RELIABILITY ANALYSIS OF MICROGRID

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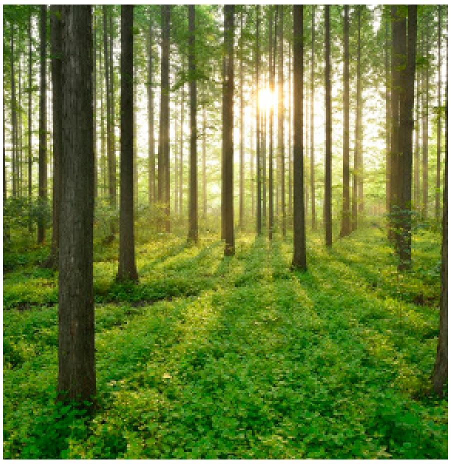

RISK- OCH TILLFÖRLITLIGHETSANALYS

Energiforsk

Reliability Analysis of Microgrid

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Förord

Programmet *Risk- och tillförlitlighetsanalys* har initierat och genomfört projektet T*illförlitlighetsanalys för mikronät*. Microgrid består av lokal distribuerad produktion, last och energilagring. Det har blivit en viktig del av distributionssystem och implementeras alltmer för att bygga framtidens elnät. Microgrid kan användas antingen i nätanslutet läge eller öläge, och har potential att förbättra tillförlitligheten vid lokala belastningar genom att smidigt växla mellan nätanslutet läge och öläge. Syftet med projektet är att tillhandahålla en användbar metod för tillförlitlighetsanalys av mikronät, som direkt kan användas för att bedöma och utvärdera tillförlitligheten hos praktiska mikronät. Metoden kommer också att kunna hantera osäkerhet och betydande fellägen i mikronätet. Projektet kommer att ge ett exempel på fallstudie på ett verkligt mikronät.

Projektet har genomförts av Ying He från Vattenfall AB. Stort tack till programstyrelsen för deras initiativ och stöd till projektet:

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Följande bolag har deltagit som intressenter till projektet. Energiforsk framför ett stort tack till samtliga för värdefulla insatser.

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These are the results and conclusions of a project, which is part of a research programme run by Energiforsk. The author/authors are responsible for the content.

Summary

Microgrid is a part of a distribution system that contains distributed generation sources such as wind and solar power. Microgrid can be operated both in grid-connected mode and in islanded mode. This flexible operation ability of microgrid offers potentially possibility to enhance the power supply reliability to the local customers.

Microgrid may reduce the power interruptions through islanding operations in the fault events upstream supplying local customers with its own generation, and thus improve the reliability. This benefit has been increasingly recognized. Microgrid has become an important component of a distribution system. The penetration of microgrid has been on the rise in recent years. This phenomenon has even been stimulated by deployment of small-scale renewable energy sources. Perhaps the most compelling consideration of developing microgrid has been going towards a more reliable power supply to consumers.

In the development of microgrid, its security and reliability analysis becomes an important issue in order to ensure reliable power supply. To perform reliability analysis of microgrids is still challenging in the design and evaluation process. The power output from local wind and solar energy resources is random and instable. The reliability analysis is even more complicated by the flexible operation modes of microgrid to switch between islanded mode and grid-connected mode. These local power characteristics and unique operation feature of microgrid make the reliability analysis of microgrid significantly different from the ones for conventional distribution systems.

This report proposes a method for practical reliability analysis of microgrid. The method is able to deal with uncertainty and significant failure modes of microgrid, and can be used to evaluate reliability of practical microgrid. The method incorporates power output characteristics of intermittency and randomness of local renewable energy as well as the flexible operation modes of microgrid so that their influence on the reliability are included in the reliability assessment.

Using the method proposed a case study on a real microgrid, Arholma system, are performed. The analysis process, illustration of assessment technique, and numerical calculations are detailed in the report. The overall structure and the workflow of the method are also given in the report.

Keywords

Microgrids, reliability, grid-connected operation, islanded operation, distributed generation, applicable method

Sammanfattning

Mikronät är del av ett distributionssystem som innehåller distribuerade produktionskällor som vind- och solenergi. Mikronät kan drivas både i nätanslutningsläge och i ö-drift. Denna flexibla driftförmåga erbjuder potentiellt möjlighet att förbättra elleveranstillförlitlighet till lokala kunder.

Mikronät kan reducera elavbrott genom ö-drift vid felhändelser i överliggandenät att försörja lokala kunder med egen produktion, och därmed förbättrar elleveranssäkerhet. Mikronät har blivit en viktig komponent i distributionssystem. Uppbyggnader av mikronät har ökat de senaste åren. Detta fenomen har till och med stimulerats av användningar av småskaliga förnybara energikällor. Det kanske mest övervägandet med att utveckla mikronät är att gå mot mer tillförlitlig elleverans till konsumenter.

För att säkerställa elleveranssäkerhet blir tillförlitlighetsanalys en viktig fråga i utveckling av mikronät. Hur ska tillförlitligheten av ett mikronät utvärderas? Att utföra tillförlitlighetanalys av mikronät är en utmaning i planering- och utvärderingsprocessen. Produktion från lokala vind- och solenergikällor är slumpmässig och fluktuerande. Tillförlitlighetsanalysen blir ännu komplicerad av mikronäts flexibla driftsätt att växla mellan nätanslutning och ö-drift. Egenskaperna hos lokala energikällor och unika driftsätt hos mikronät gör att tillförlitlighetsanalys på mikronät skiljer sig väsentligt från tillförlitlighetsberäkning för konventionella distributionssystem.

Denna rapport rekommenderar en metod för praktisk tillförlitlighetsanalys av mikronät. Metoden kan hantera osäkerheter och fel fall och användas för att utvärdera tillförlitlighet hos mikronät. Metoden har tagit hänsyn till oregelbunden och slumpmässig produktionskaraktär av lokala förnybara energikällor, samt det mikronäts flexibelt driftsätt, så att deras inverkan kan inkluderas i tillförlitlighetsbedömningen.

Med den rekommenderade metoden har en case studie genomfört i rapporten på ett riktigt mikronät, Arholma nät. Analysprocess, utvärderingsteknik och beräkningar har förklarats och beskrivits i detalj i rapporten. Metodens helhets struktur och arbetsflöde anges också i rapporten.

Nyckelord

Mikronät, tillförlitlighet, nätanslutning, ö-drift, distribuerad generering, tillämplig metod

List of content

Nomenclature

Symbol	Description
AENS	average energy not supplied (kWh/yr.cust)
ASAI	average service availability index
BESS	battery energy storage system
c	scale parameter of Weibull function (m/s)
C_i	generation capacity
C_k	amount of load curtailment = $L_i - C_i$
DG	distributed generation
EENS	expected energy not supplied
Er	reference temperature
ESS	(battery) energy storage system
$f_b(s)$	Beta distribution function of s
FF	fill factor
FTA	fault tree analysis
f(v)	probability density function
$f_r(v)$	Rayleigh probability distribution function.
F(v)	probability distribution function, probability of wind speed
G_{AC}	light intensity
G_{STC}	light intensity for the STC 1000W/m2
G_{TS}	generation output in kW in time segment TS
i	component i between load point and supply point
IEED	island expected energy efficiency
ILOLP	island loss of load probability
IOSR	Island Operation Successful Rate
I_{sc}	short circuit current (A)
I_y	current of state y (A)
j	DG j
k	shape parameter of Weibull function
K	power-temperature coefficient of 0.0047 W/ C^o

Kc	threshold value
K_i	current temperature coefficient (A/C^0)
K_v	voltage temperature coefficient (V/C^0)
$L_{a(i)}$	average load connected to load point i
$L_c(R)$	load curtailment (load not supplied)
$I_d(t)$	solar altitude angle.
L_i	expected load demand
I_{MPP}	current at maximum power point (A)
LOEE	loss of energy expectation
LOLE	loss of load expectation
L_{TS}	load demand in kW in time segment TS
MCS	Monte Carlo Simulation
MIOP	Microgrid Islanded Operation Probability
N	number of wind speed records; number of cells; total number of simulated years
ND	number of time segments when total generation output cannot satisfy total load demand in the island in one year
N_i	number of customers of load point i
NI	island formation times in one year
N_{OT}	nominal operating temperature of cell (C^0)
N_P	number of panels
n(R)	number of risk states when power insufficiency occurs
P	probability of unsuccessful isolated operation
PCC	point of common coupling

Pcharge, Pdischarge: charging and discharging power of energy storage system

Pcharge,min, Pcharge,max: minimum and the maximum charging power

PDF	probability density function
P_{DG}	DG output power

Pdischarge,min, Pdischarge,max: minimum and the maximum discharging power.

