to quantify the reliability benefit associated with the integration of ESS to a distribution system with intermittent DG. The reliability model of ESS presented here can be used to assess the contribution of ESS in reliability improvement of load point and the overall system, and its worth. In addition, the role of ESS in distribution system expansion deferral is also examined. The contribution of ESS in effective utilization of renewable DG has been quantified with appropriate indices. The findings from the range of case studies presented in this work will provide utilities, system planners and the policy makers with valuable insights.

2.3. Evaluation Approach

2.3.1. Modeling of PV Systems

The output power from a PV source depends mainly on the solar irradiation incident on its panel surface, which in turn, depends on the time of the day, season of the year, cloud coverage, and its geographic location. Historic solar irradiation data is required to create a reliability model of the PV system. When such data are not available, synthetic set of data can be generated and utilized in reliability evaluation [12]. This study uses a set of synthetic hourly solar irradiation data for a site in Swift Current, Saskatchewan, generated using the WATGEN [13] software developed by the WATSUN Simulation Laboratory. The hourly irradiation data is then converted into respective power using (2.1).

$$P = \begin{cases} P_{sn} \times \dfrac{G_{bi}^2}{G_{std} \times R_c} & 0 \leq G_{bi} \leq R_c \\ P_{sn} \times \dfrac{G_{bi}}{G_{std}} & R_c \leq G_{bi} \leq G_{std} \\ P_{sn} & G_{bi} > G_{std} \end{cases} \tag{2.1}$$

Where, P is output power of PV in Watts, G_{bi} the hourly solar irradiation in W/m^2, G_{std} the solar irradiation in a standard environment set as 1000 W/m^2, R_c is a certain irradiation point usually set as 150 W/m^2, and P_{sn} is the rated output power of solar panel in Watts-peak, W_p.

2.3.2. Modeling of Battery Energy Storage System

Studies have shown that among various storage technologies, BESS can be used for a wide range of distribution system applications [4]. References [14]-[16] discuss the effectiveness of sodium sulfur (NaS) based BESS for peak shaving/arbitrage operation, reliability improvement and facilitation of renewable energy by presenting case studies. Since the BESS is utilized for similar objectives in this paper, the study considers sodium sulfur based “PS-G50" module batteries rated at 50 kW and 360 kWh [15] capacity.

The BESS mainly consists of battery modules/strings, Power Conversion System (PCS), and battery management & control system. The transformer is used to connect the BESS to a utility grid. A system topology of a reconfigurable BESS is shown in Figure 2.1. One of the major advantages of such configuration in contrast to a classical BESS topology, where all the battery modules share a single PCS, is that the BESS can operate in a derated state even if one of the battery strings or PCS fails. The times to failure and repair for a battery module, and the components of PCS are assumed to follow an exponential distribution in this work. The failure of battery cell or module due to degradation is not considered in this work.

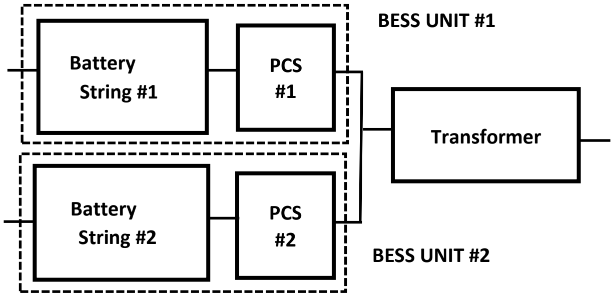

Figure 2.1. System block diagram of reconfigurable BESS.

The battery string consists of battery modules connected in series or parallel. However, from the perspective of reliability assessment, they are treated to be in series, since whole battery string is isolated from rest of the system for repair when any battery module fails. The battery string and PCS together form a BESS Unit. Again, from the reliability standpoint, components of the BESS Unit form a series system, since both battery string and PCS should be working for the BESS Unit to operate. The components of PCS, i.e. dc-link capacitor and AC/DC converter, form a series system. The failure rate of the AC/DC converter itself is the sum of the failure rates of its component diodes and IGBTs/MOSFETs. The above-mentioned model is summarized in (2.2). The mean time to repair for the BESS Unit can be obtained similarly using concept of series component system.

$$\begin{aligned} \lambda_{BESS\,Unit} &= \lambda_{BS} + \lambda_{PCS} \\ \lambda_{PCS} &= \lambda_{dc-link\,cap} + \lambda_{DC/AC\,conv} \\ \lambda_{DC/AC\,conv} &= 6 \times (\lambda_{diode} + \lambda_{IGBT}) \end{aligned} \tag{2.2}$$

Where, $\lambda_{BESS\,Unit}$, λ_{BS}, λ_{PCS} are the failure rates of BESS Unit, battery string and PCS respectively. Similarly, $\lambda_{DC/AC\,conv}$, $\lambda_{dc-link\,cap}$, λ_{diode} and λ_{IGBT} represent the failure rates of DC/AC converter, dc-link capacitor, diode, and IGBT respectively.

Figure 2.2 shows the Markov State Space diagram for the BESS configuration of Figure 2.1, where λ and μ denote the failure and repair rate of a BESS Unit. The failure of control system isn't taken into account in this study. The 2- state Markov model of transformer can be combined with this BESS reliability model. Although the State Space model shown in Figure 2.2 is for two BESS Unit systems, the model can be scaled up or down using similar approach. The associated failure rate for the PCS components are extracted from [17], whereas the mean time to repair is assumed to be 60 hours. The approximate failure and repair data for a battery module is taken from [18].

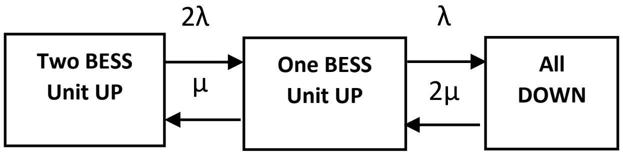

Figure 2.2. Markov State Space diagram of BESS.

2.3.3. Reliability Evaluation Framework

An ESS operates at charging, discharging and idle modes responding to the system behavior and demand. The ESS reliability model should incorporate its inter-temporal and energy limitation characteristic while operating at the different modes in correlation with the fluctuating nature of renewable DG output, time-dependent load variation, and other system variables. For this reason, a sequential MCS based approach is used to evaluate the distribution system reliability.

The load point reliability is quantified by three basic indices: the failure frequency, the average outage duration, and the unavailability. The Unavailability is a probability index generally expressed in hours per year. The system average interruption frequency index (SAIFI), system average interruption duration index (SAIDI), expected energy not supplied (EENS) and the expected cost of interruption (ECOST) are used as the reliability system indices [2] in the study. The EENS and ECOST are also used to measure the load point reliability.

The steps utilized in evaluating the reliability indices using the proposed MCS approach are summarized below in Figure 2.3. More details on the basics of implementation of MCS to evaluate the distribution system reliability and cost/worth analysis can be found in [2], [19].

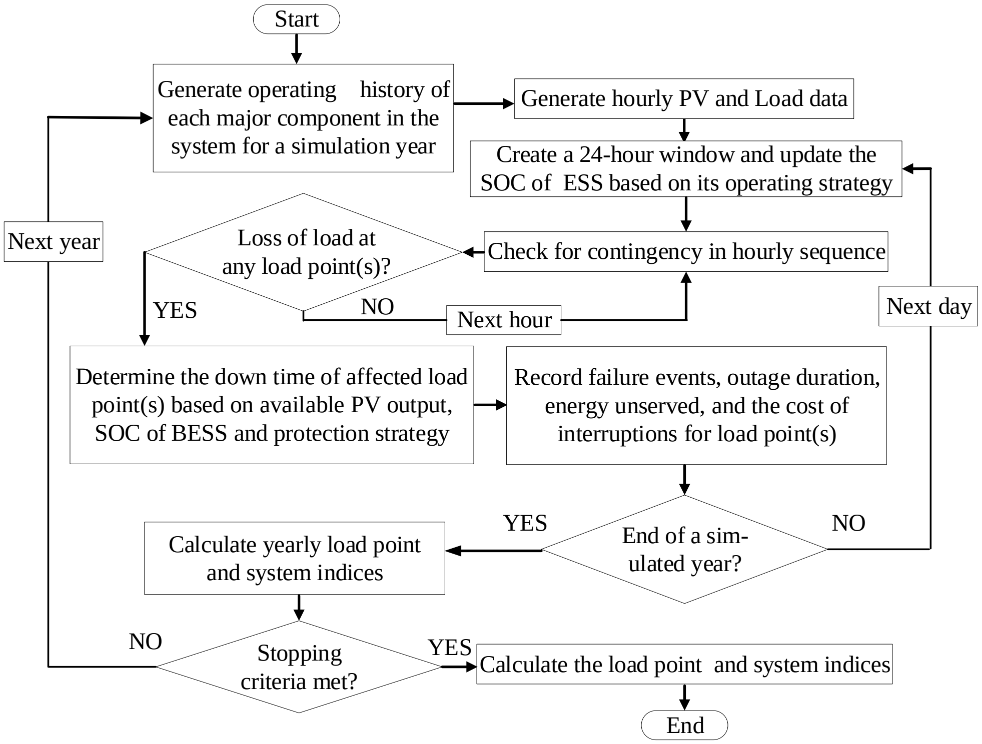

Figure 2.3. Flowchart for reliability evaluation.

The times to failure, repair and switching intervals associated with each component are assumed to follow an exponential distribution. The effect of overlapping time is ignored as the system is small and the element restoration times are short [19]. The failure of the protective equipment is neglected in this study. The reliability model of BESS developed in Section 2.3.2 is used to simulate its Up/Down history. The result of the MCS based algorithm used in this study was checked with that of analytical approach for the base case on a test network to confirm the accuracy.

2.3.4. Assessment of T&D Expansion Deferral with ESS

Transmission and distribution (T&D) expansions are capital intensive, and usually take a long time. The continuous load growth and its uncertainty in a distribution system often lead to situations where the delay in T&D expansion creates serious reliability concerns. The initiatives for new capacity addition may not be feasible due to emission constraints or environmental cost, or due to economic reasons as the added capacity will be unused [4] during off peak hours. The BESS could be a feasible alternative in such scenarios.

The following steps are utilized to assess the potential of BESS to defer the T&D expansion.

Step 1: Run the algorithm shown in Figure 2.3 for a current year scenario (Scenario 1).

Step 2: Repeat step 1 for another case with increased system load and capacity constrained substation transformer without ESS (Scenario 2).

Step 3: Repeat step 2 with ESS (Scenario 3).

Step 4: Compare the reliability indices for Scenario 1, 2 and 3.

An example case study presented in Section 2.4.2.2 illustrates this process.

2.3.5. Quantification of PV Utilization with ESS

The power output of PV is intermittent in nature, therefore, may not significantly contribute to the peak carrying capacity of the system. The role of PV to contribute to meeting the peak load should therefore be examined while evaluating the capacity value of PV [20]. The ESS can be optimally operated so that it can be charged with solar energy during off-peak time and discharged during peak load interval, thus increasing the contribution of PV to the peak load, and thus the system reliability. The capacity value of PV (PV_{CV}) considering its contribution to the peak load interval can be obtained using (2.3), where N is the number of simulation years.

$$PV_{CV} = \frac{\sum_{n=1}^{N} PV\ energy\ available\ during\ peak\ interval}{PV\ rating \times peak\ interval \times 365 \times N} \tag{2.3}$$

The contribution of BESS in increasing the capacity value of PV can be quantified using an index designated as the Expected Increment in Capacity Value (EICV) of PV for a particular PV and BESS rating as defined in (4). EICV is expressed as percentage increment in capacity value relative to the case without a ESS.

$$PV_{EICV} = \frac{PV_{CV}\ with\ BESS - PV_{CV}\ without\ ESS}{PV_{CV}\ without\ ESS} \tag{2.4}$$

The following steps summarizes the quantification of contribution of ESS to the effective utilization of PV energy.

Step 1: Set the operating strategy of ESS so that it is charged by PV systems (and from upstream supply as well, in case PV energy alone is not sufficient to charge the ESS) during low load period and discharge it during the defined system peak interval.

Step 2: Run algorithm shown in Figure 2.3, keeping track of PV energy available during system peak interval without storage, and evaluate PV_{CV} using (2.3).

Step 3: Repeat Step 2 with the operating strategy of ESS as mentioned in Step 1 and evaluate PV_{CV} using (2.3).

Step 4: Use the results from Step 2 and 3 to evaluate PV_{EICV} using (2.4).

Section 2.4.3 describes the example case study to assess the ability of ESS to enhance the capacity value of PV.

2.4. Case Studies and Results

This section presents the reliability benefit analysis associated with the integration of ESS to an active distribution system. The methodology specified in Section 2.3 is implemented in a MATLAB environment, and a range of case studies are performed on a test system.

2.4.1. Test System Under Study

Figure 2.4 shows the test distribution system, which is a modified version of feeder 1 at Bus 2 of the Roy Billinton Test System (RBTS) [21]. The time varying load for the different group of customers were obtained from [19]. The details of each load point can be found in [21]. The load points LP1 to LP4 constitute Segment 1, whereas LP5 to LP7 belong to Segment 2. An ESS and a set of PV arrays are integrated at bus B3. A reclosure at bus B3 allows the ESS, PV and Segment 2 loads, to operate in an islanded mode in case of a fault at upstream feeder sections.

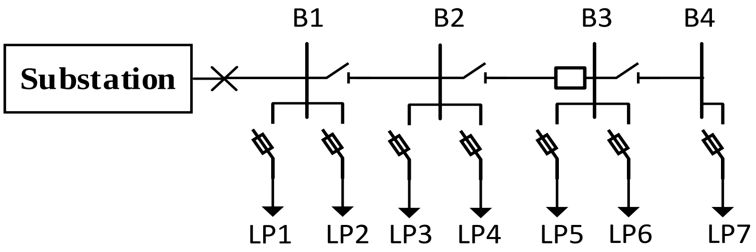

Figure 2.4. Distribution system under study.

The failure rate and repair time for the lines are 0.065 occ/yr-km and 5 hr respectively [21]. The load point transformers used in this study have the failure rate and replacement time of 0.015 occ/yr and 10 hr respectively [21]. The utility supply that includes the substation and the upstream grid is assumed to have a failure rate of 0.1 occ/yr and a repair time of 5 hours.

2.4.2. Reliability Benefit Evaluation

This section discusses the reliability benefit brought by the BESS integration to a distribution system. A sodium sulfur based BESS rated at 2 MW and 14 MWhr with topology as shown in Figure 2.1, and having charging/discharging efficiency of 90%, minimum State of Charge (SOC) limit of 10 % is used. The BESS under study consists of two battery strings, with 20 battery modules in each string.

The BESS is scheduled to charge during off-peak periods and discharge during peak periods. Therefore, a BESS is effectively operated for a daily peak-shaving purpose.

2.4.2.1. Assessment of Reliability Improvement

a) Load point reliability:

Table 2.1 presents the reliability indices for a representative set of load points before and after the integration of BESS. The failure frequency and unavailability results, prior to the integration of BESS, indicate that the load point reliability degrades as we go downstream from the substation. This is an expected scenario for a radial network without any alternate supply. After addition of BESS at bus B3, the reliability of Segment 2 load points, LP5 and LP7 is observed to be enhanced as the failure frequency, unavailability and EENS associated with them significantly decrease. This is due to the recovery of supply to these load points from the islanded operation of BESS in case of a fault at upstream feeder sections. Segment 2 load points LP5, LP6 and LP7 are in the increasing order of load supply priority in this study during islanded operation, and therefore, the load point reliability increases in this order. The reliability of Segment 1 load points, LP1 and LP3, however, does not change by the addition of BESS.

Table 2.1. Load point reliability indices.

Load Point	**Failure Frequency (occ/yr)**		**Unavailability (hr/yr)**		**EENS (kWhr/yr)**	
	Base Case	**With BESS**	**Base Case**	**With BESS**	**Base Case**	**With BESS**
LP1	0.303	0.303	1.208	1.208	598	598
LP3	0.315	0.315	1.444	1.444	701	701
LP5	0.356	0.249	1.744	0.929	900	513
LP7	0.358	0.145	1.903	0.749	771	266

b) System level reliability:

Table 2.2 shows the system level reliability indices of the two segments, and for the entire system for two different cases of with and without BESS. For the base case, SAIFI, SAIDI and ECOST of Segment 2 are higher than that of Segment 1, as it lies further downstream of Segment 1 and loses the utility supply when the fault occurs at any of these segments. However, it is apparent from the results in Table 2.2 that the addition of BESS helps improve the reliability of Segment 2 as the system indices notably decrease.

It should be noted that Segment 2 includes Commercial and Govt. & Inst. customers with high interruption costs, and therefore, the ECOST of this segment without BESS is significantly higher than the ECOST associated with Segment 1 that has mostly residential customers. The integration of BESS, however, results in a significant reduction in ECOST for Segment 2 and for entire system, which quantifies the reliability worth of BESS. The reliability enhancement due to the addition of BESS, however, is highly dependent on its operation strategy, availability, and capacity/ power rating etc.

Table 2.2. System reliability indices.

Segment	SAIFI (occ/cust-yr)		SAIDI (hr/cust-yr)		ECOST (k$/yr)	
	Base Case	With BESS	Base Case	With BESS	Base Case	With BESS
Segment 1	0.311	0.311	1.324	1.324	5.520	5.520
Segment 2	0.354	0.167	1.785	0.695	17.416	6.469
System	0.313	0.307	1.339	1.304	22.936	11.989

2.4.2.2. T&D Expansion Deferral:

This section assesses the potential of BESS to defer distribution system expansion and maintain the reliability at an acceptable level.

The BESS used in the study is operated for daily peak-shaving purpose, thus allowing the immediate T&D expansion deferral. Studies were conducted on the test system considering three scenarios. Scenario 1 study was done for the current year assuming the substation transformer is approaching its thermal limit of 5.8 MW. Scenario 2 study was done for a future year assuming a load growth of 5%. Scenario 3 study includes the BESS in the future year evaluation. When the thermal limitation of the substation transformer dictates load shedding, load curtailment is done considering decreasing priority of the load points further away from the substation. The system indices obtained for the three scenarios are shown in Table 2.3.

Table 2.3. Reliability indices for different scenarios.

Scenario	SAIFI (occ/cust-yr)	SAIDI (hr/cust-yr)	ECOST (k$/yr)
1: Current Year	0.307	1.304	11.989
2: Future Year (no upgrades)	1.708	2.735	636.819
3. Future Year with BESS	0.316	1.314	16.694

Table 2.3 shows that with BESS, the system reliability in the future year can be maintained at the same level as that of the current year without any T&D expansion. The results presented here shows that the strategically situated BESS with suitable capacity can maintain the system reliability allowing the deferral of T&D expansion planning without violating environmental constraints.

2.4.3. Contribution of ESS to Renewable Energy Utilization

This section examines how the contribution of PV during peak load, and system reliability can be enhanced with the integration of BESS. It is to be noted that for the test system under consideration, the daily peak load occurs around mid-day for summer season, but for rest of the year, the peak load appears in the evening time. A sensitivity analysis is performed by varying the rating of BESS and observing PV_{CV}, PV_{EICV} and system ECOST for a PV rated at 1.25 MW. The reliability indices are evaluated considering the islanded operation of BESS and PV system. The results are plotted in Figure 2.5. It shows that the increase in BESS capacity, enhances the capacity value of PV up to a certain point, after which it saturates and doesn’t provide further incremental benefit. It can be attributed to the fact that when the storage capacity is increased keeping the PV rating constant, it must rely more on utility supply for its charging, as there is only limited PV energy available. The system ECOST and PV capacity value results shown in Figure 2.5 confirms that the system with BESS can enhance the reliability, while utilizing PV more effectively.

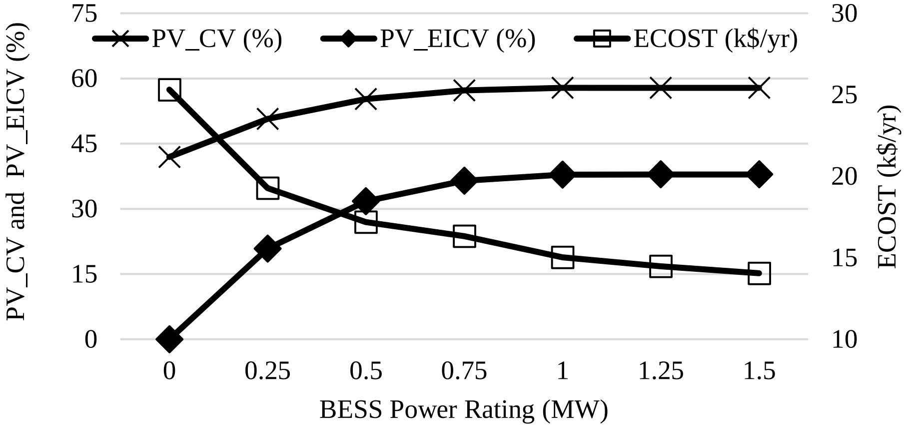

Figure 2.5. Effect of ESS capacity on capacity value of PV and reliability.