P_{ESS}	energy storage system output power
$P_{BESS}(h)$	BESS output power

P_g	probability of microgrid operating in grid connected mode
P_i	probability of specific capacity outage
P_k	individual probability of capacity in outage
P_L	power load
$P_L(h)$	total load power
P_M	main grid power
P_{PV}	output of the PV modules
$P_{PV}(h)$	PV output power
P_{PVm}	PV maximum output for a period of time
P_R	rated output power (MW)
$P_s\{G_y\}$	probability of the solar irradiance being in state y
Psr	rated output of the PV modules
P_{STC}	maximum test power at the standard test conditions (STC, intensity of sunlight 1000W/m2, ambient temperature 25 Co)
P_{sy}	output power of the PV module during state y
$P_{WTG}(h)$	WTG output power
PV	photovoltaics
p(v)	wind turbine output power at wind speed v (MW)
p(v)	wind turbine output power at wind speed v
P_{WTG}	wind power output
RER	renewable energy resources
RES	renewable energy sources
r_i	repair time of component i (h/f)
r_{lp}	outage time of load point (h/f)
r_{lp_g}	outage time of load point in grid connected mode (h/f)
r_{lp_h}	outage time of load point in hybrid mode (h/f)
r_{lp_is}	outage time of load point in island mode (h/f)
r_{up}	repair time of upstream system (h/yr)
S	solar illumination, or S_p x N_p
s	solar irradiance (kW/m^2)
SAIFI	System Average Interruption Frequency Index

SAIDI System Average Interruption Duration Index

s_{ay} average solar irradiance of state y

SD standard deviation

SOC charging state of energy storage system

SOCmin, SOCmax: the minimum and the maximum charging capacities

S_p area of the solar panel

Sr reference solar illumination.

STC standard test conditions

s_{y1}, s_{y2} solar irradiance limits of state y

Ta ambient temperature

T_c solar panels working temperature

T_{cy} cell temperature during state y (C^0)

T_{DGj} fault repair time of DG j (h/f)

t_k duration of loss of power supply in hours

T_r reference temperature of 25 C^0

t(R) time duration in the risk state

TS time segment

T_{TS} duration of time segment TS in hour

U_i annual outage time of load point i

U_{lp} annual outage time of load point (h/yr)

U_{lp_g} annual outage time of load point in grid connected mode (h/yr)

U_{lp_h} annual outage time of load point in hybrid mode (h/yr)

U_{lp_is} annual outage time of load point in island mode (h/yr)

U_{up} unavailability of upstream system (h/yr)

v wind speed, or wind speed at the height of the wind turbine hub (m/s)

V2G vehicle to grid

v_{ci} cut in wind speed (m/s)

v_{co} cut out wind speed (m/s)

v_m average wind speed (m/s)

V_{MPP} voltage at maximum power point (V)

V_{oc}	open-circuit voltage (V)
v_R	rated wind speed (m/s)
V_y	voltage of state y
WT	wind turbines
WTG	wind turbine generator
α, β	parameters of the Beta distribution function
Γ	standard gamma function
$\Gamma(x)$	Gamma function of x
$\Delta I(t)$	random amount of attenuation
η_c	conversion efficiency of PV system
λ_{DGj}	failure rate of DG j (f/yr)
λ_i	failure rate of load point i
λ_{lp}	failure rate of load point (f/yr)
λ_{lp_g}	failure rate of load point in grid connected mode (f/yr)
λ_{lp_h}	failure rate of load point in hybrid mode (f/yr)
λ_{lp_is}	failure rate of load point in island mode (f/yr)
λ_{up}	failure rate of upstream system (f/yr)
σ	standard deviation of random variable of s
μ	mean of random variable of s

1 Introduction

Microgrid is a section of a low voltage or medium voltage distribution system that contains distributed generation, loads and energy storage devices. The generation in microgrid can be wind turbines or photovoltaic (PV) systems with a rated power in a range from a few kW to a hundred kW. A microgrid can act as a single controllable entity with respect to the main grid. It can connect and disconnect from the grid to enable it to operate in grid-connected mode or islanded mode.

The microgrid's ability to operate in the islanded mode offers potentially possibility to enhance the power supply reliability to the local customers. In a fault event occurred in the main grid, the microgrid can be isolated from the grid and supply power to its customers with its own power generation. Thus the power supply to the loads in microgrid would not be interrupted by the fault upstream.

The existence of a microgrid may reduce the power interruption through islanding operation and thus improve the reliability of the power supply. This benefit has been increasingly recognized. Microgrid has become an important component of distribution systems and has been successively implemented in building the future smart grids. The penetration of microgrid has been on the rise in recent years. This phenomenon has even been stimulated by other factors, such as deployment of small-scale renewable energy sources, and avoidance of transmission and distribution expansion. Perhaps the most compelling consideration of developing microgrid has been going towards a more reliable power supply to consumers.

In the development of microgrid, its security and reliability analysis becomes an important issue in order to ensure reliable power supply to customers of the microgrid. However to perform reliability analysis of microgrids is still challenging in microgrid design and evaluation process. The power output of local wind and solar energy resources in microgrid is random and fluctuant. The reliability analysis is even more complicated by the flexible operation modes of microgrid to switch between islanded mode and grid-connected mode. These local power characteristics and unique operation feature of microgrid make the reliability analysis of microgrid significantly different from the ones for conventional distribution systems.

Reliability analysis of microgrid has been increasingly recognized to be one of the major challenges in the development of microgrid. Many efforts have been put on this area. A number of studies and projects are in progress to develop methods and to provide solutions for evaluating the reliability of microgrid.

1.1 PURPOSE OF THE PROJECT

The purpose of the project is to provide an applicable method for reliability analysis of microgrid. The method will be able to deal with uncertainty and significant failure modes of the microgrid, and can be directly used to judge and evaluate reliability of a practical microgrid.

The method will incorporate power output characteristics of intermittency and randomness of local renewable energy and the flexible operation modes of microgrid so that their influences on the reliability could be included in the reliability assessment.

It is intended that by the effort of this project, reliability of microgrid can be calculated in a simply structured and logical way, and the method provided by the project can be applied practically in microgrid design and evaluation process.

1.2 PROJECT WORK

The project is made up of three core work parts as described below:

1.2.1 Work Part 1: Literature study

The purpose of work part 1 is to search, review and capture existing well-developed and well-documented models and method for reliability evaluation of practical microgrid of power utility.

The literature study will start with searching literature and reports relating to reliability of microgrid as used for power industry. The study will focus on technologies, analysis methods, specific reliability indices for microgrid and experiences of application in power industry. The predominant aspects of the literature study include:

- Practical way to incorporate intermittent and fluctuant characteristics of local renewable power of microgrid in the reliability assessment, as well as the associated reliability indices.
- Applicable technique to quantitatively assess influence of grid-connected and islanded modes so that the effect of these two operation modes can be included in the reliability evaluation of microgrid.
- Models and method to treat battery energy storage system of microgrid and related reliability indices.
- A suitable set of reliability indices and associated input data required for reliability analysis of microgrid.

1.2.2 Work Part 2: Case study

The purpose of subsequent work part 2 is to apply the method captured from the literature study and perform case study on a real microgrid of a Swedish power company.

The case study will show reliability analysis process, and illustrate assessment technique and numerical calculations. By using the practical example the case study will explain how to account for significant failures of microgrid and how to use the method to judge reliability of a microgrid.

1.2.3 Work Part 3: Recommendation and report

The purpose of work part 3 is to recommend an applicable method for reliability analysis of microgrid based on the literature review and the case study, as well as to summarize results of the project.

1.3 PROJECT LIMITATIONS

The project is carried out under the following constraints and limitations:

- Reliability modelling and analysis of microgrid for academic research purpose will not be included in the project.
- V2G (vehicle to grid) model of electric vehicles will not be considered in the project.
- Local power generation of microgrid will not include diesel generator.
- Weather effect will not be considered in the reliability analysis of microgrid.

2 Literature study

The literature study began by searching literature relating to the reliability evaluation of microgrid used for power industry. The literature review was focused on the studies on the reliability modelling and analysis of microgrid in the field and the components of the microgrid, such as wind turbines, PV systems, and battery energy storage systems.

The literature search was focused on articles and papers covering microgrid reliability analysis. The following predominant themes were considered for the study:

- Microgrid structure and operation modes
- Reliability evaluation method categories
- Reliability indices used for microgrid
- Wind power output modelling
- Solar power output modelling
- Energy storage system reliability modelling

Articles and papers were studied for relevance to capture the main technologies, analysis methods and conclusions of each paper. The key findings and results under each theme are presented in the following sections.

2.1 MICROGRID, ITS STRUCTURE, CATEGORY AND OPERATION MODE

A microgrid is associated with a low voltage distribution network, small local power generation systems (microgenerators), loads and energy storage devices which have some local coordinated functions [1]. The microgenerators can be wind turbines, micro-turbines or PV systems with a rated power in a range from a few kW to a hundred kW.

The microgrid is usually constructed as an aggregation of loads and microgenerators operating either as grid-connected or a single system to provide power to the loads. The control flexibility allows the microgrid to operate connected to the grid as well as smooth transition to and from the island mode [2].

The basic microgrid architecture is normally radial with a few of feeders and a collection of loads. The micro energy sources are interfaced to the system through power electronics. The Point of Common Coupling (PCC) is on the primary side of the transformer and defines the separation point between the grid and the microgrid.