2.5. Conclusion

This paper presents a probabilistic MCS framework with a suitable reliability model of BESS to examine the reliability benefit of an ESS to an active distribution system. The ability of a BESS to utilize the renewable energy is also quantified. The results show that the integration of storage in distribution system helps improve the reliability of the worse performing section and the system as well. In addition, the ESS can be deployed to defer the expensive and time consuming T&D expansion, while maintaining the system reliability. Furthermore, studies conducted in this work confirm that the renewables and ESS when deployed together offers considerable environmental and reliability benefits by utilizing renewable energy more efficiently. The approach used, and the studies conducted in this paper can provide valuable insight in distribution system operation and planning.

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CHAPTER 3: PROBABILISTIC MODELING OF ENERGY STORAGE TO QUANTIFY MARKET CONSTRAINED RELIABILITY VALUE TO ACTIVE DISTRIBUTION SYSTEMS [1]

3.1. Abstract

Integration of an energy storage system (ESS) into a distribution network not only affects the supply reliability of the customer, but also has distinct reliability implications and consequences to the utility. The reliability value associated with an ESS highly depends on the ownership, market and regulatory structures. This paper presents a probabilistic framework to evaluate the reliability value of ESS to the distribution system considering aforementioned factors. In this regard, a new probabilistic reliability model of ESS is developed and integrated into a sequential Monte Carlo based simulation framework. The developed ESS model consists of the Markov based component model and the mixed integer linear programming based formulation of operating strategies that incorporate different scenarios of ownership, market structures, and the ESS characteristics. The reliability/financial risk performance of the Distribution System Operator (DSO) with ESS under quality regulations are quantified. Furthermore, the developed ESS model is utilized to explore the prospect of investor-owned ESS providing supply recovery and distribution grid capacity services to the DSO. Case studies are conducted on a test distribution network to show the effectiveness of the proposed model. Finally, the paper presents discussions on important considerations for efficient utilization of ESS in active distribution systems.

3.2. Nomenclature

i	Index of period (hour)
P(i)	Power purchased by DSO from the upstream grid for period i (MW)

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[1] **P. Gautam, R. Karki, and P. Piya, "Probabilistic Modeling of Energy Storage to Quantify Market Constrained Reliability Value to Active Distribution Systems," submitted to *IEEE Trans. on Sust. Energy* (Under review).**

$P_{pv}(i)$	Power output of PV arrays for period i (MW)
$L(i)$	System load demand for period i (MW)
$L_{is}(i)$	Load of islanded portion for period i (MW)
P_s	Maximum substation transformer capacity (MW)
$LC_{is}(i)$	Load curtailed during islanding operation for period i (MW)
$LC_{cc}(i)$	Load curtailed due to capacity constraints for period i (MW)
$PV_{sp}(i)$	Spilled PV energy for hour i
$P_{dis}(i)$,$P_{ch}(i)$	Discharged and charged power associated with ESS for period i (MW)
$P_{ES}(i)$	Power that ESS discharges/charges for period i ;takes negative value for charging (MW)
$P_{ch/dis}$	Absolute value of P_{ES} (MW)
P_{sc}^{TSO},P_{sc}^{DSO}	Contracted supply capacity by ESS to upstream grid and DSO, respectively (MW)
$SC_d^{TSO}(i)$, $SC_d^{DSO}(i)$	Supply capacity deficit of ESS for upstream grid and DSO during period i, respectively (MW)
$SOC(i)$	State of Charge of ESS at period i
SOC_{max}, SOC_{min}	Maximum and minimum SOC allowed for ESS (MW)
$P_{ch,min}^{ES}$, $P_{ch,max}^{ES}$	Maximum and minimum charging power of ESS (MW)
$P_{dis,max}^{ES}$, $P_{dis,min}^{ES}$	Maximum and minimum discharging power of ESS (MW)
n_c , n_d	Charging and discharging efficiency of ESS, respectively (%)
γ_{ch}	Binary variable representing charging status of ESS (1 for charging, 0 otherwise)
γ_{dis}	Binary variable representing discharging status of ESS (1 for discharging, 0 otherwise)
pr_d	Day-ahead energy price ($)
$pr_{es,}$ pr_{pv}	Operational cost of ESS and PV, respectively ($)
pr_{sp}	Penalty cost for spilled PV energy ($)
pr_{lc}^{is}, pr_{lc}^{cc}	Penalty cost for load curtailment during islanding and due to capacity constraints, respectively ($)

3.2. Introduction

Ongoing changes in power system structure and operational requirements due to rapid increase of intermittent renewable energy are causing increasing challenges in system planning and operation while maintaining acceptable service reliability. Energy storage systems (ESS) are perceived as potential solutions to address system reliability issues, and to enhance renewable energy utilization. ESS and distribution generation (DG) are useful distributed energy resources (DERs) available to the distribution system operator (DSO) that provide alternative to traditional network capacity enhancement, as well as contribute to outage mitigation, losses reduction, and voltage and frequency support.

The benefits to DSO by the integration of DERs into its network depend on the ownership of these resources, market structure, and the regulatory framework. For the DSO-owned DERs, the benefits from utilization of renewable energy, reduced energy purchase cost, and enhanced supply reliability are well recognized [1], [2]. The DERs can be utilized to provide supply capacity during network constraints, which might provide significant economic benefits to the DSO due to the deferral of network expansion [1]. In addition, the DERs can operate microgrids in islanded mode during the utility supply interruptions utilizing smart control and communication facilities. Electric power utilities in some jurisdictions are not allowed to own DERs [2], [3]. The lack of appropriate market structure, regulations, and the effective coordination between DSO and the private investors, in such scenario, can result in inefficient system planning and operation [2].

The electric distribution companies, under deregulated environment, are regulated because of their natural monopoly status. Many jurisdictions around the world are shifting towards the implementation of incentive/performance-based regulation (PBR) from the traditional rate-of-return/cost of service regime [4], [5] to encourage the utilities to achieve economic efficiency gain in the competitive market environment. In order to ensure that the quality of electric supply doesn’t deteriorate while utilities strive to achieve economic incentives under PBR, regulators set the reliability standards that the utilities are obligated to comply. In this context, a reward/penalty structure (RPS), formulated based on the DSO’s reliability performance, is often incorporated in PBR [4], [5] along with other incentive mechanism related to network losses and efficient utilization of network assets. The RPS design affects the DSO’s financial risk and incentive to invest in reliability. The DERs have the potential to lower such financial risks with the accrued reliability benefit associated with their operations [6].

Various literature centered on the reliability and economics associated with the deployment of ESS and DG in distribution systems are available. The work in [1] explores multiple uses of ESS at different levels of a power system and their economic aspects. The current status of deployment of distributed resources and the impact of regulatory structures on the DSO's incentive to integrate DERs into their systems are discussed in [6], [7]. References [8], [9] have proposed market structures to facilitate the utilization of DERs as an alternative to traditional network expansion. A model predictive control based ESS scheduling strategy for a distribution system load aggregator and its impact on the system reliability is presented in [10] using a sequential Monte Carlo simulation (MCS). A stochastic framework is proposed in [11] for the optimal scheduling of storage considering normal operation cost and the cost of load curtailment during contingencies in the microgrid context. In [12] an MCS based approach is proposed to investigate the impact of coordinated outage management strategies on the system reliability for a distribution system with multiple microgrids. Authors in [13] have developed a probabilistic method to determine the size of storage to defer the network expansions combining the peak shaving application of ESS and the real-time thermal rating of feeders. However, the works presented in [10]-[13] don't address the impact of different scenarios of ownership and markets, which significantly affect the reliability contribution of ESS.

Literature reviews suggest that the regulatory framework and market structures largely influence the intention of investor or DSO in the deployment of DERs. This, not only influence the financial and operational structures of DSO, but also ultimately affect the reliability of supply experienced by customers, and the associated societal cost. The current state of research indicates the need for readily applicable methodologies that systematically incorporate the major factors determining the reliability value of the ESS such as ESS characteristics, ownerships, market mechanism and regulatory structures.

This paper presents a new probabilistic model of ESS that efficiently integrates the component availability as well as the operating strategies to assess the reliability value to distribution systems including active systems and microgrids. The developed model formulates the operating strategies for investor-owned and DSO-owned ESS utilizing mixed integer linear programming (MILP). The formulations for DSO-owned ESS operation acknowledge the flexibility of DSO to utilize the ESS during the network constraints in addition to participating in the upstream market. The proposed investor-owned ESS operation model is formulated with market scenarios to examine the prospect of offering distribution grid capacity services to the DSO besides the upstream market participation. Furthermore, the islanded operation of ESS in microgrids during utility supply interruptions are incorporated in the presented model to explore the role of ESS in supply recovery. The benefit of ESS in terms of network expansion deferral and the reduced financial risk under quality regulations are assessed for the DSO-owned storage. The possibility of investor-owned ESS to offer the distribution grid capacity services and the supply recovery services are evaluated. The paper presents case studies and discussions to provide valuable insights in estimating the reliability value of ESS as the policies regarding the market participation of ESS integrated into the distribution network are not yet fully developed.

3.3. Proposed Probabilistic Model of ESS

This section develops the proposed probabilistic reliability model of ESS to investigate the reliability value to the distribution network. The proposed ESS model shown in Figure 3.1 consists of Markov based component availability model and the MILP based formulations of operating strategies. The ESS model is integrated into a sequential MCS based simulation framework to quantify the reliability value. The DG, load, and other major elements of distribution network are incorporated in the reliability assessment framework. The developed model is focused on battery energy storage systems (BESS), since these are the most common ESS technologies used in a wide range of distribution system applications including electric energy time shifting and supply capacity [1], [14].

3.3.1. Markov Based Component Reliability Model of ESS

A BESS mainly consists of a number of battery energy storage units (BES) managed by a battery management and control system. A transformer connects the BESS to the utility grid. Each BES unit consists of a battery string composed of a number of battery modules and a power conversion system (PCS) that consists of dc-link capacitor, DC-DC converter (if required), and AC/DC converter comprised of diodes and IGBTs/MOSFETs. A reliability network diagram of a reconfigurable BESS is shown in Figure 3.2. One of the major advantages of such configuration in contrast to a classical BESS topology, where all the battery modules share a single PCS, is that the BESS can operate in a derated state. The times to failure and repair for a battery module and the components of PCS are assumed to follow an exponential distribution in this work.

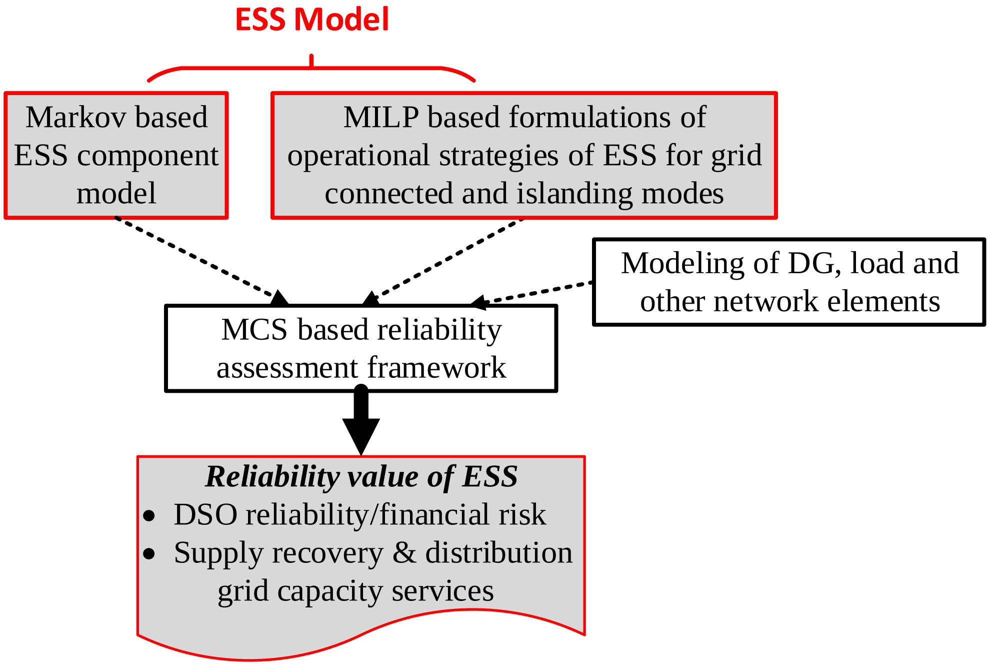

Figure 3.1. Proposed ESS model and its integration into a MCS framework.

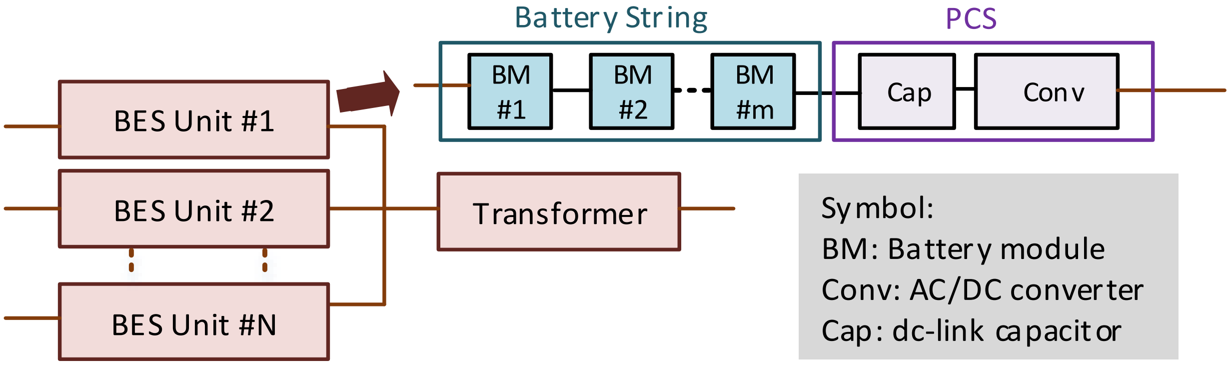

Figure 3.2. Reliability network diagram of a reconfigurable BESS.

The failure rate of the BES unit can be represented by (3.1), and the mean time to repair can be obtained by (3.2) or from the collected performance data of the BESS system. In the study, a 6-bridge AC/DC converter is considered, and the failure rates of associated components are extracted from [15], whereas the mean time to repair is assumed to be 60 hours. The approximate failure and repair data for a battery module is taken from [16].

$$\lambda_{BES\,Unit} = \lambda_{BS} + \lambda_{cap} + 6\,(\lambda_{diode} + \lambda_{IGBT}) \tag{3.1}$$

$$r_{BES\,Unit} = \sum_{c=1}^{c=\mathrm{Nc}} \lambda_c \times r_c \Big/ \lambda_{BES\,Unit} \tag{3.2}$$

Where, $\lambda_{BES\,Unit}$, λ_{BS}, λ_{cap}, λ_{diode} and λ_{IGBT} respectively denote the failure rates of a BES Unit, battery string, dc-link capacitor, diode, and IGBT; λ_c and r_c respectively represent the failure rate and the mean time to repair associated with c^{th} component of a BES unit; Nc denotes the total number of components of a BES unit.

The *N* number of BES units shown in Figure 3.2 can reside in *N+1* capacity states as described by a Binomial distribution, where the rate transition matrix for the system configuration is represented by (3.3), and capacity of the j^{th} state is given by (3.4).

$$T = \begin{bmatrix} t_{11} & .. & t_{1j} & .. & t_{1(N+1)} \\ .. & .. & .. & .. & .. \\ t_{i1} & .. & t_{ij} & .. & t_{i(N+1)} \\ .. & .. & .. & .. & .. \\ t_{(N+1)1} & .. & t_{(N+1)j} & .. & t_{(N+1)(N+1)} \end{bmatrix} \tag{3.3}$$

$$C_j = (N + 1 - j) \times Cap_{BESS} \qquad ; \forall\, j\, \epsilon\, 1\ to\ N + 1 \tag{3.4}$$

Where, t_{ij} denotes the transition rate from the ‘i’ to ‘j’ capacity state of the BESS system, and can be obtained from (3.5). In (3.5), λ_+ and λ_- respectively represent the failure rate and repair rate of a BES Unit, whereas Cap_{BESS} denote the capacity of a BESS system. The 2-state Markov model of the transformer is combined with the BESS component reliability model to obtain the overall ESS model that can be integrated with the system.

$$t_{ij} = \begin{cases} (N + 1 - j) \times \lambda_+ & ; j = i + 1 \\ (j - 1) \times \lambda_- & ; j = i - 1 \\ -\sum_{\substack{j=1 \\ j \neq i}}^{j=\mathrm{N}+1} t_{ij} & ; j = i \\ 0 & ; otherwise \end{cases} \qquad ; \forall\, i, j\, \epsilon\, 1\ to\ N + 1 \tag{3.5}$$

3.3.2. MILP based Modeling of Operating Strategies of ESS

This work considers a distribution network operated and owned by the DSO under competitive electricity market environment. The system includes PV arrays as renewable DG that is paid based on its output under a standard fixed rate [17]. The DSO is responsible for system maintenance, upgrade, and serving the customers with reliable power supply. The DSO tends to maximize the benefits by minimizing the total operational cost exploiting the flexibility introduced by the ESS operation while satisfying the operation constraints.

The DSO considers an operational horizon of 24-hours in a day-ahead market. The inputs at this stage are the forecast energy price, load and DG outputs, and substation limits. A 10-year historic price of Alberta Electric System Operator is used [18]. The forecast error is neglected, and the real-time operation is not considered in this study. It should be noted that the feeder capacity limitation is not taken into account, while only active power flows are considered in the study. The following 2 sub-sections (3.3.2.1 and 3.3.2.2) present the problem formulations for DSO-owned and investor-owned storage in grid connected operation.

3.3.2.1. Problem Formulation for DSO-owned Storage

The DSO can optimize its purchase from the upstream grid with proper scheduling of the ESS at its disposal. The ESS is assumed to be a price taker. The DSO can buy and store energy during off-peak periods and discharge ESS when the price of energy is high. The DSO can benefit from releasing energy from ESS during the period of upstream system peak, i.e. supply capacity hours [1]. It is assumed that the DSO will dispatch the ESS to provide the contracted capacity with the transmission system operator (TSO) during supply capacity hours of a day to participate in the capacity market. Use of ESS in such a way helps to improve the reliability of the upstream bulk system as well.

The objective function for the DSO with ESS is formulated as shown in (3.6). It presents the MILP model that co-optimizes the multiple application of storage, i.e. distribution system deferral, supply capacity, energy arbitrage, with the storage dispatch priorities set in respective order.

$$\textbf{Min.}\ \sum_{i=1}^{i=24} P(i)\, pr_d(i) + P_{ch/dis}(i)\ pr_{es} + P_{pv}(\mathrm{i})\, pr_{pv} + LC_{cc}(i)\, pr_{lc}^{cc} + SC_d^{TSO}(i)\, pr_{sc}^{TSO} \tag{3.6}$$

The objective function in (3.6) is subjected to the following constraints described in (3.7)-(3.9) that guarantee the total power purchased from the bulk system is adequate to serve the load demand, and the limit of the substation transformer connecting the DSO to the bulk system is not violated.

$$P(i) - P_{ch}(i) + P_{dis}(i) + P_{pv}(i) + LC_{cc}(i) = L(i) \tag{3.7}$$

$$P(i) \leq P_s \tag{3.8}$$

$$SC_d^{TSO}(i) = \left|P_{SC}^{TSO}(i) - P_{dis}(i)\right| \quad ;\forall\, i \in hr_{sc}^{TSO} \tag{3.9}$$

$$SOC(\mathrm{i}) = SOC(\mathrm{i}-1) + n_c\, P_{ch}\,(\mathrm{i}) - \frac{P_{dis}(i)}{n_d} \tag{3.10}$$

$$SOC_{min} \leq SOC(i) \leq SOC_{max} \tag{3.11}$$

$$\gamma_{ch}(i)\, P_{ch.min}^{ES} \leq P_{ch}(i) \leq \gamma_{ch}(i)\, P_{ch,max}^{ES} \tag{3.12}$$

$$\gamma_{dis}(i)\, P_{dis,min}^{ES} \leq P_{dis}(i) \leq \gamma_{dis}(i)\, P_{dis,max}^{ES} \tag{3.13}$$

$$\gamma_{ch}(i) + \gamma_{dis}(i) \leq 1 \tag{3.14}$$

$$\sum_{i=1}^{i=24} P_{dis}(i) \ \leq \pi_{dis}(SOC_{max} - SOC_{min}) \tag{3.15}$$

Where, hr_{sc}^{TSO} is the set of TSO supply capacity hours.

The battery degradation is an important aspect to be considered while formulating the battery scheduling. The degradation consists of both calendar and cycle degradation. The calendar degradation mostly depends on the state of charge (SOC), ambient temperature and charge time whereas the depth of discharge, charge/discharge rate, and cycle numbers affect the cycle degradation [19]. The charge/discharge rate, minimum/maximum SOC allowed can be regulated with (3.11) -(3.14), whereas the number of discharge cycles (π_{dis}) is adjusted with (3.15) to extend the lifetime of BESS [19], [20].

3.3.2.2. Problem Formulation for Investor-owned Storage

Two market scenarios are considered for investor-owned storage in this paper as described below.

a) ***Market Scenario #1:*** ESS without Distribution Grid Capacity Service: This scenario considers the business transaction between TSO and the storage only. The ESS can participate in energy as well as capacity market of the TSO. The ESS owner pays the interconnection fee and charging price to the DSO that provides access for the ESS operation. Based on the forecast day-ahead price and its commitment towards capacity market, the investor determines the day-ahead scheduling of ESS and informs the DSO, which will make the necessary purchase from the upstream network considering ESS scheduling as well as the forecast PV output, network constraint, and system load demand. The objective function presented by (3.16) shows the MILP formulation to maximize the total revenue from energy arbitrage and capacity market. In this scheduling problem, the constraints represented by (3.9)-(3.15) should hold for all hours.

$$\textbf{Max}.\ \sum_{i=1}^{i=24} P_{ES}(i)\, pr_d(i) - P_{ch/dis}(i)\, pr_{es} - SC_d^{TSO}(i)\, pr_{sc}^{TSO} \tag{3.16}$$

b) **Market Scenario #2:** ESS with Distribution Grid Capacity Service: This scenario considers active co-ordination between ESS and DSO. The storage can participate in DSO service in addition to its participation in the TSO market. The storage provides capacity to the DSO when the DSO load exceeds its substation capacity as part of distribution grid capacity services. The objective function formulated as given by (3.17)-(3.18) co-optimizes the use of storage for TSO and DSO services. The constraints represented by (3.9)-(3.15) hold for all times in this scheduling problem.

$$\textbf{Max}.\ \sum_{i=1}^{i=24} P_{ES}(i)\, pr_d(i) - P_{ch/dis}(i)\ pr_{es} - SC_d^{TSO}(i)\, pr_{sc}^{TSO} - SC_d^{DSO}(i)\, pr_{sc}^{DSO} \tag{3.17}$$

$$SC_d^{DSO}(i) = \left|P_{SC}^{DSO}(i) - P_{dis}(i)\right| \quad ; \forall\ i\ \in\ hr_{sc}^{DSO} \tag{3.18}$$

Where, hr_{sc}^{DSO} is the set of DSO supply capacity hours.

3.3.3. Problem Formulation for Islanded Operation of ESS

In a DERs integrated system, the ESS and DG can provide power in islanded mode for a certain group of customers during utility power interruptions. To incorporate such islanded operation of DERs an optimization problem given by (3.19) and (3.20) is formulated, where minimizing load curtailment is the objective. The load is supplied utilizing the energy from PV, and the extra energy, if available, is stored in ESS. If PV alone cannot serve the load, the energy stored in ESS is discharged to minimize load curtailment. The ESS operates within the constraints given by (3.10) -(3.14). The priority for the load points inside the islanded network can also be set while solving this optimization problem if needed.

$$\mathbf{Min.}\quad \sum PV_{sp}\,(i)\,pr_{sp} + LC_{is}(i)\,pr_{lc}^{is} \tag{3.19}$$

$$P_{dis}(i) - P_{ch}(i) + LC_{is}(i) + P_{pv}(i) - PV_{sp}\,(i) = L_{is}(i) \tag{3.20}$$

3.4. Reliability Value Assessment Framework

The ESS reliability model should incorporate its inter-temporal and energy limitation characteristic while operating at the different modes in correlation with the fluctuating nature of renewable DG output, time-dependent load variation, and other system variables. In addition, the probability distribution of reliability indices are required for the accurate estimation of financial risk under RPS. Hence, a sequential MCS approach is used to incorporate these factors in the reliability value assessment of ESS.

The ESS helps recover the supply for a certain group of customers with its islanding operation during utility supply interruptions. However, whether the ESS can form an island during the network element failures depend on the protection arrangements of the network. The components of a distribution network can be grouped under various segments [10]. Such segmentation is based on the protection device setting, i.e. any component failures inside the segment causes the same set of protection device(s) to operate. For example, all the components between circuit breakers C1 and C2 in Figure 3.3 belong to the same segment (Seg 1). The failure and repair rates of segments can be obtained from the corresponding data of its constituent components utilizing the series equivalent reliability concept [21].

Based on the location of failures, and the availability of DERs, a segment can reside in one of the following three states.

Grid connected mode: The Segment is supplied with the main utility supply.

Failed: If the failure occurs in the segment itself, its load points can not be restored with the main supply or DERs.

Islanded mode: After the failure occurs in the upstream segments, it is possible for the downstream segments with DERs to operate under islanded mode for supply recovery. For instance, segment 3 can be restored with PV and for any failure in segment 2.

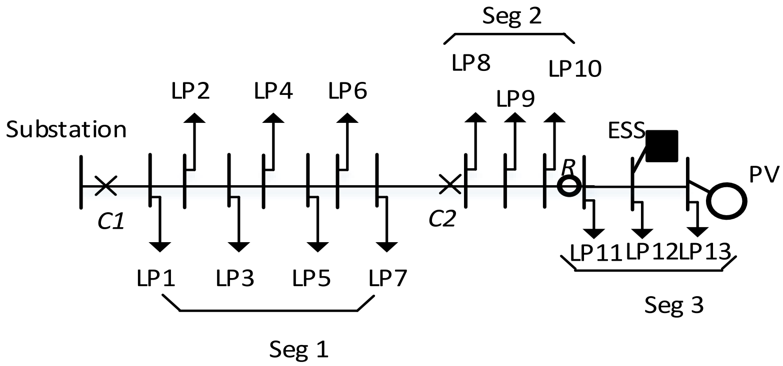

Figure 3.3. Components/segments of a distribution network.

The times to failure, repair and switching intervals associated with each component are assumed to follow an exponential distribution. The failure of protective equipment is neglected in this study. A synthetic set of data using time series approaches, or historical data on solar irradiation can be used to obtain the reliability model of PV [22]. This study uses a set of synthetic hourly solar irradiation data for a site in Swift Current, Saskatchewan, generated using the WATGEN [23] software developed by the WATSUN Simulation Laboratory. The hourly irradiation data is then converted into respective power using analytical set of equations [22]. The time varying load for the different group of customers were obtained from [24].

The steps utilized in evaluating the reliability indices using the proposed MCS approach are summarized in Figure 3.4. For any given day, a day-ahead optimization problem is executed using the operating strategies formulated in Section 3.3.2. This provides the hourly SOC profile of ESS. Note that, the SOC profile of ESS are updated considering its up/down status generated using the component reliability model developed in Section 3.3.1. The contingency is considered to occur whenever there is a network capacity constraints condition, or failures of network elements. This enables the assessment of role of ESS to provide the grid capacity services in addition to the supply recovery services due to network component failures.

For the contingency that arises from the failure of the network elements, possibility of ESS to be operated under islanded mode is examined. If the islanding operation is possible, the optimization problem formulated in Section 3.3.3 is executed. The initial SOC of ESS at the beginning of islanding is obtained from the hourly SOC profile of the ESS, which is the result of day-ahead optimization problem. The problem formulated for islanding operation is run for each hour of contingency, and the SOC is updated accordingly. The load points that are not being supplied, and the corresponding energy curtailed are tracked in time sequence. Utilizing this information on load points interrupted, the load point/system indices are obtained [21].

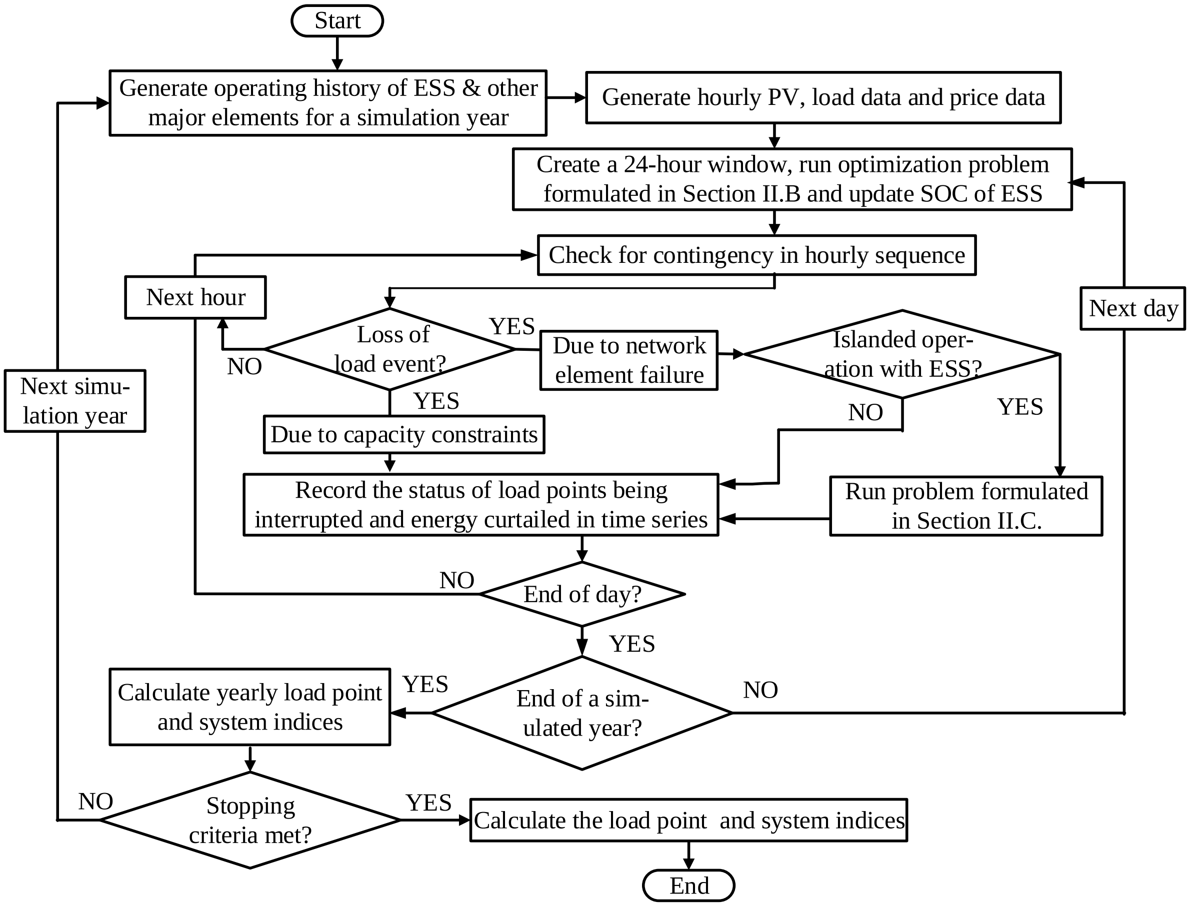

Figure 3.4. Flowchart to evaluate reliability using Monte Carlo Simulation.

The load point reliability is quantified by three basic indices: the failure frequency, the average outage duration, and the unavailability. The system average interruption frequency index (SAIFI), system average interruption duration index (SAIDI), expected energy not supplied (EENS) are used as the reliability system indices [21] in the study. The reliability worth to the customers are the evaluated with expected cost of interruption (ECOST) [25]. For the stopping criteria mentioned in the algorithm, either a large number of simulation years or a required coefficient of variation for a certain reliability index can be used [21].

3.4.1. Assessment of Supply Recovery Services of ESS

The strategically located ESS can be operated during the upstream segment failures to improve the reliability of customers located downstream of the network. For DSO-owned storage, this benefit is easily recognized [2] and reflected in the customer/system reliability indices. This paper explores the potential of investor-owned ESS to provide recovery of supply services during utility outages. This is examined by comparing the load point/system reliability indices for the cases with and without storage executing the algorithm shown in Figure 3.4. Section 3.5.2 illustrates the supply recovery services provided by the investor owned ESS, and factors affecting it.

3.4.2. Assessment of Distribution Grid Capacity Services of ESS

The DSO-owned ESS is scheduled considering the network constraints. However, the investor-owned ESS are mostly scheduled without taking the network condition into consideration, which makes it difficult for the DSO to count on them to provide the capacity support needed for network expansion deferral. In this context, the prospect of investor-owned ESS to provide the distribution grid capacity services is assessed using the system reliability indices obtained from the algorithm presented in Figure 3.4. For this purpose, the system reliability profile is analyzed for a multi-year planning horizon considering the load growth. The different market scenarios as described in Section 3.3.2.2 for investor-owned storage are simulated and the corresponding system indices are noted. With the reliability indices for multiyear planning horizon, thus obtained, the potential of ESS for the T&D expansion deferral can be analyzed. Section 3.5.3 presents the results and discussions on this aspect of ESS.

3.4.3. Assessment of DSO's financial risk under RPS based PBR

Figure 3.5 shows a general representation of RPS [4], [5]. The utilities are neither rewarded nor penalized if their service reliability falls in the dead zone. The dead zone, the penalty and reward points are set by the regulator considering the mix of customers served, geography, historic performance of the DSO, etc. The dead zone width is set as a certain parentage of a target reliability level, or a certain portion of standard deviation of such index. The DSO is rewarded/penalized if its reliability index is less/greater than the reward/penalty point as shown in Figure 3.5. The reward as well as the penalty are capped at a certain maximum value to deal with the financial risk and uncertainty associated with DSO. Usually, the maximum reward or penalty, RP_{max}, doesn't exceed 10 % of utility's revenue [4].

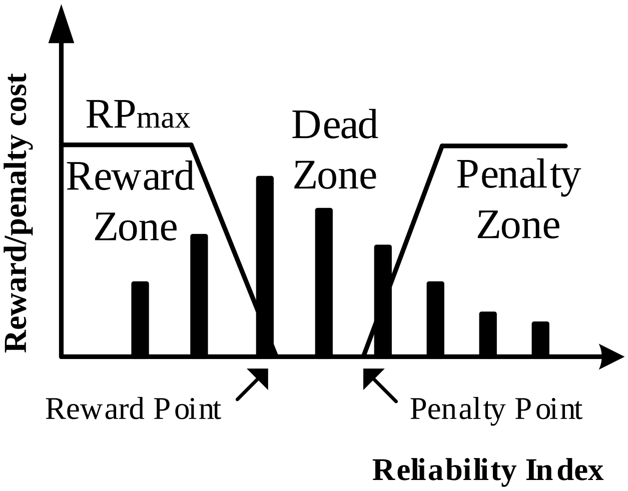

Figure 3.5. General representation of RPS under PBR.

The Expected Reward/Penalty (ERP), can be evaluated by integrating the probability distribution of reliability index into the RPS formulations given in (3.21) - (3.22). The probability distribution of the reliability index is obtained utilizing the data of yearly system indices (see algorithm in Figure 3.4. Multiple reliability indices, as felt necessary by the regulator to represent the actual reliability issues experienced by the customers, can be incorporated in such calculation by weighting the corresponding ERPs with appropriate factors [4]. The reliability/financial risk performance of the DSO with ESS operations under RPS based regulations are presented in Section 3.5.1.

$$ERP = \sum_j \sum_k RP_{j,k} \times P_{j,k} \times \alpha_j \tag{3.21}$$

$$0 \leq RP_{j,k} \leq RP_{max} \tag{3.22}$$

Where, $RP_{j,k}$ denotes reward/penalty for the j^{th} reliability index with a certain value and the probability of occurrence $P_{j,k}$; α_j represents the corresponding weighting factor of the reliability index.

3.5. Case Studies and Results

The methodology developed in this paper is implemented in a MATLAB 2017a using the 'intlinprog' solver, and a range of case studies are performed on a test system shown in Figure 3.6. The test distribution system is a modified version of Feeder 4 at Bus 6 of the Roy Billinton Test System [25]. The details of the load points used in the study are shown in Table 3.1. An ESS and a set of PV arrays are integrated in Segment 4 and 5 as shown. A recloser "R" allows the ESS, PV and Segment 4 and 5 loads, to operate in an islanded mode in case of a fault at upstream feeder sections.

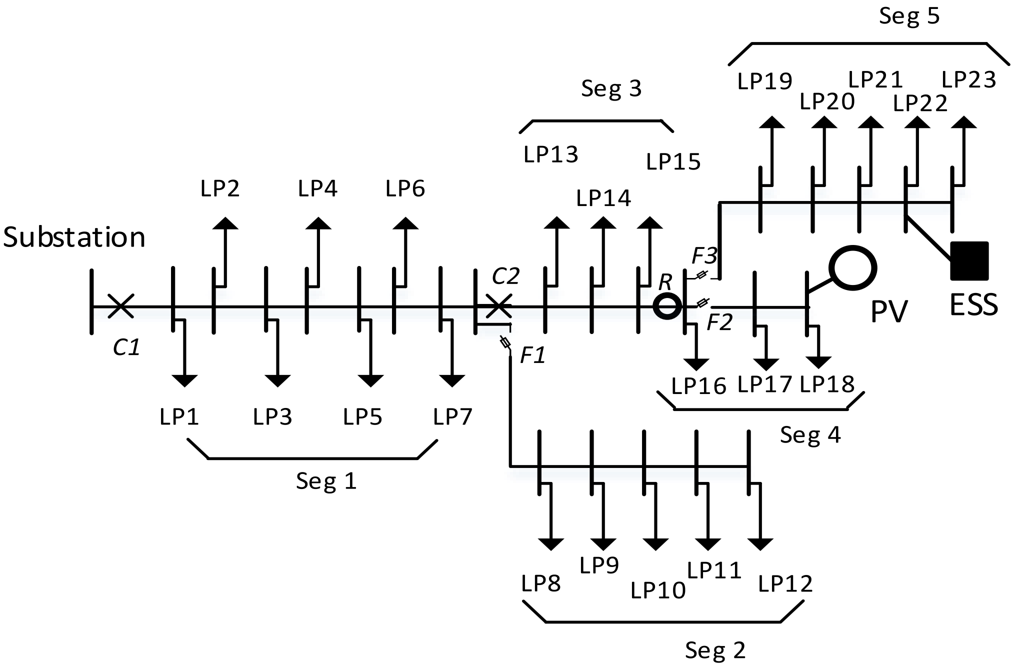

Figure 3.6. Test distribution system under study.

The circuit breaker and the fuse are indexed with “C” and “F” respectively in Figure 3.6. The failure rate and repair time for the lines are 0.046 occ/yr-km and 5 hr, respectively [25]. The failures of the lateral and the load point transformer are not taken into consideration. The utility supply that includes the substation and the upstream grid is assumed to have a failure rate of 0.1 occ/yr and a repair time of 5 hour. The operational cost associated with PV and ESS are neglected in the case studies [11]. The value of π_{dis} used in (3.21) is set to be 2 for the grid connected operation of ESS.

Table 3.1. Load point details for test system.

Load points	**Category**	**# of Customer**	**Peak load per load point(MW)**
LP1, LP2, LP5, LP6, LP8, LP10, LP14, LP16, LP19, LP22	Residential	79	0.27
LP3, LP4, LP7, LP9, LP11-LP13, LP15, LP17, LP18, LP23	Farm	1	0.5
LP20, LP21	Small Industrial	1	0.85

3.5.1. Reliability/Financial Risk Performance of DSO with ESS

This section first assesses the impact of DSO-owned ESS on the load point and system reliability indices with its islanded operation. The financial risk of DSO under RPS based PBR is also reported. A sodium sulfur based BESS rated at 4 MW and 28 MWhr with topology as shown in Figure 3.2, and having charging/discharging efficiency of 90%, minimum SOC limit of 10 % is used. The PV rated at 2 MW is considered for the study.

Table 3.2 presents the load point reliability indices before integration of ESS and PV (Base Case), and after the integration of BESS and PV (With DERs). After addition of ESS and PV, the reliability of Segment 4 and 5 load points, LP17 and LP21 is observed to be enhanced as the failure frequency, unavailability and EENS associated with them significantly decrease. This is due to the recovery of supply to these load points from the islanded operation of ESS in case of a fault at upstream feeder sections. The reliability enhancement due to the addition of ESS, however, is highly dependent on its operation strategy, component availability, and capacity/ power rating etc. The industrial customers are given the priority over other load points in this study during islanded operation.