The microgrid can be classified as AC, DC, and a combination of both, hybrid microgrids. AC microgrids are usually configurated so that all the power sources are connected to AC bus. In the case of power sources that generate DC power, the conversion is needed with the help of power electronic inverter. The AC power sources are connected directly to the AC bus without any power converter. The storage units are connected via bidirectional converters.

The configuration of DC microgrids is opposite to that of AC microgrid. All the power sources are connected to DC common coupling bus. The DC power sources are connected directly to DC loads via the DC common coupling bus. The AC power sources are connected to the microgrids through the power electronic converters.

The hybrid microgrids combine the use of AC and DC microgrids. It has two common coupling buses, a AC bus and a DC bus. In this configuration all AC power sources are connected to the AC bus, and in the same manner, all the DC power sources are connected to the DC bus. The connection between the two buses is achieved with the help of a bidirectional converter [3].

Up to now most of the installed or available microgrids corresponds to AC power infrastructure. Exchange of power among the energy sources, loads and grid is mostly done through AC point of common coupling. In today’s existing power distribution having a AC microgrid is always more feasible than DC or hybrid microgrid [4]. This report considers therefore AC microgrids.

The characteristics of a microgrid is its ability to be operated as a small scale power system capable of generating, distributing electrical energy to the local customer. Microgrids are more flexible, and have two operation modes: grid-connected mode and stand-alone mode. Normally, a microgrid is connected to the main grid for the majority of time, i.e., operates in the grid-connected mode. When an outage occurs in the upstream network the microgrid transits smoothly to the stand-alone mode (island mode). In this mode, the microgrid operates isolated from the main grid and uses local generation resources to power its customers [1]. The impact of the interruption in main grid is thus reduced and the reliability of the microgrid increases.

2.2 RELIABILITY EVALUATION METHOD CATEGORIES

Microgrid has a positive impact on the reliability of power supply. It changes the traditional power supply mode of distribution system, turns the distribution system into a network with interconnection of distributed generation and customers, so as to essentially change the model and algorithm of distribution system reliability evaluation [6].

Although the microgrid is regarded as a special type of distribution system with embedded micro generation sources, it has several unique features which impacts reliability of the microgrid. Renewable energy generations adopted in microgrids such as wind power and photovoltaics with obviously random and intermittent power output characteristic greatly increase the complexity of the reliability evaluation. Besides, the flexible operation modes have brought challenges to the reliability analysis of microgrids. How to efficiently and effectively incorporate intermittent and uncertain renewable energy as well as flexible operation modes of microgrids into the reliability assessment needs to be considered. Models must be able to quantify these effects, and reliability evaluation methods able to deal with these uncertain and bidirectional power flows of microgrid need to be developed [7].

In previous work, a variety of models and evaluation methods were addressed to deal with these issues in numerous articles. The studies on microgrids and research work in this area are focusing different aspects, such as wind power and photovoltaic reliability models of microgrid, and energy storage system reliability analysis. All these models and methods can be roughly classified by two categories: the analytical method and the Monte Carlo Simulation (MCS) [8]. Reliability analyses of microgrids and reliability index calculations are done by using either the analytical method or MCS approach [9].

The analytical methods assess the reliability of microgrid mathematically. This technique utilizes mathematical models to represent the system and its components, and evaluates the reliability indices on these models by solving the mathematical equations. The analytical evaluation technique takes the advantages of mathematical approaches to establish models of the system and perform the reliability calculations based on historical system operation data. Based on analytical theories, the models for wind power output, PV and energy storage batteries were proposed in a number of papers for evaluating reliability of microgrid [10], that are further described in the sections below.

Monte Carlo simulation, on the contrary, treats the problem as a series of real experiments, and estimates the reliability indices by simulating the actual process and random behavior of the system. It is capable of modeling the full range of operating conditions. The MCS method was used in many articles and microgrid studies to evaluate the system reliability by modeling the random output of the renewable energy sources, load variation and the forced outages of the system component over a sufficiently long simulation time period. The MCS sequential approach is frequently used for adequacy assessment of systems with renewable energy sources to calculate the loss of load expectation (LOLE) and the loss of energy expectation (LOEE) of the renewable energy sources.

The advantage of MCS method is that it can provide a wide range of output parameters including all moments and complete probability functions, and simulate DGs' random output in time sequences, whereas the output from analytical methods is usually limited only to expected values. The main drawback of the MCS method is the enormous number of iterations required for simulation convergence and hence becomes complex and time consuming to perform reliability analysis. Use of the MCS method requires specific knowledge for creating uniform random numbers, and generating occurrence time samples for each basic component of the system [11, 12]. These characteristics of the MCS method make the MCS unsuitable to apply in practical reliability study of microgrid. This report considers therefore mainly the analytic method.

It should be mentioned that a approach based on fault tree analysis (FTA) was also proposed in a number of articles for reliability analysis of microgrid. The FTA is a top-down reliability analysis method, and is one of the commonly used tools in reliability assessment. The FTA is a method of determining probabilities of undesirable events, sequences of events and conditions that lead to the top undesirable events. The FTA method identifies the relationship between component failures and system failures. It allows to get qualitative as well as quantitative information about component and system failures [13, 14].

The most significant advantage of the FTA method is its qualitative assessment of the failure processes of a system and the consequences of failure on system behavior. In this method, a particular failure condition, top event, is considered and a tree is constructed that identifies the various combinations and sequences of other failures that lead to the failures being considered. The FTA method is frequently used as a qualitative evaluation of microgrid, but can also be used for quantitative evaluation, in which case the reliability data for the individual components are inserted into the tree to give the reliability assessment of the complete system [15].

2.3 RELIABILITY INDICES USED FOR MICROGRID

Reliability indices are statistical aggregations of reliability data for a well-defined set of components, loads or customers. Most of reliability indices are numerical average values of a particular reliability characteristic of the system. Many indices are calculated to measure reliability. The term "reliability" is frequently used as a generic term for describing these reliability indices.

Microgrid is regarded as a distribution system with embedded microgenerators, which may operate in grid-connected or islanded mode. Therefore, indices defined for distribution system are still employed to assess microgrid reliability [17]. However, microgrid has unique characteristics in structure and operation compared with traditional distribution system. Thus, a number of new indices specially designed for microgrid reliability evaluation are necessary.

A series of reliability indices and new metrics are proposed for evaluating the reliability of microgrid by describing different aspects that would affect the microgrid reliability. These criteria include reliability indices for microgrid load and customers, reliability parameters for microgrid island operation mode, and indices needed to describe the distinct characteristics brought by renewable energy resources in microgrids [16]. These indices are described below.

2.3.1 Load point and customer orientated reliability indices

Microgrid is a section of a distribution system that contains loads and distributed energy resources. Researches emphasized that exiting basic reliability indices for distribution systems, such as System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), etc. could be directly used for microgrid [16]. Two sets of basic indices are used to measure the reliability of distribution systems. These are load point indices which reflect the behavior of individual load points, and system indices which reflect the overall behavior of systems.

Three load point indices are generally considered to have fundamental importance in reliability assessments, since they permit a measure of reliability at each load point of a system. These basic indices are average failure rate λ, average outage time r, and average annual outage time U. They are defined and given by [15]:

$$\lambda_{lp} = \sum_i \lambda_i \tag{2.1}$$

$$U_{lp} = \sum_i \lambda_i \cdot r_i \tag{2.2}$$

$$r_{lp} = \frac{U_{lp}}{\lambda_{lp}} \tag{2.3}$$

Where:

λ_{lp} = failure rate of load point = average number of failures per year (f/yr);

U_{lp} = annual outage time of load point = average annual time that a load point is out of supply (h/yr);

r_{lp} = outage time of load point = average outage time per outage (h/f)

i = component i between load point and supply point. Its failure leads the outage of the load point.

Based on the load point indices, a number of system reliability indices can be evaluated. The most commonly used customer based reliability indices include SAIFI, SAIDI, AENS and ASAI, They are defined and given by [15]:

$$SAIFI = \frac{\sum \lambda_i \cdot N_i}{\sum N_i} \tag{2.4}$$

$$SAIDI = \frac{\sum U_i \cdot N_i}{\sum N_i} \tag{2.5}$$

$$AENS = \frac{\sum L_{a(i)} \cdot U_i}{\sum N_i} \tag{2.6}$$

$$ASAI = \frac{\sum N_i \cdot 8760 - \sum U_i \cdot N_i}{\sum N_i \cdot 8760} \tag{2.7}$$

Where:

SAIFI = system average interruption frequency index (int./yr.cust)

λ_i = failure rate of load point i

N_i = number of customers of load point i

SAIDI = system average interruption duration index (h/yr.cust)

U_i = annual outage time of load point i

AENS = average energy not supplied (kWh/yr.cust)

$L_{a(i)}$ = average load connected to load point i

ASAI = average service availability index.

2.3.2 Generating capacity adequacy reliability indices

Although the microgrid is regarded as a type of distribution systems, it has several unique features that are significantly different from ones for conventional distribution systems. The embedded renewable micro energy sources in microgrid are weather-dependent characterized by intermittent and fluctuating and unpredictable behavior. These characteristics involve uncertainty and can affects the reliability. New indices are therefore needed to reflect these characteristics of renewable micro sources, which complement the existing reliability indices and measure the specific aspects that would affect the reliability of the microgrid [18].

Utilization of renewable energy resources (RER) such as wind and solar energy has received considerable attention in development of microgrid. The available energy from wind and solar energy is, however intermittent and random variable. The primary concern in power generation is the impact caused by this intermittent RER, whether the power supply from the RER can match with the instantaneous power demand.

The reliability of microgrid includes two aspects: adequacy and security. Adequacy refers to the capacity of power supply for customers of the system, the ability of the system to supply the aggregate demand and energy requirements of the customers, while security refers to the affordability of the sudden disturbance in the system, the ability of the system to withstand the disturbances such as electric short circuits or sudden loss of system elements.

In adequacy analysis, a power system is considered to be operating in either success state or failure state. A system is considered operating in success state when it has enough generation capacity to serve the load. When generation capacity is not sufficient to meet the load demand and loss of load occurs, the system is regarded in failure state. This system failure state is not caused by damage of a system component. The system is not in any difficulty but does not have sufficient margin to meet the specified deterministic criterion. The failure state is due to insufficient generating capacity, the load exceeds the available generating capacity. The probabilities and durations associated with the system residing in success and failure states and energy not served during failure states are the adequacy indices for reliability analysis [21].

A number of articles proposed reliability indices used for estimating overall adequacy of the system for power demand. The most popular approaches are the Loss Of Load Expectation (LOLE) and the Loss Of Energy Expectation (LOEE) methods [22]. The LOLE is the number of days (or hours) in a predefined period during which the daily peak load surpasses the accessible generating capacity. The LOEE, widely known as Expected Energy Not Supplied (EENS), is energy (kWh) expected not to supply in a year by generation unavailability or by lack of primary energy. The generating capacity adequacy of a microgrid can, therefore, be assessed using the LOLE and LOEE indices as an additional criterion to the conventional reliability indices for distribution systems.

The article [22] defines the LOLE as the number of hours a year in which the expected power generation will not meet power demand at the consumers' load points. It depicts the loss of load duration when the daily peak demand surpasses the available power generation capacity. Expected energy not supplied (EENS) is the total energy that is not delivered at the system load points. The LOEE is defined as the energy shortage in a year when the load demanded is greater than the available generating capacity. The LOLE and LOEE are given by the equations (2.8) and (2.9) below.

$$LOLE = \sum_{k=1}^{n} P_k \cdot t_k \quad (h/yt) \tag{2.8}$$

$$LOEE = \sum_{i=1}^{n} C_k \cdot P_i \cdot 8760 \quad (kWh/yr) \tag{2.9}$$

where:

P_k = individual probability of capacity in outage

t_k = duration of loss of power supply in hours

C_k = amount of load curtailment = $L_i - C_i$

L_i = expected load demand

C_i = generation capacity

P_i = probability of specific capacity outage

In view of existing developed methods, the paper [16] has presented new metrics for assessing generating capacity. The paper has proposed two indices: Island Loss of Load Probability (ILOLP) and Island Expected Energy Deficiency (IEED), which are similar to the LOLE and LOEE described above. The ILOLP is defined as the fraction of time that load demand is unsatisfied during microgrid islanded mode, and the IEED is average energy deficiency during islanded mode due to hours when island load exceeds total available island power generation. Mathematically, they are given by:

$$ILOLP = \frac{Islanded\ hours\ with\ demand\ not\ satisfied}{Total\ microgrid\ islanded\ hours} \tag{2.10}$$

$$IEED = \frac{\sum_{TS=1}^{ND} (L_{TS} - G_{TS}) \cdot T_{TS}}{NI} \quad (kWh/occurance) \tag{2.11}$$

where

ND = number of time segments when total generation output cannot satisfy total load demand in the island in one year

TS = time segment

L_{TS} = load demand in kW in time segment TS

G_{TS} = generation output in kW in time segment TS

T_{TS} = duration of time segment TS in hour

NI = island formation times in one year.

2.3.3 Operation reliability indices in islanded mode

As a part of distribution system with embedded micro energy resources, microgrid is flexible in operation: it can operate as an integrated distribution system or an islanded network. In the grid-connected mode, the microgrid is connected with the distribution network, importing or exporting energy, working as a controllable element of the network. The islanded operation takes place when an outage occurs in the upstream network. In this case, the upstream grid is unable to deliver sufficient energy, the microgrid is then switched to the islanded operation, the local micro energy resources of the microgrid are utilized to support the loads. The loads of the microgrid are left to ride through the disturbance. The impact of interruptions in upstream grid is thus reduced. Microgrids can therefore potentially improve distribution system reliability when enabled to operate in an islanded mode.

Obviously this islanding does not make sense if the microgrid fails switching to islanded operation. A positive impact on reliability requires that the microgrid is able to isolate itself in the fault event on the upstream grid. The article [16] points out that the microgrid's ability of isolated operation in emergency situation is an important factor for reliability improvement. In order to address this aspect the article proposed two operation reliability indices in islanded mode: the IOSR (Island Operation Successful Rate) and the MIOP (Microgrid Islanded Operation Probability).

The IOSR is defined as the probability of a microgrid to switch successfully from grid-connected mode to islanded mode. Mathematically, it is given by (2.12).

The MIOP is defined as the fraction of time that microgrid is operated in islanded mode. Mathematically, it is given by (2.13).

$$IOSR = \frac{Total\ number\ of\ forming\ island\ successfully}{Total\ number\ of\ outages\ on\ PCC} \tag{2.12}$$

$$MIOP = \frac{Microgrid\ hours\ in\ islanded\ mode}{Total\ microgrid\ operation\ hours} \tag{2.13}$$

Where PCC is point of common coupling of grid at which microgrid is connected.

2.4 WIND POWER OUTPUT MODELLING

In the development of microgrid, using renewable energy in microgrids becomes viable option. Among the options, wind and solar energy are the most widely utilized renewable energy sources (RES) . Wind power and photovoltaics have obviously random and intermittent output characteristic. Appropriate modeling of their power output is an important requirement in the reliability evaluation of microgrids with renewable energy. This section describes modelling of wind power output. The modelling of solar power output is dealt with in the subsequent section.

The output of wind power is weather-dependent and closely related to wind speed. It is characterized by intermittent and fluctuating behavior due to the constraints by geographical conditions and climate change. The relationship between wind speed and wind turbine power output is described by wind turbine power curve. It describes the operational characteristics of a wind turbine generator. To any wind speed, a corresponding power output can be found on this curve. Figure 2.1 shows a typical wind turbine power curve [2]. Three commonly used parameters are the cut-in, rated, and cut-out wind speeds. The wind turbine generator (WTG) starts generating at the cut-in wind speed, the power output increases nonlinearly as the wind speed increases from the cut-in speed to the rated wind speed . The rated power is produced when the wind speed varies from the rated speed to the cut out wind speed, at which the WTG will be shut down for safety reasons. The electrical power generated hourly can be calculated from the wind speed data using the power curve of the WTG [30].

The curve a-b section in the figure is often replaced by a straight line and a piecewise function can be got form this relationship between wind turbine output power and wind speed, which is given by equation (2.12). Only when the wind speed is at a specific interval, ($v_R < v < v_{co}$), output of wind turbine is equal to the rated output.

This curve is available from the wind turbine manufacturer, or can be plotted by polynomial curve fitting technique using recorded wind speed and corresponding power output data.

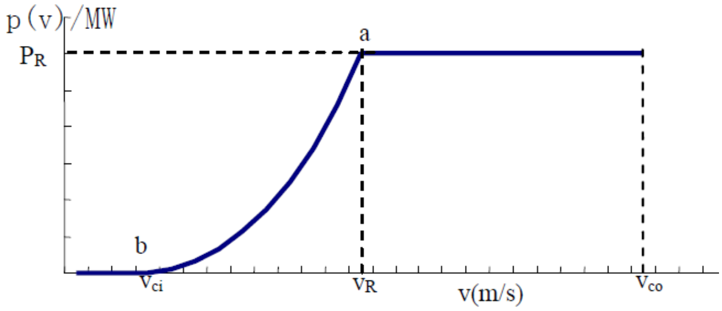

Figure 2.1: A typical wind turbine power curve

$$p(v) = 0, \quad v \le v_{ci,} \quad v \ge v_{co}$$

$$p(v) = P_R \frac{v - v_{ci}}{v_R - v_{ci}}, \quad v_{ci} < v < v_R \qquad (2.12)$$

$$p(v) = P_R, \quad v \ge v_R$$

Where:

p(v) = wind turbine output power at wind speed v (MW)

v = wind speed at the height of the wind turbine hub (m/s)

v_{ci} = cut in wind speed (m/s)

v_{co} = cut out wind speed (m/s)

v_R = rated wind speed (m/s)

P_R = rated output power (MW)

Although wind is random and intermittent, distribution of wind speed in most districts still follows some pattern, and certain probability distributions function can be adopted to represent the probability distribution of wind speed. It is widely accepted that the Weibull distribution fits actual wind speed distribution quite well. It is often recommended to express behavior of wind speed with Weibull probability density functions. This recommendation is based on a comparison of actual wind speed profiles at different sites with wind speed profiles estimated using the Weibull probability density function [24].