Table 3.3 shows that the improved level of reliability in segment 4 and 5 due to islanded operation of ESS is well reflected in customer-based system indices SAIFI and SAIDI as well. However, it should be noted that it depends on the customer-mix, network topologies and the portion of the network that is benefited from the islanded operation of ESS.

The financial risk of the DSO with ESS operation is examined with two cases. The target values of SAIFI and SAIDI for the first case are taken to be 0.4 occ/cust- yr and 1.5 hr/cust-yr, respectively. Case II considers the target value of SAIFI and SAIDI as 0.8 occ/cust-yr and 3 hr/cust-yr, respectively. The ERP costs are calculated with α =0.5 (in (3.21)) and the maximum value of reward/penalty is assigned as RP_{max}. The dead bandwidth of 20% of target value is considered. Table 3.3 shows the RPS cost for these two cases. It results indicate that the integration of ESS and DGs contributes towards lowering the financial risks under RPS set by the regulators. The incremental benefit, however, depends on various factors, such as the target level of reliability, reliability indices used, width of dead zone set, reward/penalty maximum cost set by the regulator, the ESS/DG characteristics, network topologies and the recovered portion of the network with islanding etc.

Table 3.2. Load point reliability indices.

Load Point	Failure Frequency (occ/yr)		Unavailability (hr/yr)		EENS (MWhr/yr)	
	Base Case	**With DERs**	**Base Case**	**With DERs**	**Base Case**	**With DERs**
LP8	1.289	1.289	6.532	6.532	0.990	0.990
LP17	1.560	0.991	7.989	5.258	1.518	0.858
LP21	1.783	1.167	9.003	5.790	6.374	3.965

Table 3.3. System reliability indices and financial risk.

Cases	SAIFI (occ/cust-yr)	SAIDI (hr/cust-yr)	ECOST (k$/yr)	Penalty cost Case I (% of RP_{max})	Reward cost Case II (% of RP_{max})
Without DERs	1.158	5.881	113.3	22.22	30.99
With DERs	0.989	5.074	77.72	10.08	45.31

3.5.2. Supply Recovery Services of ESS

This section explores the role of investor-owned storage in recovering supply to the customers during utility supply interruptions. If the DSO would coordinate with the investor for the islanded operation with ESS during outage events, customers located at the healthy part of the network can be restored with the supply. Table 3.4 shows the result of the improvement in the customer reliability with islanded operation of 4 MW/28 MWhr ESS (located in segment 5 of Figure 3.6). Note that both scenarios formulated in Section 3.3.2.2 provide the same result for this case study, since it is performed for the base year (without any capacity constraints on substation transformer). As the islanding operation of ESS serves the customers located at segment 4 and 5, the customers located in this part of the network experiences lesser number and duration of outages.

The utilization of storage for the supply recovery services reduces the financial losses incurred to the customers. The appropriate co-ordination between DSO and the investor on the use of ESS for supply recovery services could be an alternative to alternate feeder, or the other means of system upgrade requirements to improve the reliability level of the valuable customers. It should be noted that the location, sizing and the operating strategy are important factors that determine the effectiveness of ESS for such application. The DSO could negotiate with the storage owner to locate ESS in such a location where it could supply the certain group of valuable customers in case of utility supply interruption. The investor can be remunerated based on its contribution towards mitigating reliability issues of its customers. The recognition of the contribution made by the investor-owned storage in outage mitigation and improving the customer reliability is crucial to encourage the efficient utilization of resources.

Table 3.4. Supply recovery services with ESS (for segment 4-5).

	Δ SAIFI (%)	**Δ SAIDI (%)**	**Δ ECOST (%)**
Segment 4-5	29.61	28.33	31.29

3.5.3. Distribution Grid Capacity Services of ESS

In this section, the prospect of investor-owned ESS to contribute towards the distribution grid capacity enhancement, thus providing an alternative to the traditional system expansion is assessed. A 5-year planning horizon, with a homothetic load growth of 4.5 %, substation transformer thermal limit of 10 MW, and BESS rated at 2 MW & 14 MWhr is considered for this purpose. The different market scenarios for investor-owned storage are explored and its impacts on the system reliability performance are analyzed.

Figure 3.7. shows the reliability performance of DSO for different years of planning horizon for the case of DSO-owned and investor-owned storage. Two different market scenarios (Sc#1 and Sc#2) are considered for investor-owned storage as discussed in Section 3.3.2.2. For market scenario#1, where ESS owners schedules ESS based on its participation in TSO market, the EENS values for year 3 onwards are significantly higher than that of base year (year 0). Therefore, the DSO can't rely on ESS for the capacity contribution during its system peak. However, it should be noted that this result is highly dependent on the correlation between upstream system peak and the DSO peak, as well as the correlation between high day-ahead price period and the DSO peak. It follows that the DSO would have to invest on substation transformer upgrade immediately to keep the reliability at an acceptable level. Whereas if the ESS scheduling is performed for the TSO services as well as for DSO services, i.e. market scenario #2, then the system reliability in the future years of planning horizon remains within the range of base year as can be seen from the trend of EENS in Figure 3.7. Thus, the results show the effectiveness of the distribution grid capacity services provided by the ESS, allowing the DSO to defer the network reinforcements. Results in Figure 3.7 shows that the system reliability for planning horizon considered with DSO-owned and investor-owned storage (operating in market scenario #2) are similar. It is because the scheduling of DSO-owned storage (described in Section 3.3.2.1) is formulated to discharge it during capacity constraints hours. The deferral years depend on the storage technologies, rated power, and energy capacity, as well as the feeder ampacity limitation, etc.

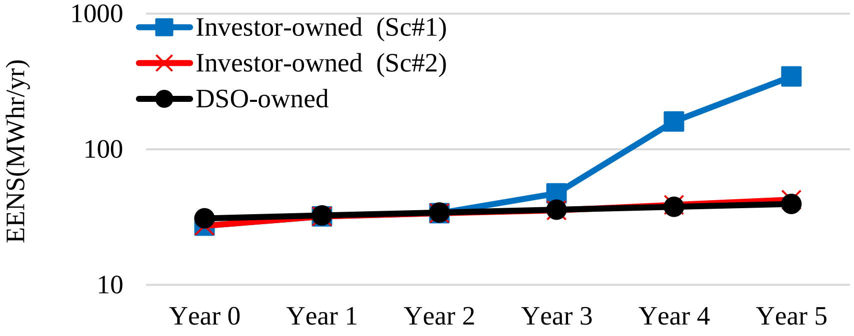

Figure 3.7. System reliability performance for a planning horizon.

For the DSO to count on the distribution grid capacity services of ESS, it can formulate a contract with the ESS few years ahead of actual load growth. It can reserve the capacity needed in planning stage, and request for the dispatch of ESS during interval of network constraints in operation stage. The ESS should be remunerated for its contribution towards the deferral of capacity addition to encourage the participation of resource developers in distribution system level, and to help formulate efficient network expansion policy in presence of storage. Moreover, the regulator should include an incentive scheme to recognize the DSO's attempts towards the efficient utilization of DERs. The regulatory framework should be set to penalize the DERs that cannot deliver the committed capacity supply to the DSO, either due to delay in project completion, or its involvement in other services, or component failure during such periods, as it has significant impact on system reliability.

3.6. Conclusion

This paper presents a generalized approach to evaluate the reliability value of ESS in the context of active distribution systems considering different scenarios of ownership, market and regulatory structures, and ESS characteristics. A new probabilistic reliability model of ESS is developed, and it is integrated into the sequential MCS framework to assess the reliability value. The developed ESS model consists of Markov based component model, and the MILP based formulation of operating strategies. The formulated operation strategies incorporate different scenarios of ownership, market structures, and the ESS characteristics. The reliability/financial risk performance of the Distribution System Operator (DSO) with ESS under quality regulations are quantified. Furthermore, the developed ESS model is utilized to explore the prospect of investor-owned ESS providing supply recovery and distribution grid capacity services to the DSO. The study results show that strategic deployment of ESS in distribution system helps improve the reliability of the worse performing section and the overall system lowering the financial risk of DSO under RPS based PBR. It also reveals that the effective co-ordination between DSO and the ESS owner can ensure that the ESS can offer reliability services to the DSO, e.g. supply recovery to valuable customers during utility interruptions, distribution grid capacity enhancement. The reliability services provided by the ESS should be evaluated recognizing pertinent regulatory framework and market structures in order to efficiently exploit ESS and achieve the socioeconomically optimal level of reliability. The methodology developed in this work can be used to derive quantitative indicators to assess market mechanism, policy and regulatory implications regarding ESS in future distribution system operation and planning.

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CHAPTER 4: GRAPH THEORY EMBEDDED AGGREGATED RELIABILITY EVENT MODELING FOR MODERN DISTRIBUTION SYSTEMS [1]

4.1. Abstract

The random failures in a distribution network lead to different reliability events, such as voltage sag, momentary and sustained interruptions. Even short duration reliability events i.e., voltage sag and momentary interruptions cause significant financial losses to many customers. This paper presents a novel *graph theory embedded aggregated reliability event model* for the reliability studies of modern distribution systems incorporating the short duration reliability events in addition to sustained interruptions. The developed model examines the impacts of temporary and permanent failures on the customers considering different reliability events. A graph theory based search algorithm is utilized to efficiently recognize different protection settings, alternate supplies, and presence of Distributed Energy Resources (DERs)/microgrids in the network. Furthermore, the proposed model efficiently incorporates the possible mitigation measures brought by the DERs/microgrids while quantifying the reliability profile of load points and the overall system. The case studies conducted on a practical test system shows the effectiveness of the proposed model to evaluate the reliability and to carry out system upgrades in the context of smart distribution systems.

4.2. Nomenclature

l/L	Index of load point & Set of load points in a network.
N_l	Number of customers at load point l.
d, m	Index of DERs and microgrids, respectively.

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[1] **P. Gautam, P. Piya, and R. Karki, "Graph Theory Embedded Aggregated Reliability Event Modeling for Modern Distribution Systems," submitted to *IEEE Trans. on Power Syst.* (Under review).**

c^x	Index of contingency; x equals tm and pm for temporary and permanent failure, respectively.
RE	Reliability event; denotes sag $(DSE), MI$, and SI for voltage sag (disruptive sag event), momentary and sustained interruptions, respectively.
$f^{c,x}$	Rate of occurrence of contingency c^x (occ/yr).
$t_r^{c,pm}$	Repair time associated with c^{pm} (hr).
$PD_{cl}^{c,x}$	Protection device(s) operated in an attempt to clear c^x.
$L_{RE}^{c,x}$	Set of load points experiencing RE due to c^x.
$L'^{c,x}_{RE}$	Intermediate value of $L_{RE}^{c,x}$.
$L_m^{c,x}$	Set of load points capable of switching into isolated microgrid m during contingency c^x.
$L_d^{c,x}$	Set of load points capable of being supplied with DER d during contingency c^x.
$L_{Int,T}^{c,x}$	Set of load points interrupted for time T due to c^x.
$T_{l,SI}^{c,x}$	Interruption time for l experiencing SI due to c^x.
$T_{l,d}^{c,x}$	Interruption time for l restored with DER d during c^x.
$F_{l,RE}^{c,x}$	Frequency of occurrence of RE for l due to c^x(occ/yr).
$F'^{c,x}_{l,RE}$	Value of $F_{l,RE}^{c,x}$ without considering DERs/microgrids.
$U_{l,SI}^{c,x}$	Unavailability due to SI for l due to c^x (hr/yr).
$U'^{c,x}_{l,SI}$	Value of $U_{l,SI}^{c,x}$ without considering DERs/microgrids.
$D_{l,RE}^{c,x}$	Damage cost of RE for l due to c^x (hr/yr).
$P_{m,s}^{c,x}$	Probability of microgrid m to be successful during c^x.
$P_{d,s}^{c,x}$	Probability of DER d to be successful during c^x.
$F_{l,RE}$	Frequency of occurrence of RE for l (occ/yr).
$U_{l,SI}$	Unavailability of l due to SI (hr/yr).
F_{RE}	System frequency index of RE (occ/cust-yr).
U_{SI}	System index of outage duration of SI (hr/cust-yr).
$D_{l,RE}$	Damage cost due to RE for l (k\$/yr).
D_{RE}	System index of damage cost due to RE (k\$/yr).
$R_l(.)$	Load point reliability profile for l.
$R_S(.)$	System reliability profile.

4.3. Introduction

With the widespread use of sensitive digital and power electronic equipment such as adjustable speed drives, computers, automated manufacturing lines etc., the quality of supply is receiving increased attention in modern distribution systems. These devices are susceptible to mis-operation even with short duration reliability events, which include voltage sag and momentary interruptions. The financial losses of an industrial facility due to industrial process disruption or malfunction of equipment due to short duration reliability events could be substantial [1], [2]. The economic losses incurred to the commercial customers (banks, data centers, customer service centers, etc.) is also significant [1], [2]. It is, therefore, necessary to consider these short duration reliability events in the reliability studies. IEEE Std. 493 [3] also underlines the importance of incorporating voltage sag and momentary interruptions while performing the reliability evaluation for commercial/industrial customers.

The customers' concerns on the power quality/reliability issues play a significant role in a competitive electricity environment. Regulators are adopting reward penalty integrated performance based rates for investor-owned utilities to maintain a desired level of reliability. Public owned utilities (municipal, co-op owned, etc.) also take the customer level reliability into account while carrying out system upgrades. Mostly, the reliability indices used in the utility planning and regulatory compliance structure are based on the frequency and duration of sustained interruptions [1], [4]. Thus, there is no significant incentives for the utilities and system planners to invest in the reliability based upgrades to improve the short duration reliability performance. However, with the ongoing changes in distribution systems, the regulators and utilities are increasingly recognizing the voltage sag and momentary interruptions in addition to sustained interruptions- together termed as Reliability Events (RE) [1] - in the policy making and reliability planning [4].

The integration of Distributed Energy Resources (DERs) into distribution networks can provide solutions to various reliability events [5], [6], [7]. Reliability studies should recognize such possible mitigation measures. The microgrids, which consist of DERs and the controllable loads, are integrated at the point of common coupling (PCC) of the distribution network utilizing the control and communication facilities of smart grid [7], [8]. Such microgrids have the ability to switch into an isolated mode whenever it detects the fault in the upstream sections, thus providing solutions even for short duration reliability events [6], [8]. The DERs can also be integrated along the distribution feeder without the capability to form a microgrid but with the possibility of islanded operation during long duration utility supply interruptions [9]. This work incorporates such distinction while assessing the mitigation provided by the DERs/microgrids.

Significant work has been reported in assessing the equipment trips and the corresponding financial losses due to random network failures with major focus on voltage sag [10]-[14]. In [4], authors have proposed an incremental cost based approach to consider momentary interruptions for the reliability studies of radial distribution system. However, it lacks a general systematic approach to assess reliability considering different protection settings and network topologies. Analytical frameworks to evaluate reliability considering momentary interruptions for a radial distribution system are developed in [15], [16]. The impact of DERs/microgrids, however, cannot be investigated with these frameworks. References [7], [17], [18] have developed a set of analytical expressions to evaluate distribution system reliability considering DERs operation for a range of protection settings. These approaches, however, are applicable only for the sustained interruption resulting from permanent faults. The reliability of the distribution network incorporating voltage sag and momentary interruptions are assessed in [19], [20]. However, they are applicable only for the system without DERs/microgrids.

Literature reviews suggest that the short duration reliability events have significant impact on customer reliability and the associated financial losses. However, a systematic modeling of these events in addition to long duration reliability events is necessary to plan the system upgrades considering the reliability needs of customers. Moreover, such modeling should also incorporate possible mitigation measures brought by the DERs/microgrids and the impact of different protection settings for the comprehensive reliability assessment of modern distribution systems. In this context, this paper presents a novel *graph theory embedded aggregated reliability event model* to quantify the impact of various distribution system borne random failures on the customers. The developed model considers both short and long duration reliability events due to temporary and permanent failures. The model efficiently recognizes different protection settings, alternate supplies, and DERs/microgrids utilizing the graph theory based search algorithm. Moreover, the model incorporates the possible mitigation measures brought by the DERs/microgrids. The reliability at load point/customer and system level is quantified with the load point reliability profile and system reliability profile that consists of frequency/duration based metrics, as well as the associated damage cost for the short and long duration reliability events. The proposed framework can be utilized for the reliability assessment and planning system upgrades in the context of a utility-scale modern distribution systems.

4.4. Reliability Events in Power Distribution Systems

The utilities in a deregulated environment report their system performance to the regulators. There is, however, a substantial variation in current practices on the types of reliability events, and their definition considered in such reporting [1]. Generally, service interruptions for one to five minutes are classified under momentary interruptions. The discontinuity in supply beyond that interval is considered to be a sustained interruption. The definitions of sustained/momentary interruptions are not consistent in IEEE Std. 1366 [21] and IEEE Std. 1159 [22] as well. The following definitions of reliability events are adopted for the purpose of discussion in this paper:

1) **Voltage sag:** Upon occurrence of a fault in the network, the root mean square voltage magnitude drops below nominal voltage. However, the severity of voltage sag depends on the fault location, fault impedance, fault-clearing time, etc. The voltage sags caused by self-extinguishing faults, large motors starting or those transferred from transmission network are not considered in this work.
2) **Momentary interruption:** A brief loss of continuity of supply resulting from the opening and closing of a protective device for the duration of 1 min or less ($T_{MI} \leq 1$ min). The multiple interruptions caused by the recloser operating sequence is not considered; only the event of momentary interruption is reported.
3) **Sustained interruption:** Any interruption event, other than momentary interruption is considered as sustained interruption.

Depending on the nature of the contingency and the protection settings, different load points experience different reliability events. This paper considers all these reliability events, i.e. voltage sag, momentary interruptions, and sustained interruptions resulting from both temporary and permanent failures for the reliability assessment. Furthermore, a load point may encounter a situation where one reliability event evolves to another one due to the sequence of protection device operations, upon the occurrence of a contingency. For instance, a load point may experience a voltage sag for a brief period before momentary/sustained interruptions, or a momentary interruption before a sustained interruption. In these situations of evolving reliability events, the final reliability event due to a contingency is assigned to the load point. It ensures a better estimation of customer reliability profile and the associated financial losses.

4.5. Graph Representation of the Network

Analytical methods for distribution system reliability assessment based on network reduction method or the construction of state space diagrams cannot fully incorporate the complex protection and restoration strategies, and the impact of DERs/microgrids. Furthermore, deducing min cut sets based on continuity of supply to load points fail to consider the complex protection settings and voltage sag events. In this regard, a graph theory embedded aggregated reliability event model is developed in this paper to address those limitations. The general schematic of the proposed methodology is shown in Figure 4.1. The distribution network is modeled as a graph network. This graph network is an input to the developed model. This methodology develops the contingency model, simulates all the contingencies, assesses their impact on load points, and updates the contribution towards a particular reliability event for each load point. The output of this model is the load point (customer) and system reliability profile.

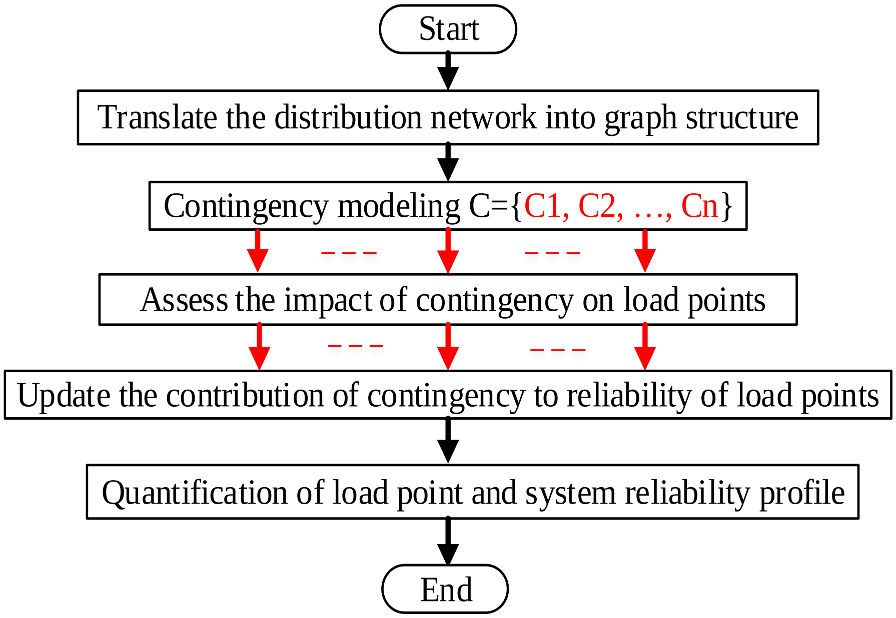
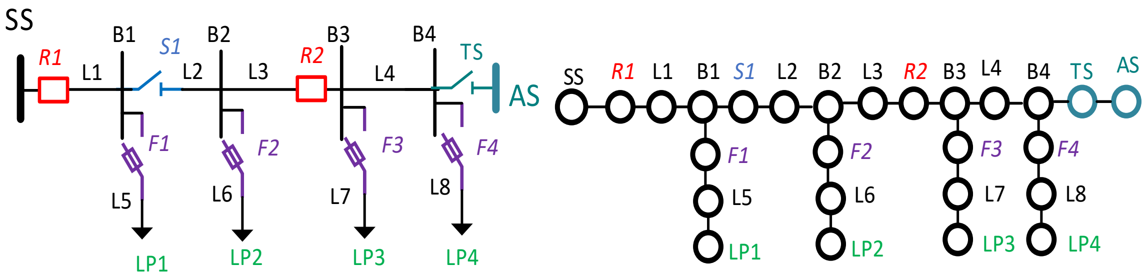


Figure 4.1. General schematic of the proposed methodology.

The graph network for the simple distribution system (Figure 4.2a) is shown in Figure 4.2b. Each distribution network component is represented by a node. Each node is an object with its attributes representing the properties of the component. The nodes representing the protection device has attributes such as device type (fuse, circuit breaker, recloser, sectionalizer/switch, etc.), identifier for fault interrupting/isolating device, device operating/switching time, fault clearing time, and failure statistics. For the buses and the line sections, the failure statistics, impedance, and other short circuit parameters are assigned as attributes. Any distribution network component with its set of attributes can be easily incorporated in this model. The edges show the connection between nodes.



(a) (b)

Figure 4.2. (a) Simple distribution network, (b) The graph representation.

A Depth First Search (DFS) algorithm and its modified form, which are based on graph theory [23], are adopted in this work to investigate the load points affected after a contingency occurs. The following steps demonstrate the application of the developed search algorithm for a simple network of Figure 4.2. A permanent fault on line section L3 of Figure 4.2 is considered.

1. Search for the fault interrupting device that attempts to clear the fault.
   - The modified DFS function is executed with two parameters; the input source (SS) and the faulted node (L3)*; i.e. DFS (SS, L3)*. The second parameter acts as a stopping criteria for the DFS algorithm.
   - The output is the path consisting of nodes between the input source and the faulted node; $Path_{S-F} = \{SS, R1, L1, B1, S1, L2, B2, L3\}$.
   - Identify the nearest fault interrupting device from the faulted node in $Path_{S-F}$; $D_{FIn} = \{R1\}$.

- Find the load points interrupted LP_{FIn} due to the operation of D_{FIn}, using DFS function DFS (D_{FIn}); $LP_{FIn} = \{LP1, LP2, LP3, LP4\}$.

2. Check for possible supply restoration from the input source.

- Look for the fault isolating device(s) between D_{FIn} and faulted node in $Path_{S-F}$; $D_{FIs} = \{S1\}$.
- Obtain load points restored with input source LP_{IS} = $LP_{FIn} \backslash LP_{FIs}$ {LP: LP ∈ LP_{FIn}, LP ∉ LP_{FIs}}. Here, LP_{FIs} = DFS (D_{FIs}) = $\{LP2, LP3, LP4\}$. Hence, $LP_{IS} = \{LP1\}$.

3. Check for the service restoration with alternate supply.

- Find the path between the input source and the alternate supply ($Path_{S-A}$) using DFS (SS, AS); $Path_{S-A} = \{R1, L1, B1, S1, L2, B2, L3, R2, B3, L4, B4, TS\}$.
- Look for the designated switching device in $Path_{S-A}$for service restoration with alternate supply; $D_{SW1} = \{R2\}$.
- Look for another designated switching device (D_{SW2}) in $N1$ for service restoration with alternate supply, where $N1 = DFS\ (D_{SW1})$. Hence, $D_{SW2} = \{\}$.
- Find the load points supplied with alternate supply; $LP_{AS} = N1 \backslash N2 = \{LP3, LP4\}$. Here, $N2 = DFS\ (D_{SW2})$.

4. Find the load points experiencing an outage for the duration of fault repair time; $LP_{rep} = LP_{FIn} \backslash (LP_{IS} \cup LP_{AS}) = \{LP2\}$.

Note that, this algorithm is also applicable to a distribution network with multiple alternate supply points. A designated switching device(s) is considered to be operated for a particular alternate supply to restore service to a certain portion of the network in order to comply with the network constraints.

4.6. Proposed Graph Theory Embedded Aggregated Reliability Event Model

This section develops the *graph theory embedded aggregated reliability event model t*o quantify the impact of contingency on load points and the overall system. Both short and long duration reliability events (explained in Section 4.4) are considered in quantifying the reliability profile. The contingency is modeled in Section 4.6.1 to incorporate both temporary and permanent failures. Section 4.6.2 and 4.6.3 describe the framework to assess the impact of contingency on load points incorporating the complex interdependence of protection settings, restoration with alternate supplies, and the integration of DERs/microgrids using the search algorithm based on graph theory (illustrated in Section 4.5). The impact of DERs/microgrids towards mitigating these reliability events are incorporated while updating the contribution of each contingency to load point's reliability profile using the analytical set of equations developed in Section 4.6.4. Finally, the system reliability profile is obtained using the load point profiles, which is illustrated in Section 4.6.5.

4.6.1. Contingency Modeling

The failures (contingency, fault, and failure are used interchangeably in this paper) in the power system are of either active or passive in nature [24]. However, the occurrence of passive failures is rare in the power system. Active failures originate from short- circuit faults and cause the operation of protection devices, whereas the passive failures do not trigger their operation. Some of the active failures are temporary in nature, e.g. lightning strikes, animal or tree branch contact in power line for a brief period of time, where the service can be restored by automatic switching. The permanent active failures need the manual intervention. All failures that cause protection device operation are considered in this work. The active failures can be further divided into single line to ground (*SLG)*, line to line *(L-L)*, double line to ground *(L-L-G)*, and three phase fault *(3-ph)*. All these aspects associated with a contingency can be preserved with a probabilistic representation based on historical data. The tree diagram shown in Figure 4.3 describes the contingency associated with a component and its probabilistic model. This work develops a contingency model of a component by probabilistic merging all failure modes enumerating the categories of fault contingency scenario as shown in Figure 4.3.

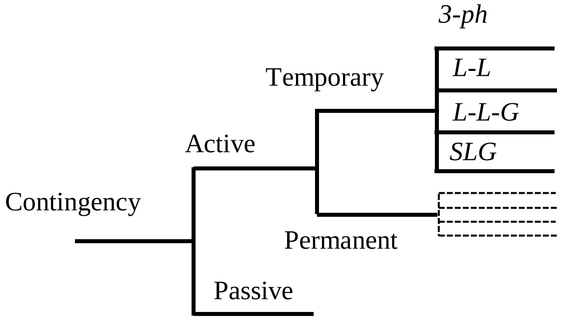


Figure 4.3. Contingency model.

4.6.2. Impact Assessment of Contingency on Load Points

This section presents the developed methodology to examine the load points experiencing different reliability events due to a particular contingency. The search algorithm developed in Section 4.5 is utilized to track the necessary switching actions and their impact on load points.

The methodology (see Figure 4.4) is illustrated with an example of a fault on a line section between S1 and R2 in Figure 4.5. Due to this fault, all the load points will experience voltage sag ($L'^{c,x}_{sag} = L$) whose severity depends mainly on the location, fault type, etc. The nearest upstream fault interrupting device(s) to be operated is searched. In this case, R1 operates ($PD^{c,x}_{cl} = R1$). For the permanent fault, R1 tries to clear the fault with the predefined operating sequence. Thus, the load points downstream of R1, i.e. LP1 – LP23 will experience momentary interruption ($L'^{c,x}_{MI} = \{LP1 - \text{LP23}\}$). Then, R1 will lock-open after a preset number of operations, causing sustained interruption to LP1-LP23 ($L^{c,x}_{SI} = \{LP1 - \text{LP23}\}$).

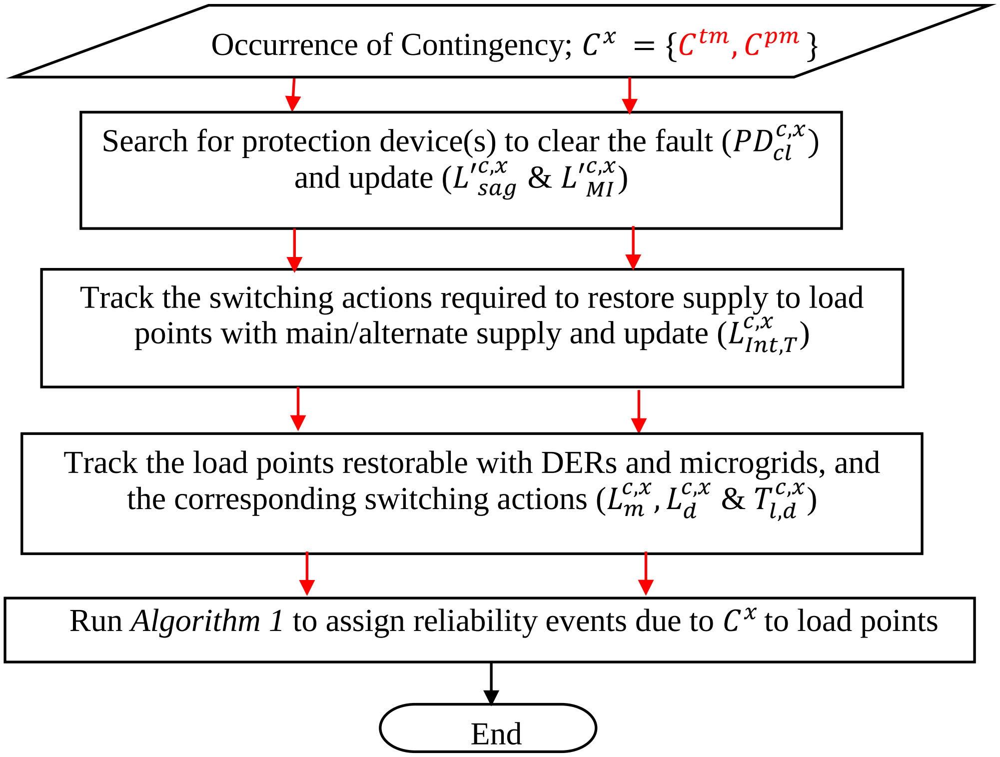


Figure 4.4. Flowchart to assess impact of contingency on load points.

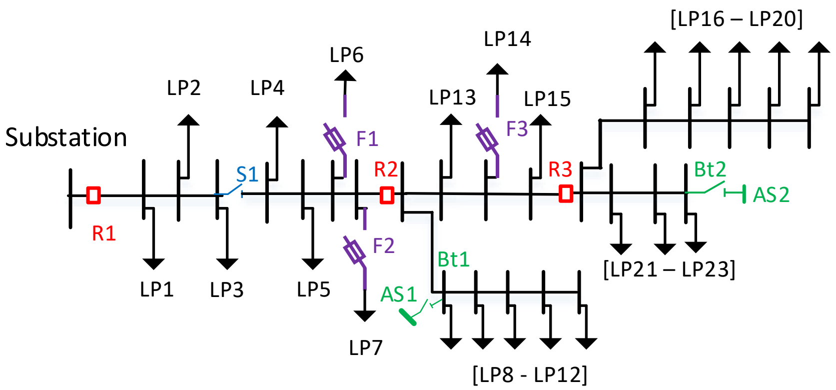


Figure 4.5. Weakly-meshed test distribution network.

In the next stage, the possible switching actions are assessed to isolate the fault and restore the load points located on the healthy part of the network with main supply/alternate supply. Such switching actions are tracked and the duration for which the load points are interrupted are recorded ($L^{c,x}_{Int,T}$). Following the opening of S1 (automatic, 0.015 hr), the supply is restored to LP1-LP3 ($L^{c,x}_{Int,0.015} = \{LP1 - LP3\}$). LP8-LP15 can be restored with opening of R2, and closing the tie-switch (manual; 0.5 hr), thus connecting the alternate supply (AS1) to Bt1 ($L^{c,x}_{Int,0.5} = \{LP8 - LP15\}$). Similarly, LP16-LP23 can be restored with opening of R3 and closing the tie-switch (automatic, 0.015 hr), thus connecting the alternate supply (AS2) to Bt2 ($L^{c,x}_{Int,0.015} = \{LP16 - LP23\}$).

These parameters on the switching actions, supply restoration, and the affected load points obtained so far are passed to *Algorithm 4.1* to update the load points experiencing different reliability events due to a contingency. The output for this case is; $L^{c,x}_{sag} = \{\}$, $L^{c,x}_{MI} = \{LP1 - LP3, LP16 - LP23\}$, $L^{c,x}_{SI} = \{LP4 - LP7, LP8 - LP15\}$, $T^{c,x}_{A,SI}$ =5 hr, and $T^{c,x}_{B,SI} = 0.5\ hr$. Here, A is a set of load points experiencing outage duration until repair (5 hr), i.e. $A = \{LP4 - LP7\}$, and B is a set of load points experiencing interruption for the duration until service is restored with alternate supply (0.5 hr), i.e. $B = \{LP8 - LP15\}$.

Algorithm 4.1: Assign reliability events to the load points for a contingency.

```
Input: $L'^{c,x}_{sag}, L'^{c,x}_{MI}, L^{c,x}_{Int,T}$
Output: $L^{c,x}_{sag}, L^{c,x}_{MI}, L^{c,x}_{SI}, T^{c,x}_{l,SI}$
for all $l \in L^{c,x}_{Int,T}$ do
    if $T \leq T_{MI}$ then
        $L'^{c,x}_{MI} \leftarrow L'^{c,x}_{MI} \cup l$
    else
        $L'^{c,x}_{SI} \leftarrow L'^{c,x}_{SI} \cup l, T^{c,x}_{l,SI} \leftarrow T^{c,x}_{l,SI} \cup T$
    end if
end for
for all $l \in L$ do
    if $l \in L'^{c,x}_{sag}$ and $l \in L'^{c,x}_{MI}$ then
        $L'^{c,x}_{sag} \leftarrow L'^{c,x}_{sag} \setminus l$    $\{LP: LP \in L'^{c,x}_{sag}, LP \notin l\}$
    end if
    if $l \in L'^{c,x}_{sag}$ and $l \in L'^{c,x}_{SI}$ then
        $L'^{c,x}_{sag} \leftarrow L'^{c,x}_{sag} \setminus l$    $\{LP: LP \in L'^{c,x}_{sag}, LP \notin l\}$
    end if
    if $l \in L'^{c,x}_{MI}$ and $l \in L'^{c,x}_{SI}$ then
        $L'^{c,x}_{MI} \leftarrow L'^{c,x}_{MI} \setminus l$    $\{LP: LP \in L'^{c,x}_{MI}, LP \notin l\}$
    end if
end for
$L^{c,x}_{sag} \leftarrow L'^{c,x}_{sag}, L^{c,x}_{MI} \leftarrow L'^{c,x}_{MI}, L^{c,x}_{SI} \leftarrow L'^{c,x}_{SI}$
```

4.6.3. Consideration of DERs and Microgrids

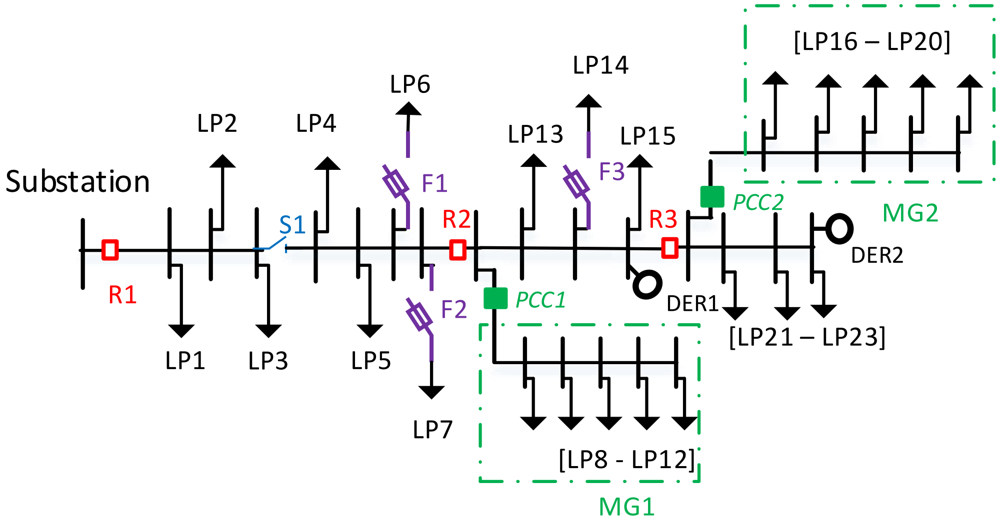


Figure 4.6. DERs/microgrids integrated test distribution network.

Figure 4.6 shows a distribution system with two DERs (DER1 and DER2) integrated along the main feeder and two microgrids MG1 and MG2 connected to PCC1 and PCC2, respectively. The DERs generally disconnect as soon as they detect a fault [5]. If the islanding operation is permitted, they reconnect after the fault is isolated to supply the load points located on a healthy section of the network. Although such provision doesn’t contribute towards mitigating the impact of voltage sag and momentary interruptions, it decreases the outage time experience by the customers. It should be noted that the provision of ride- through/additional reactive power injection during network fault might contribute towards reducing the impact of voltage sag [6]. However, it is not covered in this paper.

The cluster of customers with sensitive equipment/processes can benefit with the implementation of the microgrid. Such microgrids generally have the DGs, storage and controllable loads necessary to balance voltage and frequency while operating in an isolated mode in case of a fault in the utility supply side. The smart microgrid management control system has the ability to switch the microgrid to the isolated mode in a sub-cycle range with the help of fast acting switch at PCC, thus, preventing the damage to the sensitive loads. Any fault within the microgrid would cause the same fast acting switch at PCC to open, thereby not affecting other utility customers [7]. The successful microgrid operation with seamless transfer to the isolated mode and resynchronization helps mitigate voltage sag and momentary/sustained interruptions.

The inclusion of DERs/microgrids in the developed methodology is illustrated for the case of a permanent fault in a line section between S1 and R2 in Figure 4.6. The search process associated with service restoration with DERs is handled with the same algorithm used when the alternate supply is considered, whereas PCC identifies the possible microgrid operation. The methodology includes the following steps:

1. Obtain $PD_{cl}^{c,x}$, $L'^{c,x}_{sag}$, $L'^{c,x}_{MI}$ & $L^{c,x}_{Int,T}$ as explained in Section 4.6.2 by executing the first two steps of the flowchart shown in Figure 4.4.
2. Search the load points restorable with DERs and track the protection device operations, and update $LP_d^{c,x}$, $T_{l,d}^{c,x}$ and $P_{d,s}^{c,x}$. For this case, $LP_{d1}^{c,x} = \{LP13 - LP15\}$, $LP_{d2}^{c,x} = \{LP21 - LP23\}$, $T_{l,d1}^{c,x}$ =*1 min*, and $T_{l,d2}^{c,x}$ =*1 min*.
3. Search for the load points restorable with microgrids, and update $LP_m^{c,x}$, and $P_{m,s}^{c,x}$. For this case, $LP_{m1}^{c,x} = \{LP8 - LP12\}$ and $LP_{m2}^{c,x} = \{LP16 - LP20\}$. Pass the parameters obtained in above

steps to *Algorithm 4.1*, then to the set of equations presented in Section 4.6.4 to update the impact of contingency on load points considering DER/microgrid operations.

The impact of DER/microgrid operation in the mitigation of reliability events has been represented utilizing the method of expectation (4.1), (4.2). Its elaborated form is presented in Section 4.6.4. The probability of load points being successfully restored with DER depends on their hardware availability, adequacy considering intermittency/variability, energy limitation, etc. This probability is represented with $P_{d,s}^{c,x}$. The probability of successful microgrid operation is denoted by $P_{m,s}^{c,x}$. The successful restoration of load points with supply from DERs/microgrids also depend on the fault location and the fault isolating capability of protection systems. Appropriate modeling of microgrid and DERs for different reliability events can be done separately and integrated into this framework for the reliability studies.

$$RI_l^{c,x} = RI'^{c,x}_l \times (P_{m,s}^{c,x}) + RI''^{c,x}_l \times (1 - P_{m,s}^{c,x}) \ \forall\, l \in L_m^{c,x} \tag{4.1}$$

$$RI_l^{c,x} = RI'^{c,x}_l \times (P_{d,s}^{c,x}) + RI''^{c,x}_l \times (1 - P_{d,s}^{c,x}) \ \forall\, l \in L_d^{c,x} \tag{4.2}$$

Where, RI' is the value of reliability index for the successful DER/microgrid operation, and RI'', for the failed operation.