The Weibull probability distribution is a single-peak and two-parameter function, whose probability density function and cumulative distribution function are expressed below by equations (2.13) and (2.14) [8, 25].

$$f(v) = \frac{k}{c} \cdot \left[\frac{v}{c}\right]^{k-1} \cdot exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{2.13}$$

$$F(v) = P(V \leq v) = 1 - exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{2.14}$$

Where

f(v) = probability density function

v = wind speed (m/s)

k = shape parameter

c = scale parameter (m/s)

F(v) = (cumulative) probability distribution function, probability of wind speed.

The scale parameter c describes the abscissa scale on a plot of the distribution, reflecting the average wind speed, whereas the shape parameter k describes the shape of the distribution, reflecting the skewness of the Weibull distribution, having the value of 1.8 to 2.3, in general taking k = 2.

The paper [12] studied wind speed data and presented Weibull probability density functions with different values of scale and shape parameters. Figure 2.2 and 2.3 show how the shape of the Weibull function varies with these two parameters, where the scale parameter c was calculated based on the annual mean wind speed which was not constant from year to another.

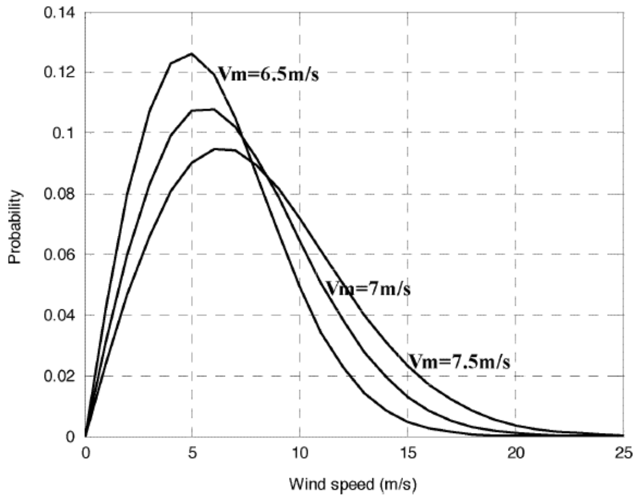

Figure 2.2: Weibull probability density functions with different values of scale parameter c [12].

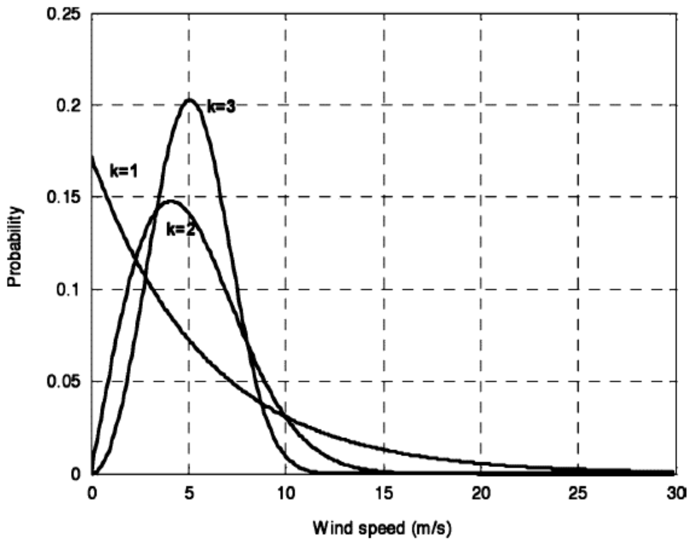

Figure 2.3: Weibull probability density functions with different values of shape parameter k [12].

Both of them can be calculated from the average wind speed v_m and the standard deviation SD by equations (2.15) and (2.16): [6, 25].

$$k = \left(\frac{SD}{v_m}\right)^{-1.086} \tag{2.15}$$

$$c = \frac{v_m}{\Gamma\,(1 + 1/k)} \tag{2.16}$$

Where

SD = standard deviation of wind data

v_m = average wind speed of wind data (m/s)

Γ = standard gamma function

The standard gamma function is given by equation (2.17):

$$\Gamma(x) = \int_0^\infty t^{x-1} \exp(-t)\, dt \tag{2.17}$$

The average wind speed and the standard deviation of the measured wind speed values can be calculated according to the following equations (2.18) and (2.19) respectively [25].

$$v_m = \frac{1}{N} \sum_{i=1}^{N} v_i \tag{2.18}$$

$$SD = \left(\frac{1}{N-1} \sum_{i=1}^{N} [v_i - v_m]^2 \right)^{1/2} \tag{2.19}$$

Where N = the number of wind speed records

When the shape parameter k equals 2, the probability density function is called a Rayleigh probability distribution function as given by equation (2.20). This probability density function fits most wind speed profiles, and is used therefore frequently in wind power related studies to model the wind speed [24].

$$f_r(v) = \left(\frac{2v}{c^2}\right) \cdot \exp\left[-\left(\frac{v}{c}\right)^2\right] \tag{2.20}$$

Where $f_r(v)$ = Rayleigh probability distribution function.

The scale parameter c in the Rayleigh function can be found using the following acceptable approximation [24]:

$$c \approx 1.128 \cdot v_m \tag{2.21}$$

It should be mentioned that the Weibull probability density function can be used to simulate the randomness of wind speed, but it is difficult to reflect the seasonal variation of wind meteorological parameters. If possible, historical wind record data can be adopted for more accurate modeling of wind speed.

2.5 SOLAR POWER OUTPUT MODELLING

Photovoltaic (PV) system changes light energy directly into electrical energy based on the photovoltaic effect of semiconductor interface. PV generation directly converts sunlight into electricity. Its output depends on several factors such as solar radiation or the intensity of sunlight received by the solar panel, temperature, and relative humidity among others. Several research projects and papers present methods for modelling solar power output. These methods are described below.

2.5.1 Method 1

Paper [27] points out that due to the great influence of external factors (temperature, sunlight intensity, etc.), the power output of a PV system is primarily determined by the meteorological factors. The paper proposes that the PV power output can be calculated by equation (2.22):

$$P_{PV} = P_{sr}[1 - 0.0045(T_a - E_r)]\frac{S}{S_r} \tag{2.22}$$

Where:

P_{PV} = output of the PV modules

Psr = rated output of the PV modules

Ta = ambient temperature

Er = reference temperature

S = solar illumination

Sr = reference solar illumination.

Figure 2.4-1 shows an example of meteorological condition of illumination in a summer day.

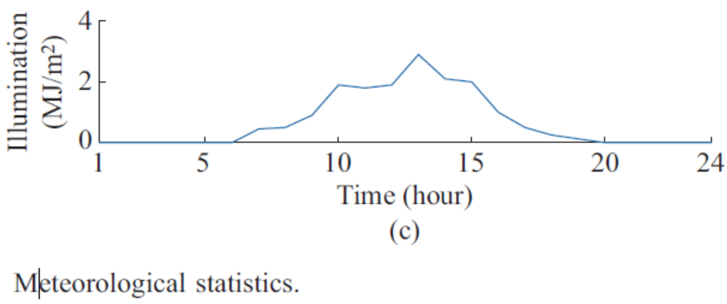

Figure 2.4-1 An example of meteorological statistics of illumination [27].

2.5.2 Method 2

The researches who author the paper [33] show that the solar panel is the central element of a PV system, its output depends on several factors, but the most important one being solar radiation, which can vary from month to month, as illustrated in Figure 2.4. The paper defines I(t) being the solar radiation received at time t, and proposes the equations (2.23) and (2.24) for calculating P_{PV}, the output power of the solar panel.

$$P_{PV} = \frac{\eta_c}{K_c} \times S \times I(t)^2 \quad 0 < I(t) \le K_c \tag{2.23}$$

$$= \eta_c \times S \times I(t) \quad I(t) > K_c \tag{2.24}$$

Where:

η_c = conversion efficiency of PV system, including the inverters

Kc = threshold value

$S = S_P \times N_P$

S_P = area of the solar panel

N_P = number of panels.

When I(t) ≤ Kc, η_c varies linearly, and P_{PV} has a second order relationship with I(t). When (t) > Kc, η_c is usually constant and P_{PV} has a linear relationship with I(t).

Solar radiation depends mainly on the solar altitude angle and the attenuation effect of cloud occlusion. The variation of the solar altitude angle with time in a day can be determined by a definitive function, while the occlusion of the clouds is random as the weather changes. Thus, I(t) can be calculated by:

$$I(t) = I_d(t) + \Delta I(t) \tag{2.25}$$

Where:

$\Delta I(t)$ = random amount of attenuation

$I_d(t)$ = solar altitude angle.