4.6.4. Quantification of Load Point Reliability Profile

4.6.4.1. Evaluation of Disruptive Voltage Sag

Both the temporary and the permanent faults cause voltage sag until the responsible protection device actuates. For a distribution network with multiple feeders, the fault on the neighboring feeder also causes the voltage on anther healthy feeder to drop below the nominal value. The severity of voltage sag mainly depends on its retained magnitude and duration [2], [25]. The vulnerability of voltage sag to equipment and the process depends on the sensitivity and the ride-through capability of the equipment used against voltage sag event.

The magnitude of voltage sag greatly depends on the location of the fault as well as the fault impedance. To incorporate the locational aspect of the line related fault, a fault position method [25] is adopted, where, a line is divided into multiple sections, and the fault analysis is performed on the basis of classical symmetrical - component based method for various types of short circuit fault [14]. In case of an unsymmetrical fault, the sag magnitude of the most affected phase is reported [14]. The corresponding duration of a voltage sag depends on the short circuit level, fault-clearing times of protective devices, self-extinguishing nature of fault and delay used in the protection setting, which generally needs elaborate modeling and computation [10], [12]. The probabilistic representation of fault clearing time associated with a primary protection device ($PD_{cl}^{c,x}$) that interrupts the fault can be represented with a probability distribution function (PDF) [12], [13]. Here, it is represented with a normal distribution as shown in Figure 4.7. Such PDF is discretized into multiple intervals, and a mid point value (sD) is represented as the value of sag duration. The weightage associated with that interval is also noted as $w(s\mathrm{D})$.

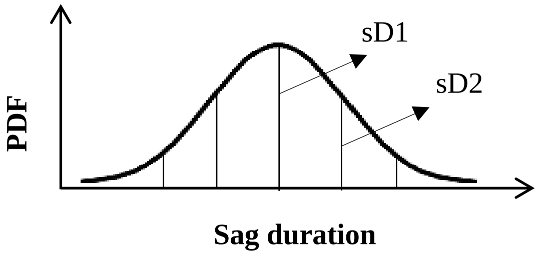


Figure 4.7. PDF for sag duration.

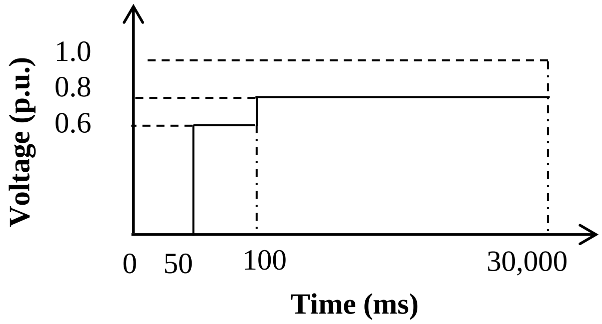


Figure 4.8. Illustrative sensitivity curve to voltage sag [11].

The magnitude, as well as the duration of voltage sag, are evaluated for a particular contingency as described in *Algorithm 4.2*. Only those sags that have magnitude and duration beyond the tolerance curve of equipment as shown in Figure 4.8 are disruptive in nature. Such voltage sags are termed as *Disruptive Sag Event (DSE)* in this paper. The frequency of those events are noted with $F'_{l,DSE}$ as described in *Algorithm 4.2*. Moreover, different categories of customers have different levels of reliability needs. The voltage sag tolerance curve for different categories of customers are used to determine the frequency of *DSE* [19].

Algorithm 4.2: Evaluation of disruptive sag event.

```
Input: $f^{c,x}, PD_{cl}^{c,x}, L_{sag}^{c,x}$
Output: $F_{l,DSE}'^{c,x}$
1:  if the contingency is associated with line then
2       Divide the line into multiple fault points ($nfp$).
3:        for $fp = 1{:}nfp$ do
4:            Create an impedance matrix model.
5:              for all $st \in$ {3-ph, L-L, L-L-G, SLG} do
6:                  Evaluate sag magnitude $sM_{fp,l}^{c,x,st}$ & update $FsM_{fp,l}^{c,x,st}$ using (4.3).
7:              end for
8:        end for
9:  else,
10:  Repeat steps 2-8 with $nfp$ set to 1.
11: end if
12: Obtain discretized probability distribution of voltage sag magnitude { $FsM_{l}^{c,x}(sM)$}.
13: Obtain discretized probability distribution of voltage sag magnitude ($sM$) & duration ($sD$) associated with a bus of interest; $sag_{l}^{c,x} = \{VsF_{l}^{c,x}(sM, sD)\}$ using (4.4).
14: Check for $sag_{l}^{c,x}$ that are beyond the tolerance curve of the load point equipment/processes and update $F'_{l,DSE}$.
```

$$FsM_{fp,l}^{c,x,st} = \left(f^{c,x} \times w(\mathrm{st}) \times \frac{1}{nfp}\right) \qquad \forall\, l \in L_{sag}^{c,x} \tag{4.3}$$

$$VsF_{l}^{c,x}(sM, sD) = FsM_{l}^{c,x}(sM) \times w(sD) \quad \forall\, l \in L_{sag}^{c,x} \tag{4.4}$$

Where, $w(\mathrm{st})$ and $w(\mathrm{sD})$ are weightage of corresponding short circuit type and sag duration interval associated with pdf of sag duration, respectively.

The impact of microgrid can be assessed with (4.5) - (4.6) using the concept described in Section 4.6.3. The frequency of disruptive sag event for a load point is then obtained by cumulating the impact of each contingency towards such event, as given in (4.7). The damage cost due to disruptive sag even is represented with (4.8).

$$F_{l,DSE}^{c,x} = F_{l,DSE}'^{c,x} \times (1 - P_{m,s}^{c,x}) \quad \forall\, l \in L_{sag}^{c,x}, \forall\, l \in L_{m}^{c,x} \tag{4.5}$$

$$F_{l,DSE}^{c,x} = F_{l,DSE}'^{c,x} \qquad \forall\, l \in L_{sag}^{c,x}, \forall\, l \notin L_{m}^{c,x} \tag{4.6}$$

$$F_{l,DSE} = \sum\nolimits_{c} F_{l,DSE}^{c,x} \tag{4.7}$$

$$D_{l,DSE} = F_{l,DSE} \times D_{DSE}(.) \tag{4.8}$$

Where, $D_{DSE}(.)$ is a function of damage cost due to *DSE*.

4.6.4.2. Evaluation of Momentary Interruption

In addition to the temporary fault, the permanent fault can also lead to a momentary interruption. For instance, during the supply interruptions due to a permanent fault, if the service of a certain group of customers can be restored with main/alternate supply with automatic switching, these customers would only experience momentary interruptions. The contribution of contingency to the frequency of momentary interruption for a load point, without considering the impact of DERs/microgrid is given by (4.9). The impact of microgrid operation is represented by (4.10)-(4.11). The momentary interruption introduced by the DERs due to the restoration of supply by the islanded operation with automatic switching is also considered in this work as given in (4.12).

$$F'^{c,x}_{l,MI} = f^{c,x} \quad \forall\, l \in L^{c,x}_{MI} \tag{4.9}$$

$$F^{c,x}_{l,MI} = F'^{c,x}_{l,MI} \times (1 - P^{c,x}_{m,s}) \quad \forall\, l \in L^{c,x}_{MI}, \forall\, l \in L^{c,x}_{m} \tag{4.10}$$

$$F^{c,x}_{l,MI} = F'^{c,x}_{l,MI} \quad \forall\, l \in L^{c,x}_{MI}, \forall\, l \notin L^{c,x}_{m} \tag{4.11}$$

$$F^{c,x}_{l,MI} = f^{c,x} \times P^{c,x}_{d,s} \quad \forall\, l \in L^{c,x}_{SI}, \forall l \in L^{c,x}_{d} \;\; ;if\ T^{c,x}_{l,d} \leq T_{MI} \tag{4.12}$$

The frequency of momentary interruption and corresponding damage cost for a load point are obtained with (4.13) - (4.14).

$$F_{l,MI} = \textstyle\sum_c F^{c,x}_{l,MI} \tag{4.13}$$

$$D_{l,MI} = F_{l,MI} \times D_{MI}(.) \tag{4.14}$$

Where, $D_{MI}(.)$ is a function of damage cost due to *MI*.

4.6.4.3. Evaluation of Sustained Interruption

Temporary failures generally do not lead to the sustained interruptions for the perfectly reliable protection operations. However, if a temporary failure causes a fuse to operate, the customers downstream the fuse would experience sustained interruption until the fuse is replaced. The contribution of contingency to the frequency and the unavailability associated with a sustained interruption for a load point are represented by (4.15), (4.16).

$$F'^{c,x}_{l,SI} = f^{c,\mathrm{x}} \quad \forall\, l \in L^{c,x}_{SI} \tag{4.15}$$

$$U'^{c,x}_{l,SI} = f^{c,\mathrm{x}} \times T^{c,x}_{l,SI} \quad \forall\, l \in L^{c,x}_{SI} \tag{4.16}$$

The sustained interruption at the load points last until repair, or fuse replacement time, or is restored with main/ alternate supply after isolating the fault. In the case of load points being restored with successful microgrid operation, they would not experience any interruption. This is explained by (4.17), (4.18).

$$F^{c,x}_{l,SI} = F'^{c,x}_{l,SI} \times (1 - P^{c,x}_{m,s}) \quad \forall\, l \in L^{c,x}_{SI}\,, \forall\, l \in L^{c,x}_{m} \tag{4.17}$$

$$U^{c,x}_{l,SI} = U'^{c,x}_{l,SI} \times (1 - P^{c,x}_{m,s}) \quad \forall\, l \in L^{c,x}_{SI}\,, \forall\, l \in L^{c,x}_{m} \tag{4.18}$$

If the load point is successfully restored with DER, it will be interrupted for the duration of $T^{c,x}_{l,d}$. If the duration is longer than T_{MI}, it will not reduce the frequency of interruption, however, it will reduce the outage duration. This is illustrated with (4.19), (4.20). The impact of contingency on the reliability of load points that cannot be restored with DERs/microgrids are updated with (4.21), (4.22).

$$F^{c,x}_{l,SI} = \begin{cases} f^{c,x}\left(1 - P^{c,x}_{d,s}\right) & \forall l \in L^{c,x}_{SI}, \forall l \in L^{c,x}_{d} \quad ; if\ T^{c,x}_{l,d} \le T_{MI} \\ f^{c,x} & \forall l \in L^{c,x}_{SI}, \forall l \in L^{c,x}_{d} \quad ; else \end{cases} \tag{4.19}$$

$$U^{c,x}_{l,SI} = \begin{cases} f^{c,x} \times T^{c,x}_{l,SI}\left(1 - P^{c,x}_{d,s}\right) \forall l \in L^{c,x}_{SI}, \forall l \in L^{c,x}_{d}; if\ T^{c,x}_{l,d} \le T_{MI} \\ f^{c,x}(T^{c,x}_{l,d} P^{c,x}_{d,s} + T^{c,x}_{l,SI}\left(1 - P^{c,x}_{d,s}\right)) \forall l \in L^{c,x}_{SI}, \forall l \in L^{c,x}_{d}; else \end{cases} \tag{4.20}$$

$$F^{c,x}_{l,SI} = F'^{c,x}_{l,SI} \qquad \forall\, l \in L^{c,x}_{SI}, l \notin L^{c,x}_{m}\,, \forall l \notin L^{c,x}_{d} \tag{4.21}$$

$$U^{c,x}_{l,SI} = U'^{c,x}_{l,SI} \qquad \forall\, l \in L^{c,x}_{SI}, l \notin L^{c,x}_{m}\,, \forall l \notin L^{c,x}_{d} \tag{4.22}$$

The load point indices are obtained as given in (4.23) -(4.25).

$$F_{l,SI} = \textstyle\sum_c F^{c,x}_{l,SI} \tag{4.23}$$

$$U_{l,SI} = \textstyle\sum_c U^{c,x}_{l,SI} \tag{4.24}$$

$$D_{l,SI} = F_{l,SI} \times D_{SI}(.) \tag{4.25}$$

Were, $D_{SI}(.)$ is a function of damage cost due to SI [26].

After obtaining the reliability indices for voltage sag, momentary and sustained interruptions, the load point reliability profile can be represented with the set of frequency/duration indices and the damage cost associated with different reliability events;$R_l(.)$=$\{F_{l,DSE}, F_{l,MI}, F_{l,SI}, U_{l,SI}, D_{l,DSE}, D_{l,MI}, D_{l,SI}, D_{l,tot}\}$. Here, $D_{l,tot}$ is the damage cost incurred to the load point l, due to all the reliability events.

4.6.5. Quantification of System Reliability Profile

The system indices can be obtained with (4.26) -(4.29). The subscript RE denotes the disruptive sag event, momentary and sustained interruptions when replaced by DSE, MI and SI, respectively. The system reliability profile is given by $R_S(.)$= $\{F_{DSE}, F_{MI}, F_{SI}, U_{SI}$,$D_{DSE}, D_{MI}, D_{SI}$, $D_{tot}\}$. Here,F_{MI}, F_{SI}, and U_{SI} are equivalent of MAIFIe, SAIFI, and SAIDI as defined in [21].

$$F_{RE} = \sum_{l \in L} F_{l,RE} \times N_l \Big/ \sum_{l \in L} N_l \tag{4.26}$$

$$U_{SI} = \sum_{l \in L} U_{l,SI} \times N_l \Big/ \sum_{l \in L} N_l \tag{4.27}$$

$$D_{RE} = \sum_{l \in L} D_{l,RE} \tag{4.28}$$

$$D_{tot} = \sum_{RE} D_{RE} \tag{4.29}$$

4.7. Case Studies

4.7.1. Test System and Basic Data

The proposed models and methodology are applied for illustration to test systems in Figure 4.5 and Figure 4.6, which are the modified version of feeder 4 at Bus 6 of the Roy Billinton Test System (RBTS) [26]. The proposed methodology is however applicable to large practical distribution network with multiple feeders. The customer composition shown in Table 4.1 is used in the case studies. The recloser, fuse, and sectionalizer are indexed with “R”, “F” and “S”, respectively in Figure 4.5 and Figure 4.6. The permanent failure rate and repair time for the lines are taken to be 0.046 occ/yr-km and 5 hr respectively [26]. The temporary failure rate is assumed to three times the permanent failure rate [4]. The switching time for the manual switches/sectionalizers is 0.5 hr. The fuse replacement time is taken as 1.5 hr. The line impedance and other short circuit parameters are taken from [13]. The load current and the connection of load point transformers are neglected, and zero fault impedance is used for the sag analysis. The automatic switches are assumed to operate within T_{MI} such that they are responsible for momentary interruption only. The mean value of fault clearing time for fuse and reclosers are assumed 50 ms and 300 ms. The standard deviation of 10% is taken in this work. The ride-through capability for different customer categories is assumed as follow: sag magnitude of 0.85 and duration of 40 ms for commercial/industrial customers. The corresponding values for residential customers are 0.75 and 300 ms, respectively. The following additional set of assumptions have been made.

1) The distribution network is radially operated [7], [17], [18], and a fault is cleared/repaired before subsequent one occurs [17], [18].
2) Circuit breakers/reclosers are equipped with sectionalizes on both sides for the purpose of fault isolation [7], [18].
3) The fault interrupting device(s) that are closest to the fault trip first [7], [17], [18], and the failure of protection devices is not considered [7], [12], [17].
4) Probability distribution of short circuit fault is as follows: 5 % *3-ph*, 15% *L-L*, 10% *L-L-G*, and 70% for *SLG* [12].

The damage cost associated with sag event is assumed equal to that of momentary interruption. For damage cost associated with momentary and sustained interruptions, data from the Canadian survey [26] is used. Thus, the results associated with the customer financial losses serve for comparative studies. The damage cost is the function of the customer category, outage duration and average demand of a customer [26].

Table 4.1. Customer demand profile for the test system.

Load points	**Category**	**# of Customer**	**Peak Load per Load point(MW)**
LP3-LP7, LP11- LP14, LP22, LP23	Residential	79	0.27
LP8, LP15, LP16, LP19-LP21	Commercial	7	0.5
LP1, LP2, LP9, LP10, LP17, LP18	Small Industrial	1	1

The following section illustrates the application of the proposed methodology to weakly-meshed test network (Case I) and network with DERs and microgrids (Case II).

4.7.2. Results for Case I

This section first illustrates the importance of incorporation of voltage sag and momentary interruptions in the reliability studies, and then reports the reliability profile of load points and system for the test network shown in Figure 4.5. Table 4.2 presents the reliability profile for the case of LP9 being residential (Res.) and small industrial (Ind.) customer. Among the indices of reliability profile, $F_{l,MI}$, $F_{l,SI}$ and $U_{l,SI}$ are similar for both the cases. However, due to a different level of vulnerability against voltage sag, the values of $F_{l,DSE}$ are different. The damage cost due to these reliability events are also different. It can be observed that given the same location and peak demand, that the financial losses incurred to the industrial customer are significant. The damage cost due to sag and momentary interruptions comprises of 28 % of total cost in case of industrial customers, which amounts to be negligible for residential customers. The inclusion of voltage sag and momentary interruptions in the reliability studies for sensitive customers provide the accurate estimation of financial losses incurred to them, which cannot be obtained otherwise. The results for the selected load point and system reliability for the test system under consideration using the proposed methodology are show in Table 4.3 and 4.4, respectively.

Table 4.2. Reliability profile of LP9.

Case	$F_{l,DSE}$	$F_{l,MI}$	$F_{l,SI}$	$U_{l,SI}$	D_{DSE}	D_{MI}	D_{SI}
Res.	2.70	5.08	1.69	5.90	0.001	0.003	4.46
Ind.	4.30	5.08	1.69	5.90	5.87	6.93	33.20

Table 4.3. Reliability profile of load points for Case I.

Load	$F_{l,DSE}$	$F_{l,MI}$	$F_{l,SI}$	$U_{l,SI}$	$D_{l,tot}$
LP3	1.69	2.06	0.23	1.13	0.23
LP7	5.75	1.71	0.71	3.18	0.65
LP9	4.30	5.08	1.69	5.90	45.99
LP15	4.30	5.08	1.69	5.90	14.90
LP18	0.36	9.72	0.98	4.92	40.65
LP21	0.36	9.72	0.98	4.92	12.66

4.7.3. Results for Case II

This section illustrates the reliability profile of the network with DERs/microgrids and discusses the possible 'smart reliability solutions' with these resources. The test system shown in Figure 4.6 is used for the analysis. The reliability indices for both the load point and system level are altered by the inclusion of microgrids and DERs, as can be observed in the results reported in Table 4.3, 4.4 and 4.5. It should be noted that the difference in the reliability indices in the two case studies (Case I and Case II) also come from the change in protection settings to integrate microgrids/DERs, apart from the inclusion/exclusion of these resources. The probability of successful isolated microgrid operation and DER restoration is taken as 0.98, given that the fault isolation is possible. It can be observed from the results in Table 4.4 that the load points within the microgrids (e.g. LP9 and LP18) benefit from an improved level of reliability in terms of both short and long duration reliability events. However, it is highly sensitive to the successful microgrid operation during contingencies. The reliability profile of the load points restored with DERs (e.g. LP15 and LP21) in case of sustained interruption greatly depend on the availability of DERs.

Table 4.4. Reliability profile of load points for Case II.

Load	**$F_{l,DSE}$**	**$F_{l,MI}$**	**$F_{l,SI}$**	**$U_{l,SI}$**	**$D_{l,tot}$**
LP3	0.83	2.06	0.23	1.13	0.23
LP7	2.49	1.71	0.71	3.18	0.65
LP9	0.0385	1.90	0.63	3.17	19.95
LP15	1.92	3.80	0.52	2.61	6.75
LP18	0.0001	1.87	0.62	3.11	19.56
LP21	0.36	5.48	0.41	2.06	5.48

Table 4.5. System reliability profile.

Case	**F_{DSE}**	**F_{MI}**	**F_{SI}**	**U_{SI}**	**D_{tot}**
I	2.74	4.60	1.06	4.30	286.43
II	0.99	2.83	0.55	2.65	148.33

The results imply that the DERs can be operated appropriately to reduce the outages seen by the customers located far from the substation, which gives a competitive alternative to the investment in back feed or alternate supplies. Moreover, the microgrid operation not only reduces the long duration outages but also helps mitigate the sag and momentary interruptions. With the implementation of such microgrids/DERs, the utility can have a premium reliability contract with customer requiring a high level of reliability. Such practices help assure the reliable supply for the customer, in the meantime increasing the utility’s source of revenue. The results of the case studies support the possibility of ‘smart reliability solutions’ with DERs/microgrids in the context of smart distribution systems.

4.8. Conclusion

This paper presents a novel graph theory embedded aggregated reliability event modeling approach for the reliability studies of the modern distribution system. The developed model considers both short and long duration reliability events due to temporary and permanent failures. The graph theory-based search algorithm is utilized to efficiently recognize the protection device operation, the presence of alternate supply and microgrids/DERs. Furthermore, the impact of DERs and microgrids towards mitigating the reliability problems is also incorporated in the developed model. The reliability profiles of load points and the overall system are quantified incorporating the frequency/duration indices and the associated financial losses resulting from different reliability events. The case studies conducted in a practical test system shows the effectiveness of the proposed framework to evaluate the reliability and to carry out the system upgrades in the context of modern smart distribution systems.

4.9. References

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CHAPTER 5: UTILIZING ENERGY STORAGE FOR RELIABILITY SOLUTIONS IN ACTIVE DISTRIBUTION SYSTEMS [1]

5.1. Abstract

The stochastic failures in a distribution network result in different reliability events, such as voltage sag, momentary and sustained interruptions, causing the significant financial losses for many customers. The strategic utilization of energy storage system (ESS) can help mitigate these reliability events. This paper investigates the role of ESS towards providing reliability solutions in the context of the active distribution system. In this regard, a scenario-based probabilistic modeling of reliability event mitigation with the ESS is presented, which is integrated into the reliability evaluation framework. The proposed approach is efficient in assessing the reliability solutions with ESS considering storage technology type, the power/energy rating, hardware availability, the presence of other distributed energy resources, etc. A range of case studies is conducted to evaluate mitigation of reliability events at the different level of the distribution system. The valuable insights into the efficient utilization of ESS are provided based on the findings.

5.2. Introduction

The quality of supply is getting increased attention in the modern society with the widespread use of sensitive equipment and industrial processes. These devices/processes are subject to mis-operation even with short duration reliability events- voltage sag and momentary interruptions. The financial losses due to short duration reliability events are significant for an industrial/commercial customer [1]. Mostly, the sustained interruption based reliability indices are utilized in the system planning and the regulatory compliance structures [2]. Such practice, however, fails to provide incentives for the utilities to invest in the system upgrades to improve the

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reliability performance considering the short duration reliability events. However, the regulators and electric utilities are taking into account the disruptive voltage sag and the momentary interruption in addition to sustained interruptions- together termed as Reliability Events (RE) [1] – in system planning and regulatory policies with the ongoing changes in the modern distribution system [2].

The commercial/industrial customers generally install a standby supply system in the form of the uninterruptible power supply (UPS), or emergency generators to deal with the short and long duration reliability events [3]. The sensitive customer loads can be connected to multiple supply points, such that in case of a disturbance in the primary supply point, the secondary supply will take up the load with fast switching action [4]. The voltage sag mitigation with power electronic based devices, e.g. dynamic voltage regulator (DVR), dynamic sag corrector (DSC), Thyristor voltage regulator (TVR), flexible ac transmission system (FACTS) devices, etc. are also common in modern distribution system [5], [6].

With the advent of smart control, monitoring and communication systems, the distributed energy resources (DERs), which includes energy storage system (ESS) and distributed generation (DG), are also being utilized to mitigate different reliability events. DERs can help reduce the impact of sag event by injecting the additional reactive power in case of voltage dips during system contingencies [7]. The energy storage installed at the customer premises can override short and long duration reliability events [8], [9]. The microgrid, which consists of controllable loads and DERs, integrated at the point of common coupling (PCC) of distribution network operates in isolated mode during utility supply disturbances [10], thereby protecting critical load against all sorts of reliability events. The DERs that are not the part of such microgrids and integrated along the distribution feeder can also operate in an islanded mode to reduce long-duration outages [11].

Various aspects of utilization of ESS and other distributed energy resources to mitigate different reliability events have been explored in the existing literature. Reference [3] provides the analytic method to assess the contribution of energy storage and a backup generator to reduce the impact of sustained outages. A new method of protecting sensitive load against momentary interruptions using inverter-coupled ESS is developed in [9]. The potential of sodium sulfur batteries to protect the customer devices/processes are investigated in [8]. Authors in [7] have discussed the role of DG in the mitigation of reliability events with the microgrid-like operation and the additional current injection method. Reference [5], [6] have presented methodologies to model the contribution of power electronic based devices to the lower the impact of voltage sag on the individual load point and the overall network. A Monte Carlo simulation based approach is developed to quantify the role of ESS in reducing the sustained outages experienced by the customers in [11].

The above-reported literature, however, lack the systematic approach to assess the role of ESS to mitigate short and long duration reliability events at the different level of the distribution system. Such a comprehensive assessment provides a basis to examine the cost-effectiveness of reliability-centric upgrades at the customer and system planning level. In this regard, this work explores the role of ESS, along with other resources, to mitigate the reliability events that arise from the random failures in the distribution network. A scenario-based probabilistic modeling of reliability event mitigation with the ESS is presented, which is integrated into the reliability evaluation framework. The proposed approach is efficient in assessing the reliability solutions with ESS considering storage technology type, the power/energy rating, hardware availability, the presence of other distributed energy resources, etc. The possible use of other resources to alleviate the reliability/power quality issues is also discussed. A range of case studies is performed considering the ESS at the end-user premise, and the utility/microgrid-scale ESS to examine their potential to provide reliability solutions. Finally, valuable insights into the efficient utilization of ESS are provided based on the findings.

5.3. Quantification of Reliability Events

This section illustrates different reliability events and their causes and presents a framework to assess the reliability of the distribution network. Upon the occurrence of a fault in the network, the root mean square voltage magnitude drops below the nominal voltage, thus leading to voltage sag. Both the temporary and the permanent faults cause the voltage sag until the responsible protection device operates [12]. The severity of voltage sag mainly depends on the fault location, fault impedance, fault-clearing time, etc.

A momentary interruption occurs due to a brief loss of continuity of supply resulting from the opening and closing of a protective device for a short duration (usually, the duration of 1 to 5 min is taken). The multiple interruptions caused by the recloser operating sequence is designated as one momentary interruption event in this work. The permanent fault, besides the temporary fault, can lead to a momentary interruption due to the service restoration with an automatic switching [2]. The momentary interruption introduced by the DERs due to the restoration of supply with the islanded operation with automatic switching [13] is also considered in this work. The sustained interruption is defined as any interruption event, other than the momentary interruption. It should be noted that the temporary failure might cause the sustained interruption as well. For instance, if a temporary failure causes a fuse to operate, the customers downstream the fuse would experience sustained interruption until the fuse is replaced [2].

It should be noted that depending on the nature of the contingency and the protection settings different load points experience different reliability events. The voltage sag, momentary interruptions and sustained interruptions resulting from both temporary and permanent failures are considered in this work. Sometimes, one reliability event experienced by the customer evolves to another one upon the sequence of protection device operations. It is illustrated with an example of a permanent fault on L4 in Figure 5.1. It causes the R2 to operate in order to clear the fault; therefore, LP3 and LP4 experience a momentary interruption during recloser operation. It should be noted that before R2 actuates, all the load points in the network experience voltage sag. However, after a preset number of operations, R2 lock-opens resulting in sustained interruptions for LP3 and LP4 until the repair is done. In these situations of the temporally evolving reliability events, the final reliability event due to a contingency is assigned to the load point. Such practices result into the better estimation of customer reliability profile and the associated financial losses.

Reliability evaluation frameworks are mostly based on failure mode and effect analysis (FEMA) using the contingency enumeration technique. This paper adopts the same approach. The steps illustrated in *Algorithm 5.1* quantifies different reliability events for load points and the system. It should be noted that the detailed protection system setting and restoration strategy is not explained in this work. Graph theory [14] or other suitable approaches [10] can be adopted for this purpose.

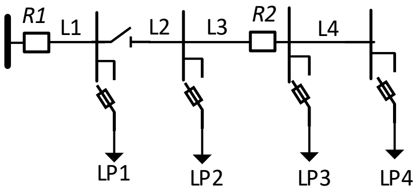

Figure 5.1. Distribution network for illustration purpose.

Algorithm 5.1: Quantification of reliability events. [2]

Step 1: Model contingency C^x (x equals tm and pm, for temporary and permanent fault). The fault can be further subdivided into three phase (3-ph), line to line (L-L), line to line to ground (L-L-G), and single line to ground (SLG). The temporary failure rate is assumed to be three times the permanent failure rate in this work [2], and the probability distribution of short circuit fault is assumed as follows: 5 % 3-ph, 15% L-L, 10% L-L-G, and 70% for SLG [12].

Step 2: Pick a contingency and simulate its impact on load points considering all the reliability events as described above in Section 5.3. Assign the load points experiencing sag and momentary interruptions to $L_{sag}^{c,x}$ and $L_{MI}^{c,x}$. Note $L_{SI}^{c,x}$ and $T_{l,SI}^{c,x}$ for the load points experiencing sustained interruption and the corresponding outage duration.

Step 3: Update the contribution of contingency towards the reliability events experienced by load points with (5.1) – (5.4).

$$F_{l,DSE}^{*c,x} = \Psi\left(M_{sag}, D_{sag}, S_{sag}^{cc}\right) \ \forall\, l \in L_{sag}^{c,x} \tag{5.1}$$

$$F_{l,MI}^{*c,x} = f^{c,x} \quad \forall\, l \in L_{MI}^{c,x} \tag{5.2}$$

$$F_{l,SI}^{*c,x} = f^{c,x} \quad \forall\, l \in L_{SI}^{c,x} \tag{5.3}$$

$$U_{l,SI}^{*c,x} = f^{c,x} \times T_{l,SI}^{c,x} \quad \forall\, l \in L_{SI}^{c,x} \tag{5.4}$$

Where, l is the load point index, and $f^{c,x}$ is the rate of occurrence of the contingency C^x (occ/yr). $F_{l,DSE}^{*c,x}$, $F_{l,MI}^{*c,x}$, and $F_{l,SI}^{*c,x}$ denote the frequency of 'disruptive voltage sag' (DSE), momentary and sustained interruption (occ/yr), respectively. $U_{l,SI}^{*c,x}$ represents the unavailability of a load point. The damage cost incurred to the load points ($D_{l,RE}^{c,x}$) for each type of reliability events due to the contingency is also evaluated [15]. These indices with an asterisk are obtained without considering the DERs/microgrids. The corresponding value after considering DERs/microgrids operation (to be discussed in Section 5.4) are denoted without an asterisk.

Step 4: Repeat Step 1 to Step 3 for all possible contingencies in the network and obtain load point reliability profile as given in (5.5) - (5.8).

$$F_{l,RE} = \sum\nolimits_c F_{l,RE}^{c,x} \quad \forall\, RE \in \{DSE, MI, SI\} \tag{5.5}$$

$$U_{l,SI} = \sum\nolimits_c U_{l,SI}^{c,x} \tag{5.6}$$

$$D_{l,RE} = \sum\nolimits_c D_{l,RE}^{c,x} \tag{5.7}$$

$$D_{l,tot} = \sum\nolimits_{RE} D_{l,RE} \tag{5.8}$$

Where, RE denotes the disruptive voltage sag, momentary interruptions and sustained interruptions when replaced by DSE, MI, and SI, respectively. $D_{l,RE}$ and $D_{l,tot}$ denote the damage cost (\$/yr) for load point l due to RE, and all the reliability events, respectively.

Step 5: Obtain the system reliability profile using load point reliability profile [15].

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[2] **Graph theory embedded aggregated reliability event model developed in Chapter 4 can be used for this purpose.**

It should be noted that the severity of voltage sag, as represented in (5.1), mainly depends on its retained magnitude$\left(M_{sag}\right)$, duration(D_{sag}), and the sensitivity of customer equipment/process to voltage sag(S_{sag}^{cc}) [12], [16]. In this paper, the sag events that are beyond the tolerance characteristic of customer equipment/processes are reported under 'disruptive voltage sag' (DSE) [16]. The voltage sag due to self-distinguishing faults are not considered.

The magnitude of voltage sag $\left(M_{sag}\right)$ greatly depends on the fault type, location of the fault, as well as the fault impedance. The fault position method is adopted, and the fault analysis is performed on the basis of classical symmetrical-component model to evaluate M_{sag} [17].

The corresponding duration of voltage sag (D_{sag}) depends on the short circuit level, fault-clearing times of protective devices, self-extinguishing nature of fault and the delay used in the protection settings [12], [16]. The probabilistic representation of fault-clearing time associated with a primary protection device can be represented with a probability distribution function (PDF) [16], [18]. This work incorporates the sag magnitude and the duration in a probabilistic manner to obtain the frequency of disruptive sag event as illustrated in [16], [18].

5.4. Scenario-Based Probabilistic Modeling of Reliability Solutions with ESS

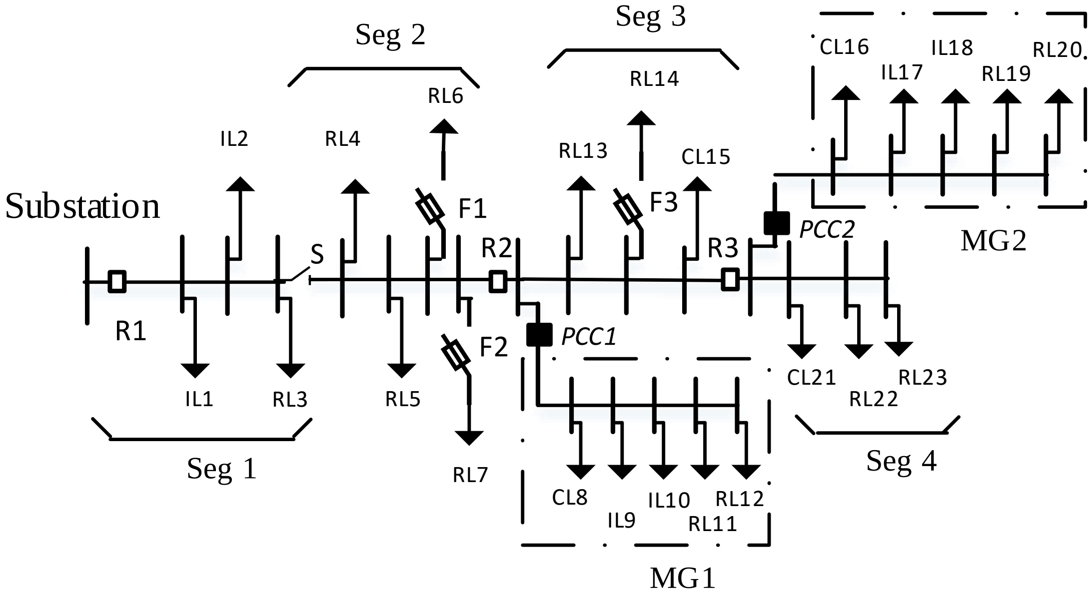


Figure 5.2. Test distribution network with DERs/micrograms.

This section develops the scenario-based stochastic modeling approach to assess the mitigation of reliability events with the ESS. The ESS could be present at the customer premise, integrated along the main feeder along with other distributed resources, or in a microgrid protecting one or more customer loads (MG1 and MG2 in Figure 5.2). Such microgrids generally have DGs, storage and controllable loads necessary to balance voltage and frequency while operating in an isolated mode in case of a fault in the utility supply side. The management and control system of the microgrid has the ability to switch into the isolated mode in a sub-cycle range with the help of fast acting switch at PCC, thus, preventing the damage to the sensitive loads [10]. The same switch at PCC [10] would clear any fault within the microgrid. The seamless transfer to the isolated mode and resynchronization with the utility grid helps mitigate voltage sag and momentary/sustained interruptions experienced by the microgrid customers.

The DERs integrated along the main feeder (Seg 3 and Seg 4 in Figure 5.2) generally disconnect as soon as they detect a fault [13]. However, they can be reconnected, and supply the load points located on a healthy segment of the network if the islanding operation is permitted. Such provision reduces the sustained outages experienced by the customers but cannot reduce the impact of voltage sag and momentary interruptions. Thus, the ESS (DERs) present at customer-premise, or inside the microgrid are considered to be able to mitigate both short and long duration reliability events, whereas the ESS (DERs) integrated along the feeder are considered to mitigate long duration reliability events only. The developed model incorporates the hardware availability, power rating, state of charge (SOC) levels, discharge duration of ESS. It also considers the intermittency of renewable DG, varying load level and energy limitation characteristics of ESS and the correlation between renewable DG output and the load. The following steps within *Algorithm 5.2* illustrate the probabilistic modeling of reliability event mitigation assessment with ESS. The model, thus obtained is integrated into the reliability evaluation framework (developed in Section 5.3) as described in *Algorithm 5.3*, thus completing the scenario-based probabilistic modeling of reliability event mitigation with ESS.

Algorithm 5.2: Probabilistic modeling of reliability event mitigation with the ESS.

Step 1: Obtain the original scenario set of hourly renewable DG output, e.g. solar photovoltaic (PV) output, wind generator output, and load level using the historical data.

Step 2: Divide the original set of scenarios into two groups; one with data from the daylight hours and one with data from the night hours to preserve the typical characteristic of PV not being available during nighttime.

Step 3: Use the scenario reduction method [10], [19] on both sets obtained from Step 2 and merge them to obtain the representative scenario set; $SC_{d,l} = \{SC_{d,l}^{sn},\ P_{sc,dg1}^{sn}, P_{sc,dg2}^{sn}, l_{sc}^{sn}, \pi_{sc}^{sn}\}$. Here, sn represents a scenario number representing the particular DG output $P_{sc,dg1}^{sn},\ P_{sc,dg2}^{sn}$, and load level l_{sc}^{sn} with the probability of π_{sc}^{sn}. The output of DGs for a scenario can be combined to get the DG output $P_{sc,dg}^{sn}$.

Step 4: Incorporate the ESS in the scenario set obtained above as follows:

4 Evaluate the power required from ESS, for a scenario sn ; $P_{sn}^{ES,req} = \left(l_{sc}^{sn} - P_{sc,dg}^{sn}\right)$

5 Evaluate $chk_p = P_{ava}^{ES} - P_{sn}^{ES,req}$. The available power of ESS (P_{ava}^{ESS}) depends on the hardware availability and rated power.

6 If $chk_p < 0$, assign $\pi_{ES}^{sn} = \pi_{sc}^{sn}$, else; $\pi_{ES}^{sn} = \pi_{sc}^{sn}\, e^{\frac{-D_{ava}^{ESS}}{r_l^c}}$ where r_l^c is the average outage time for load point l due to contingency without considering ESS operation. The discharge duration available (D_{ava}^{ESS}) for a scenario sn is given by $D_{ava}^{ES} = max(\frac{\eta \times SOC_{ini} \times P_{ava}^{ES} \times T_{rated}^{ES}}{min(P_{sn}^{ES,req},\ P_{ava}^{ESS})}, 0)$ where η, T_{rated}^{ES}, and SOC_{ini}, respectively denote the efficiency, the discharge duration at the rated ESS power, and the SOC of ESS (expressed in per unit).

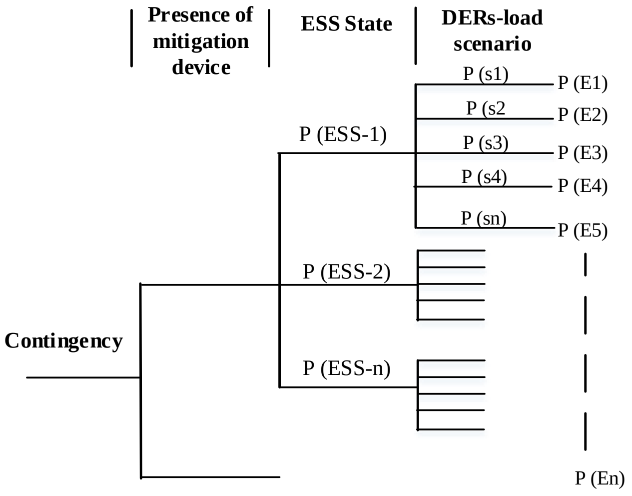


Figure 5.3. Tree diagram of scenarios following a contingency.

Algorithm 5.3: Integration of model developed in Algorithm 5.2 into the reliability assessment framework.

Step 1: Form an event tree considering all the possible events (Ex) following an occurrence of C^x. It incorporates the status of fault isolation and the presence of mitigation measures, hardware availability, the capacity state of ESS, different scenarios of DG output level and load level, as shown in Figure 5.3.

Step 2: Evaluate the probability of events, $P(Ex)$, where x is the event number ranging from 1 to a total number of events (n).