$I_d(t)$ is defined as the average value of sunlight at time t in a statistical time range (usually one year). If the change in sunrise and sunset times during the year is not considered, $I_d(t)$ can be approximated by the following quadratic function [6]:

$$I_d(t) = I_{max}\left(-\frac{1}{36}t^2 + \frac{2}{3}t - 3\right) \quad 6 \le t < 18 \tag{2.24}$$

$$= 0 \quad 0 \le t < 6, 18 \le t < 24$$

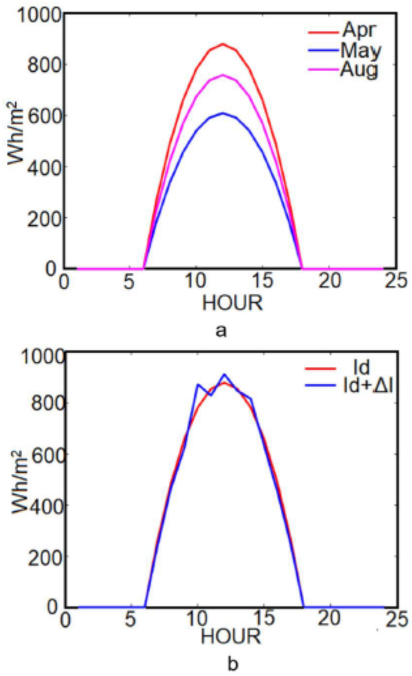

FIGURE 4. (a) Solar radiation $I_d(t)$ for April, May and August; (b) typical variation of solar radiation received by a solar panel in one day, for Colombia.

Figure 2.4: (a) Solar radiation; (b) typical variation of solar radiation received by a solar panel in one day [33].

In the equation (2.24), t is the time in a day (hours), and I_{max} is the maximum intensity of sunlight in a day. It is assumed that the maximum intensity occurs at noon, that is, Imax = I (12).

The studies have shown that the variation in I(t) follows a normal distribution [33], Figure 2.4 (b) and Figure 2.5 show the typical variation of solar radiation received by a solar panel in one day. For simplicity, it is assumed that **Δ**I(t) obeys a standard Normal distribution [6]. Probability density function of normal distribution can be represented by the function:

$$f(\Delta I) = \frac{1}{\sqrt{2\pi}} exp\left(-\frac{\Delta I^2}{2}\right) \quad (2.25)$$

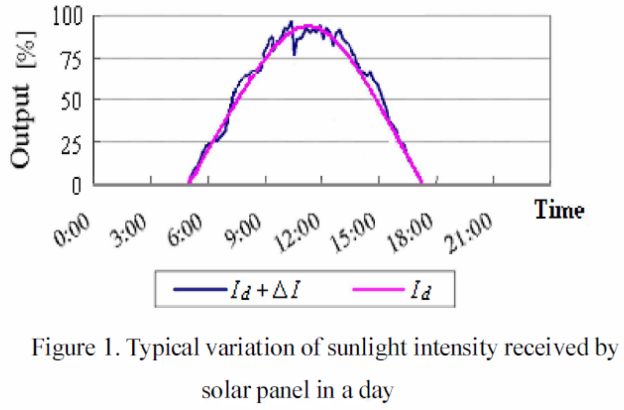

Figure 2.5: Typical variation of sunlight intensity received by solar panel in a day [6].

2.5.3 Method 3

The study documented in the paper [34] shows that the PV output power is obviously nonlinear due to the great influence of external factors like temperature, sunlight intensity, as shown in Figure 2.6. The PV output power can be calculated by equation (2.26):

$$P_{PV} = P_{STC}\frac{G_{AC}}{G_{STC}}(1 + k(T_c - T_\tau)) \tag{2.26}$$

Where:

P_{STC} = the maximum test power at the standard test conditions (STC, intensity of sunlight 1000W/m2, ambient temperature 25 Co).

G_{AC} = light intensity

G_{STC} = light intensity for the STC 1000W/m2

K = power-temperature coefficient of 0.0047 W/ C^o

T_c = solar panels working temperature

T_τ = reference temperature of 25 C^0

This method is similar as that as the method 1, but differs with the input data available, one uses rated output of the PV modules and the other uses the standard test conditions.

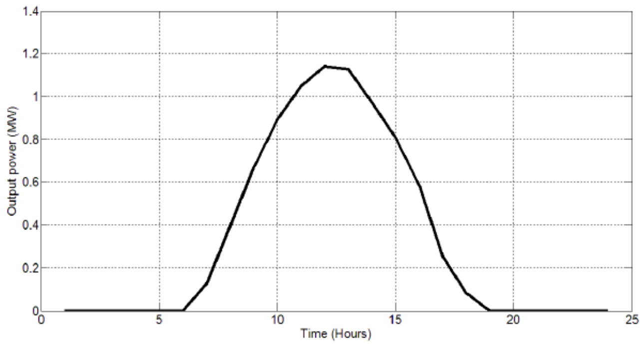

Fig. 2. PV output power in July 21th

Figure 2.6: Typical PV output power in a day [34].

2.5.4 Method 4

The papers [35] [24] [31] have developed a method for modelling PV module generators based on the Beta probability density function. It is pointed out that the output of each PV module depends on the amount of solar irradiance, ambient temperature and characteristics of the PV module itself, and that under normal working conditions, the random output of PV obeys the Beta distribution approximately. The papers model therefore the hourly solar irradiance by the Beta probability density function (PDF) using historical data. In order to get the PDF of solar irradiance, a period of one year can be selected and then four days are chosen as representatives of four seasons. The day representing each season is further divided into 24-hour time segments, each having a PDF for describing the random phenomenon of the solar irradiance. When the solar irradiance is modeled for each hour, the probabilistic function of the output power of PV modules can be generated easily. The Beta PDF used to describe the probabilistic nature of solar irradiance, is set out by equation (2.27).

$$f_b(s) = \frac{\Gamma(\alpha + \beta)}{\Gamma(\alpha)\,\Gamma(\beta)} \times s^{(\alpha-1)} \times (1 - s)^{(\beta-1)} \qquad 0 \leq s \leq 1, \alpha \geq 0, \beta \geq 0 \tag{2.27}$$

$$= 0, \quad \text{otherwise}$$

Where:

s = solar irradiance (kW/m^2)

$f_b(s)$ = Beta distribution function of s

$\Gamma(x)$ = Gamma function of x

α, β = parameters of the Beta distribution function

The parameters of the Beta distribution function are calculated by using the mean and standard deviation of random variable s as shown in equations (2.28) and (2.29).

$$\beta = (1-\mu) \times \left(\frac{\mu \times (1+\mu)}{\sigma^2} - 1\right) \tag{2.28}$$

$$\alpha = \frac{\mu + \beta}{1-\mu} \tag{2.29}$$

Where:

μ = mean of random variable of s

σ = standard deviation of random variable of s

To incorporate the output power of the solar energy, each continuous PDF of solar irradiance can be divided into states (periods), in each of which the solar irradiance is within specific limits, i.e., for each time segment, there are a number of states for the solar irradiance, the number of states is carefully selected for the Beta distributions because a small number of states affects accuracy, while a large number increases the complexity of the calculations.

The probability of the solar irradiance for each state during a specific hour can be calculated using the equation (2.30).

$$P_s\{G_y\} = \int_{s_{y1}}^{s_{y2}} f_b(v)\, dv \tag{2.30}$$

Where:

$P_s\{G_y\}$ = probability of the solar irradiance being in state y

s_{y1}, s_{y2} = solar irradiance limits of state y

Once the Beta probability density function is generated for a specific time segment, the output power during the different states can be calculated for this segment by using the following equations (2.31) – (2.35):

$$T_{C_y} = T_A + s_{ay}\left(\frac{N_{OT} - 20}{0.8}\right) \tag{2.31}$$

$$I_y = s_{ay}\left[I_{sc} + K_i(T_{C_y} - 25)\right] \tag{2.32}$$

$$V_y = V_{oc} - K_v \times T_{C_y} \tag{2.33}$$

$$P_{S_y}(s_{ay}) = N \times FF \times V_y \times I_y \tag{2.34}$$

$$FF = \frac{V_{MPP} \times I_{MPP}}{V_{oc} \times I_{sc}} \tag{2.35}$$

Where:

T_{cy} = cell temperature during state y (C^0)

T_A = ambient temperature

s_{ay} = average solar irradiance of state y

N_{OT} = nominal operating temperature of cell (C^0)

I_y = current of state y (A)

I_{sc} = short circuit current (A)

K_i = current temperature coefficient (A/C^0)

V_y = voltage of state y

V_{oc} = open-circuit voltage (V)

K_v = voltage temperature coefficient (V/C^0)

P_{sy} = output power of the PV module during state y

N = number of cells

FF = fill factor

V_{MPP} = voltage at maximum power point (V)

I_{MPP} = current at maximum power point (A)

Alternatively the papers [29] [31] shows that the random output of PV itself obeys the Beta distribution approximately under normal working conditions, and accordingly its probability density function can be expressed by the equation (2.36):

$$f(P_{PV}) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\,\Gamma(\beta)} \times \left(\frac{P_{PV}}{P_{PVm}}\right)^{(\alpha-1)} \times \left(1-\frac{P_{PV}}{P_{PVm}}\right)^{(\beta-1)} \quad \alpha \geq 0, \beta \geq 0 \qquad (2.36)$$

$$= 0, \quad \text{otherwise}$$

Where:

P_{PV} = PV random output for a period of time

P_{PVm} = PV maximum output for a period of time

2.6 RELIABILITY MODELLING OF ENERGY STORAGE SYSTEM

Energy storage system is a significant component in a microgrid utilizing wind and/or solar energy, especially in stand-alone applications. The available energy from wind and solar energy is intermittent and variable. In order to use these energy sources as viable power generation, energy storage is incorporated in microgrid applications in order to match the power supply with the power demand. Energy storage is an essential component of the system for handling the accompanying uncertainty in the operation.