Step 3: Pick an event (from $(E1)$ to (En)) from an event tree and execute *Algorithm 5.2* to find the probability of reliability event (RE) not being mitigated for a load point as given in (5.9).

$$P^{c,x}_{l,RE}(Ex) = P(Ex) \times \pi_{ES} \tag{5.9}$$

Step 4: Repeat the Step 2 – Step 3 until all the scenarios of the event tree are covered, and update (5.10).

$$P^{c,x}_{l,RE} = \sum_{x=1}^{n} P^{c,x}_{l,RE}(Ex) \tag{5.10}$$

Step 5: Modify the frequency/duration indices in (5.1)-(5.4) as represented by (5.11)-(5.12).

$$F^{c,x}_{l,RE} = F^{*c,x}_{l,RE} \times P^{c,x}_{l,RE} \quad \forall\, RE \in \{DSE, MI, SI\} \tag{5.11}$$

$$U^{c,x}_{l,SI} = U^{*c,x}_{l,SI} \times P^{c,x}_{l,SI} \tag{5.12}$$

5.5. Case Studies and Discussions

Figure 5.2 shows the test distribution system, which is the modified version of feeder 4 at Bus 6 of the Roy Billinton Test System (RBTS) [15]. The residential, commercial and the small industrial customer load points are indexed with “RL”, “CL”, and “IL”, respectively. Each residential customer load point “RL” is assumed to have 79 customers with a peak load of 0.27 MW. The corresponding values for “CL” and “IL” are 7 and 0.5 MW, and 1 and 1 MW, respectively. The recloser, fuse, and automatic sectionalizer are indexed with “R”, “F” and “S”, respectively in Figure 5.2. The times to failure and repair are characterized by exponential distributions. The permanent failure rate and average repair time for the lines are taken to be 0.046 occ/yr-km and 5 hr respectively. The switching time for the manual switches/sectionalizers is 0.5 hr. The fuse replacement time is taken as 1.5 hr.

The line impedance and other short circuit parameters are taken from [20]. The mean values of fault clearing time for fuse and reclosers are 50 ms and 300 ms with 10% standard deviation. The ride-through capability for different customer categories is assumed as follows: sag magnitude of 0.85 and duration of 40 ms for commercial/industrial customers, and the corresponding values for residential customers are 0.75 and 300 ms, respectively. The damage cost associated with sag event is assumed to be equal to that of momentary interruption. The damage cost data for sustained outages is taken from the Canadian survey [15]. The results associated with the customer financial losses in the presented studies compliment the information obtained from the reliability indices. The damage cost is the function of the customer category, outage duration and average demand of a customer [15].

5.5.1. End-User Reliability Profile with ESS

This section explores the role of ESS towards mitigating different reliability events for a customer sensitive to short duration reliability events. In addition, the reliability impacts from other resources is also discussed. The critical loads are fed with utility supply during normal condition. The ESS take up the load in isolated microgrid mode in case of utility supply disturbances within a fraction of cycle [8]. The supply is transferred back to the utility after the utility supply becomes normal. Based on this assumption, the reliability benefit from ESS is assessed executing the algorithm developed in Section 5.3 and 5.4. The component availability model of ESS as described in [21] is used. This study considers Sodium Sulfur based “PQ-50" module [21] batteries rated at 1 MW and 7 MWhr capacity. The efficiency and the allowed minimum SOC are taken as 90 % and 10%, respectively. The hardware unavailability for ESS is assumed 2%. The ESS rated capacity is matched to support the entire load, hence the variation in load is neglected in this study.

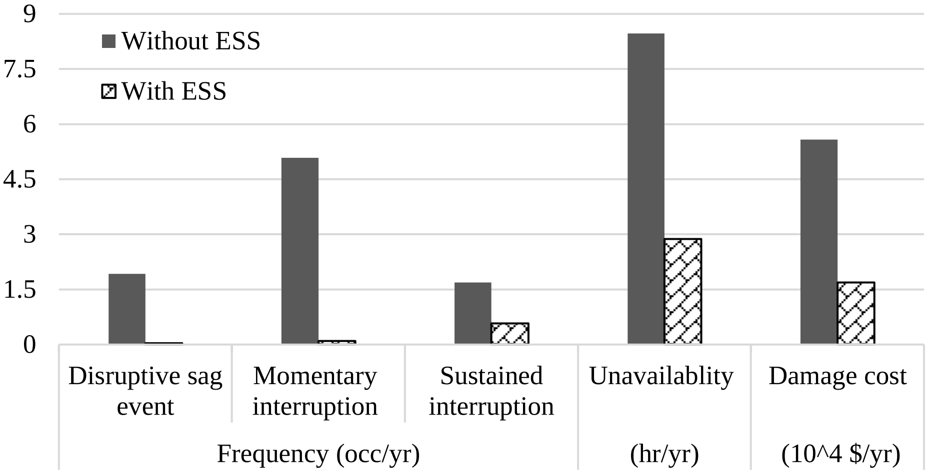
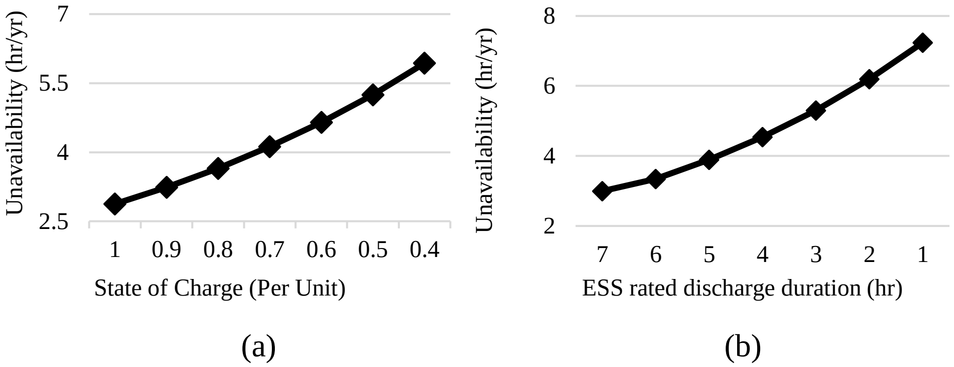


Figure 5.4. Improvement in the reliability profile of IL9 with ESS.

It should be noted that reliability performance of load point IL9 is poor, as it is located far from the substation in a radial distribution feeder. Figure 5.4 shows the reliability indices of IL9 with and without ESS (without considering the operation of DERs/microgrids). The y-axis of Figure 5.4 shows the magnitude of annual outage time, damage cost and frequency of disruptive sag, momentary and sustained interruptions. The results indicate that the ESS is effective in improving the reliability performance in both the short and long duration reliability events. It should be noted that the frequency of short duration reliability events are reduced significantly compared to the sustained interruption based indices. It is because the discharge duration and the SOC of ESS can significantly limit the mitigation of sustained interruption but have little impact on short duration reliability events. The mitigation of sustained interruptions greatly depends on the initial SOC at the time of contingency, efficiency, and the discharge duration of BESS. In addition, the reliability improvement depends on the hardware availability as well.

Another study is conducted to analyze the impact of initial SOC at the time of occurrence of the contingency, and the rated discharge duration of ESS to mitigate the long duration outages. Figure 5.5 (a) and (b) respectively show that load point unavailability increases with a decrease in SOC and rated discharge duration in the case of sustained forced outages. The sustained interruption frequency follows the similar trend. That means if the ESS is utilized for peak shaving, or other application instead of standby mode, the ability of ESS mitigating the sustained outages reduces. However, it does not significantly affect the mitigation for short duration reliability events. Given that the batteries suffer from degradation and need the periodic replacement due to limited life cycle, the other ESS technologies, such as Flywheel, Magnetic energy storage systems (SMES), Supercapacitor, etc. are also used to protect critical loads. These technologies, however, cannot retain energy for a long duration, and therefore, need to be used with other resources (battery, backup generator, etc.) to reduce the financial impact due to long duration reliability events.



(a) (b)

Figure 5.5. Impact of (a) ESS sate of charge and (b) the rated discharge duration on the unavailability of IL9.

The hardware failure of ESS also plays a vital role in the relative reliability improvement. Both the short and long duration reliability event based indices are affected by component failures. A case study was conducted by varying the hardware unavailability of ESS, and the total damage cost incurred to the customer connected at IL9. Figure 5.6 shows the increase in damage cost with increase in ESS unavailability. The hardware availability depends on the maintenance practices, the configuration of ESS, failure characteristics of components, etc. The results in Figure 5.6 provides useful information in investing in ESS component reliability.

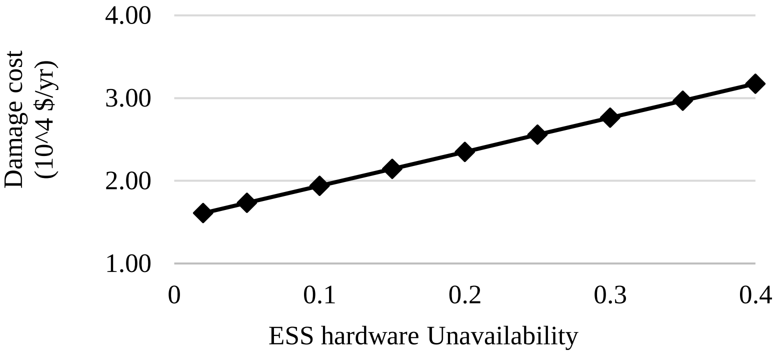


Figure 5.6. Impact of ESS hardware unavailability on the financial losses of IL9.

Apart from using the ESS in microgrid mode taking up the critical loads in case of utility supply disturbances (as described above), other means of reliability solutions, especially for voltage sag, are also in practice in industries. The injection of series voltage or the series voltage by extending the existing power electronic interface used for the DG operation help reduces the impact of voltage sag [7]. The power electronic based devices such as FACTs, STATCOM, SVC, DVR, TVR, etc. can also be used to mitigate the voltage sag of the overall system as well as the individual buses [5], [6]. Their effectiveness to mitigate voltage sag depend on the rating and the location. Although such practices are effective to mitigate voltage sag, it does not contribute to mitigating the interruptions.

5.5.2. DERs/microgrids and Reliability Improvement

In this section, the role of DERs/microgrid in mitigating the reliability events is discussed. The microgrids (MG1 and MG2), and the DERs are integrated (in Seg 3 and Seg 4) into the distribution network as shown in Figure 5.2. For the purpose of illustration, the microgrids and the DERs are assumed to consist of PV arrays, wind generators, and an ESS. The historical data for the wind speed and the PV irradiance is taken from [22], and the corresponding power outputs are obtained using the analytical set of equations [23]. The microgrids have the installed PV and wind generator capacity of 0.6 MW each, and an ESS rated at 1.4 MW/9.8 MWhr. The Segment 3 and Segment 4 of Figure 5.2 are assumed to have half the capacity of each resource inside the microgrid. The SOC and the hardware unavailability used in Section 5.5.1 is used.

Table 5.1 shows the reliability improvement for the customers benefited with DER/microgrid operations. The reliability profile of the customers within MG1 indicate that the implementation of microgrid helps reduce the impact of voltage sag, momentary interruption, sustained interruptions. The customers within MG2 experience the similar improvement in their reliability profile. The islanding operation of DERs in Segment 3 reduces the associated annual outage time (Unavailability). However, the frequency of momentary interruptions for these customers appears to be increased. It is due to the restoration of supply with DERs through automatic switching, as mentioned in Section 5.3. There is no change in the frequency of disruptive sag event since the voltage sag mitigation with such DERs is not considered. The customers within Segment 4 of the test network experience the similar reliability improvement as that of Segment

3. The total customer damage cost reported in Table 5.1 shows that the integration of DERs/microgrid reduces the financial losses incurred to the customers.

Table 5.1. Reliability improvement (%) with DERs/microgrids.

MG/ Segment	Disruptive sag frequency	Momentary int. frequency	Unavailability	Total damage cost
MG1	33.85	21.61	18.75	19.72
Seg 3	0	-10.34	30.31	29.63

In the deregulated environment, the utilities are rewarded/penalized based on their system reliability performance as part of the performance-based rate-making. Integration of DERs/microgrids improves the reliability of the worse performing load points as well as the overall network as reported in Figure 5.7. The results show the decrement in the system indices of annual outage time, damage cost, and the frequency of disruptive sag event, momentary and sustained interruptions with the DERs/microgrids operation. However, the incremental reliability benefits are highly influenced by the network topologies, provision of fault isolation within the microgrid/segments of the network, the rated power/energy capacity of the resources, intermittency/variability of renewable DGs, the system load profile, operation modes of ESS, hardware availability of resources, etc. The results of the case studies presented in this section support the possibility of reliability solutions with DERs/microgrids in the context of the distribution system.

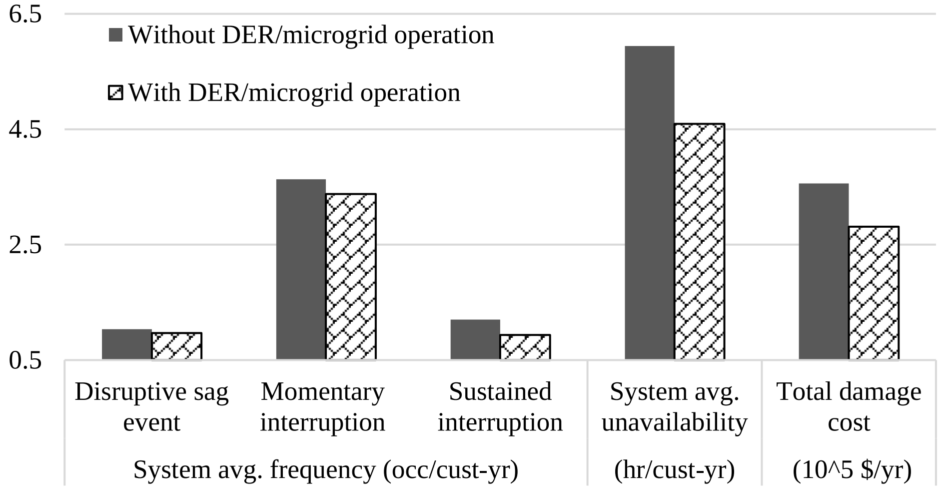


Figure 5.7. System reliability performance with DERs/microgrids.

5.6. Conclusion

This paper explores the role of ESS towards providing reliability solutions in the context of the active distribution system. In this regard, a scenario-based probabilistic modeling approach is presented to assess the role of ESS, together with DGs, to mitigate different reliability events (voltage sag, momentary interruptions, and sustained interruptions). A range of case studies conducted shows that the incremental reliability benefits with ESS highly depend on the technology type, rated power, hardware availability, rated energy, operating mode and the presence of other distributed energy resources. The results and the discussion presented in this paper imply that the sensitive customer can protect the critical load against the disruptive reliability events with ESS. Furthermore, the integration of DERs/microgrids can provide reliability solutions utilizing the advanced control, monitoring and the communication facilities of the smart grid. The approach and the case studies provide the valuable insights for the reliability-centric system upgrades/investments in the context of the active distribution system.

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CHAPTER 6: SUMMARY AND CONCLUSIONS

In recent years, the penetration levels of renewable energy based distributed generations (DGs) in distribution networks are increasing mainly driven by environmental concerns and technological advancements. The renewable energy based DGs, however, affect the reliability and the optimal operation of the power distribution system due to the associated intermittency and variability. The strategic utilization of energy storage systems (ESSs), microgrids, and smart distribution technologies is perceived as solutions to the aforementioned issues. Furthermore, electric customers in today's deregulated environment are increasingly expecting better reliability and power quality, especially with the widespread use of the sensitive equipment/processes. Thus, the supply reliability is an important concern in the planning and regulation of distribution systems.

The reliability benefits introduced by the integration of distributed energy resources (DERs) depend on the ownership of these resources, market structure, and the regulatory framework. The benefits from utilization of renewable energy, deferral of network expansion, and enhanced supply reliability are well recognized for the distribution system operator (DSO)-owned DERs. Electric power utilities in some jurisdictions are not allowed to own DERs. In this context, it should be ensured that there is an appropriate market structure, regulations, and the effective coordination between DSO and the private investors to avoid inefficient system planning and operation. A generalized probabilistic framework has been developed in this thesis to evaluate the reliability value of ESS in the context of active distribution systems considering different scenarios of ownership, market and regulatory structures, and ESS characteristics. A probabilistic reliability model of ESS is developed, and it is integrated into the sequential Monte Carlo simulation framework to assess the reliability value. The developed ESS model consists of Markov based component model, and the mixed integer linear programming (MILP) based formulation of operating strategies. The formulated operation strategies incorporate different scenarios of ownership, market structures relevant to the future distribution systems, and the ESS characteristics. Further, the developed ESS reliability model preserves its inter-temporal and energy limitation characteristics while operating at the different modes in correlation with the fluctuating nature of renewable DG output, time-dependent load variation, and other system variables. Utilizing the proposed model, the financial risk/reliability performance of the DSO with ESS under quality regulations are quantified. Furthermore, the prospect of investor-owned ESS providing supply recovery during sustained outages of utility supply and distribution grid capacity services to the DSO are explored. The discussions on the changes to be made in the existing market structures and polices are presented with a range of case studies.

The results from the case studies indicate that the integration of storage in distribution system helps improve the reliability of the worse performing section, as well overall system lowering the financial risk of DSO under quality regulations. ESS offers considerable environmental and reliability benefits by utilizing renewable energy more efficiently when it is deployed together with renewable resources. It is revealed through the case studies that the effective coordination between DSO and the ESS owner can ensure that the ESS can offer reliability services to the DSO, e.g. supply recovery to valuable customers during utility interruptions and distribution grid capacity enhancement. The location, sizing, market scenarios, and the operating strategy are found to be important factors to determine the effectiveness of ESS for such applications. The reliability services provided by the ESS should be evaluated recognizing pertinent regulatory framework and market structures in order to efficiently exploit ESS along with other distributed resources and achieve the socioeconomically optimal level of reliability.

Another important aspect of a modern distribution system is the increased reliability needs of customers, especially with the introduction of sensitive process/equipment. These devices are susceptible to mis-operation even with short duration reliability events (voltage sag and momentary interruptions). The financial losses of an industrial facility/commercial customer due to industrial process disruption or malfunction of equipment due to short duration reliability events could be substantial. These short duration reliability events have been modeled and incorporated in the presented reliability studies. An aggregated reliability event modeling approach is developed and presented in this thesis to address these issues. The developed model considers both short and long duration reliability events due to temporary and permanent failures. In addition, the model efficiently recognizes different protection settings, alternate supplies, and DERs/microgrids utilizing the graph theory based search algorithm. The developed methodologies are effective to assess the reliability solutions with ESS considering storage technology type, the power/energy rating, hardware availability, and the presence of DGs and microgrids in detail. The reliability at the load point/customer and the system level is quantified with the load point reliability profile and system reliability profile that consists of frequency/duration based metrics, as well as the associated damage costs for different reliability events. The proposed frameworks can be utilized for the reliability assessment and planning system upgrades in the context of a utility-scale active distribution systems.

The results reported in the thesis underscore the importance of inclusion of voltage sag and momentary interruptions in the reliability studies to provide more accurate estimation customer reliability owing to the higher reliability needs of modern electric customers. The studies reveal that the protection setting has a significant impact on a wide range of reliability events experienced by the customers. The DG, ESS, and microgrids are effective in providing reliability solutions utilizing the advanced control, monitoring and the communication facilities of the smart grid. The case studies conducted on the use of ESS in mitigating the adverse reliability impacts on the end-users show that the ESS is effective in improving the reliability performance in both the short and long duration reliability events. The mitigation of sustained interruptions greatly depends on the initial state of charge of ESS at the time of contingency, its efficiency, and the discharge duration. The hardware failure of ESS also plays a vital role in the relative reliability improvement. Both the short and long duration reliability event based indices are affected by such failures. It is shown that the incremental reliability benefits brought by the ESS, DGs and microgrids are highly influenced by the distribution network topologies, protection settings, the rated power/energy capacity of the resources, intermittency/variability of renewable DGs, the system load profile, operation modes of ESS, and hardware availability of resources.

This thesis has investigated different aspects of modern distribution systems and their impact on supply reliability. The overall significance of this thesis is that it provides systematic and generalized approaches to examine the reliability issues and the possible solutions with ESS and other distributed energy resources in the context of modern distribution systems. The methodologies proposed are readily applicable, thus can be utilized by the policy-makers, regulators, and the electric utilities to study the implications of new trends and technologies of distribution system on the customer reliability. Furthermore, the case studies and the discussions presented in this work provide valuable insights in formulating market mechanism and regulatory policies regarding the use of ESS in future distribution system operation and planning.