Microgrid integrates distributed generations, load, and energy storage into a single controllable system. The primary application of energy storage systems is to coordinate with generation resources to guarantee the microgrid generation adequacy. The advantage of installing storage system is to increase the self-sufficiency of the microgrids. Its major function is to smooth out the fluctuating power sources and improve the generation system availability. This important feature has a strong impact on the capacity adequacy of the microgrid. The basic operating strategy of an energy storage is that whenever the generation exceeds the load, the excess energy is stored in the energy storage facility and used whenever there is a generation shortage. The maximum charging and discharging rate of the energy storage facility determines the maximum energy stored and supplied from the facility at a specific time point.

Distributed generation and energy storage system in a microgrid constitute the combined power generation system. If the energy storage system is fully charged, it works as a source, otherwise it may be as a load. The storage system is modeled as load during the charging period and as a generator during discharging period. The energy storage has three operation modes of charging, discharging and idle. The power from energy storage is positive when the storage is discharging, negative when charging, and zero when in idle mode. It can be assumed that the combined distributed generation output and the load and energy storage system can reach equilibrium, and the power balance equation keeps that the power generated from local units, power generated (consumed) by energy storage units and the power imported (exported) from (to) the main grid would meet the hourly load of the microgrid. The power balance between the output of different systems and the load can be expressed as [36, 37]:

$$\sum_{i} P_{DG}(h) + P_M = \sum_{j} P_L(h) \tag{2.37}$$

$$P_{DG}(h) = \mathrm{P_{WTG}(h)} + \mathrm{P_{PV}(h)} + \mathrm{P_{ESS}(h)} \tag{2.38}$$

Where:

P_{DG} = DG output power

P_M = main grid power

P_L = power load

P_{WTG} = wind power output

P_{PV} = PV power output

P_{ESS} = energy storage system output power

The main grid power is positive when the power is imported from the main grid, negative when the power is exported to the main grid, and zero when the microgrid operates in islanded mode. In grid-connected model, whether DGs generate power does not influence the power supply to customers of the microgrid because of the power support from the main grid. While in islanded mode, the states of DGs and storage units will influence the power supply for customers within the microgrid. The storage system acts as a power source to maintain the balance of power supply and consumption. When the DG output is greater than the load, the residual energy is stored in the storage system according to its load capacity. When the DG output is less than the load, the stored energy is released to supply the customers. It can be assumed that when the microgrid switches to island mode, the energy storage system can be considered as fully charged, because, when the microgrid connected to the main grid, the storage system can be charged if necessary.

The charging and discharging power and capacity of the storage system need to satisfy the following constraints [37]:

$$P_{charge,min} \le P_{charge} \le P_{charge,max} \tag{2.39}$$

$$P_{discharge,min} \le P_{discharge} \le P_{discharge,max} \tag{2.40}$$

$$SOC_{min} \le SOC \le SOC_{max} \tag{2.41}$$

Where:

Pcharge, Pdischarge = charging and discharging power of energy storage system

Pcharge,min, Pcharge,max = the minimum and the maximum charging power

Pdischarge,min, Pdischarge,max = the minimum and the maximum discharging power.

SOC = charging state of energy storage system

SOCmin, SOCmax = the minimum and the maximum charging capacities

2.7 EVALUATION OF LOAD POINT AND CUSTOMER ORIENTATED RELIABILITY INDICES

Microgrid is built on distribution network. It can operate in two modes: grid connected or island mode. In the grid connected mode, the microgrid is connected to the distribution network. This means that, from the point of view of the distribution network, the microgrid is a controllable element of the network. The island mode takes place when an outage occurs in the upstream network. The microgrid is then disconnected from the distribution network and operates isolated using the local DG resources to supply its customers. The impact of interruptions in the upstream network is hence reduced and the reliability of the microgrid increases.

2.7.1 Grid connected mode

When a microgrid is grid connected, it is operated radial as a part of the distribution network. This characteristics facilitates the reliability analysis using the existing logic and methods for distribution network. The principle of series system can therefore be applied directly to calculate reliability of the microgrid.

A radial distribution system consists of a set of series components, including lines, cables, disconnectors, etc. A customer connected to any load point of such a system requires all components between himself and the supply point to be operating. Three basic load point indices described in section 2.3 are given by equations 2.42-2.44 [38].

$$\lambda_{lp\_g} = \sum_i \lambda_i + \lambda_{up} \tag{2.42}$$

$$U_{lp\_g} = \sum_i \lambda_i \cdot r_i + U_{up} \tag{2.43}$$

$$r_{lp\_g} = \frac{U_{lp\_g}}{\lambda_{lp\_g}} \tag{2.44}$$

Where:

λ_{lp_g} = failure rate of load point in grid connected mode (f/yr)

U_{lp_g} = annual outage time of load point in grid connected mode (h/yr)

r_{lp_g} = outage time of load point in grid connected mode (h/f)

i = component i between load point and supply point. Its failure leads the outage of the load point.

λ_i = failure rate of component i (f/yr)

r_i = repair time of component i (h/f)

λ_{up} = failure rate of upstream system (f/yr)

U_{up} = unavailability of upstream system (h/yr)

After calculated the load point indices, the system indices can be evaluated as described in section 2.3.1.

2.7.2 Island mode

When there is disturbance on the upstream system, the microgrid is transformed to operate in island mode to minimize the disturbance to the customers. Of course the islanding does not make sense if there is not enough local generation to meet the demands of the loads. If the isolation operation of the microgrid is successful, the microgrid can remain operating provided the microgrid has the capacity to supply the customers inside it. It is reasonably assumed that the sufficient local capacity is available in a case that microgrid is required to switch to the island mode. The microgrid is islanded from the main grid using upstream switches at the point of common coupling (PCC), and the microgrid load is fully supplied using local resources [36].

Based on the discussion above, the following three events can lead to failure to supply the customers of the microgrid:

- failed to switch to island mode when an outage occurs on the upstream system;
- component failure on its minimal paths (i.e. failure on a component between the load point and the power supply point);

- the success isolated operation when the outage occurs on the upstream system, but the distributed local power fails (as a second-order failure event).

The load point indices can then be expressed as [2]:

$$\lambda_{lp\_is} = \sum_i \lambda_i + P\lambda_{up} + (1-P)\sum_j \frac{\lambda_{DGj}\lambda_{up}(T_{DGj} + r_{up})}{1 + \lambda_{DGj} \cdot T_{DGj} + \lambda_{up} \cdot r_{up}} \quad (2.45)$$

$$r_{lp\_is} = \frac{\sum_i \lambda_i r_i}{\sum_i \lambda_i} + P\frac{\lambda_{up} r_{up}}{\lambda_{up}} + (1-P)\sum_j \frac{T_{DGj} r_{up}}{T_{DGj} + r_{up}} \quad (2.46)$$

$$U_{lp\_is} = \lambda_{lp\_is} r_{lp\_is} \quad (2.47)$$

Where:

λ_{lp_is} = failure rate of load point in island mode (f/yr)

r_{lp_is} = outage time of load point in island mode (h/f)

U_{lp_is} = annual outage time of load point in island mode (h/yr)

λ_i = failure rate of component i on the minimum path of the load point

r_i = repair time of component i on the minimum path of the load point

λ_{up} = failure rate of upstream system (f/yr)

r_{up} = repair time of upstream system (h/yr)

j = DG j

λ_{DGj} = failure rate of DG j (f/yr)

T_{DGj} = fault repair time of DG j (h/f)

P = probability of unsuccessful isolated operation

The DGs considered in the microgrid include WT, PV, and battery energy storage system. For DGs, two reliability related aspects are considered: (1) the availability of resources, which represents the availability of wind speed and/or solar radiation in the required amount; (2) the availability of equipment that represents damage and failed states of the DGs. The first aspect will be dealt with by the generating capacity adequacy reliability indices, which is described in the subsequent section.

Once the load point indices are calculated, the system reliability indices can be evaluated straightforward using the formulas described in section 2.3.1.

2.7.3 Hybrid operation mode

An important feature of a microgrid is its ability to be islanded from the main power distribution network. Islanding is typically performed to rapidly disconnect the microgrid from a faulty distribution network to ensure that the microgrid is not disturbed by the upstream faults and allow an uninterrupted supply to the loads.

The microgrid can be eventually reconnected to the main distribution network after the fault has been isolated or repaired.

The microgrid controller, however, is not aware of the time and duration of the upstream faults. It is assumed that the microgrid operates in grid-connected mode with a probability of P_g. The calculation of reliability of hybrid mode operating both in grid-connected and islanded modes in terms of load point indices can be performed by the equations (2.48) – (2.50):

$$\lambda_{lp\_h} = \lambda_{lp\_g} P_g + \lambda_{lp\_is}(1 - P_g) \quad (2.48)$$

$$U_{lp\_h} = U_{lp\_g} P_g + U_{lp\_is}(1 - P_g) \quad (2.49)$$

$$r_{lp\_h} = \frac{U_{lp\_h}}{\lambda_{lp\_h}} \quad (2.50)$$

Where:

λ_{lp_h} = failure rate of load point in hybrid mode (f/yr)

r_{lp_h} = outage time of load point in hybrid mode (h/f)

U_{lp_h} = annual outage time of load point in hybrid mode (h/yr)

P_g = probability of microgrid operating in grid connected mode

Based on the load point indices, the system reliability indices in hybrid operation mode can be calculated using the formulas described in section 2.3.1.

2.8 EVALUATION OF GENERATING CAPACITY ADEQUACY RELIABILITY INDICES

Microgrids can potentially improve distribution system reliability when enabled to operate in an islanded mode after a fault occurrence on upstream network. When microgrid operates in stand-alone mode, its DGs, such as wind and solar energy sources are utilized to supply the local customers. Future microgrids will likely contain substantial amounts of stochastic DGs, which would have a more uncertain impact on reliability compared with dispatchable generation sources.

The power supply from the wind and solar energy sources fluctuate randomly and at a higher rate relative to the load variations. Because of this, the DG units of the microgrid may not provide the proper power balance. The rapid fluctuations in the wind power supply become the root cause for power imbalance that occurs in stand-alone microgrid.

A primary concern in microgrid stand-alone operation is, therefore, whether the generating capacity could satisfy the load demand. The generation capacity can be affected by two major factors, the first is failure or damage on the generation facilities. The second is varying weather condition that influences the amount of renewable energy generated. The outputs of photovoltaics and wind turbine generator used by microgrid are not constant, they are significant random, intermittent and unstable, which is very different from conventional power supply. Wind speed is fluctuant and unpredictable. Sunlight is not always available when there is power demand. Duo to the intermittent characteristics of wind and sunlight, the most difficult task of microgrid reliability evaluation is to assess the capacity adequacy in address demand of customers.

The influence of failures of the generation facilities has been considered in the reliability assessment of the load point and included in the calculation of load point for island mode described in section 2.7.2.

In generating capacity adequacy reliability analysis described in this section, a power system is considered to be operating in either success state or failure state. A system is considered operating in success state when it has enough generation capacity to serve the load. When generation capacity is not sufficient to meet the load demand and loss of load occurs, the system is considered in failure state, as in the case when the intermittent wind and solar power generation cannot match with the instantaneous power demand. This system failure state is not caused by failure of a system component. The system is not in any problem but does not have sufficient generation capacity to meet the load demand. This system failure state is considered by the generating capacity adequacy reliability indices described in this section. The probabilities and durations associated with the system residing in success and failure states and energy not served during this failure states are the adequacy reliability indices.

Adequacy is defined as the existence of sufficient generation of electric power system to satisfy the consumer demand. The adequacy of an isolated microgrid can, therefore, be assessed using the criterion LOLE and LOEE in addition to the conventional load point indices.

Loss of load expectation LOLE is the number of days (or hours) in a predefined time period in which the daily peak load surpasses the accessible generation capacity due to the generation shortage, that is, the LOLE expresses the number of hours in a period in which the expected power generation will not meet power demand, This indices is associated with capacity outage, the inability of the generating system to satisfy the load requirement. Loss of energy expectation, LOEE, is also known as expected energy not supplied, EENS.

A microgrid system consists of PV, WTG, BESS and load. When it operates in island mode, lacks upper level grid support, the energy generated needs to be consumed within the system in order to maintain the system power balance [29]:

$$P_L\,(h) = \mathrm{P_{WTG}(h) + P_{PV}(h) + P_{BESS}(h)} \tag{2.51}$$

Where:

$P_L(h)$ = total load power

$P_{WTG}(h)$ = WTG output power

$P_{PV}(h)$ = PV output power

$P_{BESS}(h)$ = BESS output power

The power balance equation ensures that the power generated from local WTG and PV units, as well as power generated by BESS would meet the hourly microgrid load. The BESS power is positive when the storage is discharging, negative when charging, and zero when BESS is in idle mode.

To determine the expected number of hours in a time period that the load exceeds available generation capacity, involves three aspects: identifying generation, determining a load model, and the convolution of the generation and load to produce the adequacy indices. The time period considered is normally a year, so that the indices calculated are year based. The power available from all the generating units are combined to create the generation model, which is compared with the hourly load demand based on the system power balance equation (2.51). The simulation proceeds chronologically from one hour to the next repeated for the whole time period. At each time point the simulation recognizes the generation and load characteristics of the system, and identifies the difference between the total available power from generating and energy storage units and the total load at that time point. A positive margin indicates power sufficiency, while a negative margin means power insufficiency, indicating that a capacity outage has occurred [30, 39].

The load model is a chronological hourly load pattern. The load is usually modelled in one hour time steps, although smaller steps could be used. The load model can be represented by a daily peak load variation curve or a load duration curve. The desired adequacy indices can be determined from the margins by superimposing the generation and the load models. The LOLE and LOEE are then calculated by recording the loss of load duration in hours for each load curtailment, the energy not supplied at each curtailment and the total number of load curtailment [30, 39].

The paper [30] proposes the following equations for calculation of the adequacy indices:

$$LOLE = \frac{\sum_{i=1}^{n(R)} t(R)_i}{N} \tag{2.52}$$

$$LOEE = \sum_{i=1}^{n(R)} t(R)_i \cdot Lc(R)_i \tag{2.53}$$

Where:

n(R) = number of risk states when power insufficiency occurs

t(R) = time duration in the risk state

N = total number of simulated years

L_c(R) = load curtailment (load not supplied)

A system operates in the healthy state when it has enough power capacity to meet the load demand. In the risk state, the load exceeds the available power capacity, the risk is associated with the inability of the generating system to satisfy the load demand.

Energy storage system has a strong impact on the capacity adequacy of the microgrid. The main function of the energy storage system is to smooth out the fluctuating power sources and increase the generation system availability. Whenever the generation exceeds the load, the excess energy is stored in the energy storage facilities and used whenever when there is generation shortage. The maximum charging and discharging rate of the energy storage facilities determines the maximum energy stored and supplied from the facilities at a specific time point.

When microgrid switches to island mode, the energy storage system can be considered as fully charged, because when the microgrid is connected to the main grid, the storage system can be charged if necessary. In calculation of the adequacy indices the charging and discharging characteristics of the energy storage facilities are considered. Energy storage state time series are obtained from the load time series and the available generation time series and incorporated in the overall system adequacy evaluation.

Based on the LOLE, the Loss of Load Probability (LOLP) can be calculated. The LOLP is defined as probability of being unable to satisfy the load demand with the available generation, and can be calculated by equation (2.54) [41].

$$LOLP = \frac{LOLE\ (hours/yr)}{8760\ (hours)} \tag{2.54}$$

In order to efficiently evaluate adequacy reliability indices, a systematic approach is presented by the paper [35]. The paper proposes that the evaluation can be done over a selected period of one year, and then four days can be selected as representatives of four seasons. A typical day is selected for each season in order to represent the random behavior of the different renewable energy resources during each season. The day representing each season is further divided into 24-hour time segments, each referring to a particular hourly interval for the entire season. Thus, there are 96 time segments for the year. For each of the time segments the output power from DGs is generated. The DGs' output power then matches with the hourly load. All the generations and loads are combined hourly to find the loss of load expectation and the frequency of generation capacity deficiency for the hour under study. This procedure is repeated for all time segments and accomplished for the whole time period. The adequacy reliability indices are then deduce based on the equations (2.52) and (2.53).

Since the output of wind power and PV in microgrid is random and intermittent, it is not easy to evaluate the power supply capability of these renewable DGs by means of analytical method. The well-developed techniques applied to conventional generation system adequacy reliability analysis, associate fixed capacity output cannot be readily extended to reliability evaluation for microgrid with renewable energy sources that have highly fluctuating generation capacity. It is therefore more suitable and reasonable to use time sequential simulative technique to evaluate capacity adequacy reliability indices, because this technique can include DGs' random output in a time sequency and reflect realistically DGs' generation states [6].

The paper [16] proposes a series of new metrics for reliability assessment of microgrid. These metrics assesses the reliability of microgrid from various aspects, including indices indicating distributed generation and load characteristics in the microgrid. For operation in islanded mode, the index Island Expected Energy Deficiency (IEED) (kWh/yr) is proposed to measure energy deficiency during islanded operation mode. The IEED measures average energy deficiency during island mode due to hours when island load exceeds the total available island power generation. To calculate this index the equation (2.55) can be used:

$$IEED = \frac{\sum_{TS=1}^{ND}(L_{TS} - G_{TS}) \cdot T_{TS}}{NI} \tag{2.55}$$

Where:

TS = time segment

ND = number of time segments when total generation output cannot satisfy total load demand in the island operation in a year.

L_{TS} = load demand in time segment TS in kW

G_{TS} = generation output in time segment in kW

T_{TS} = duration of time segment in hour

NI = island times in one year

Both the LOLE and the IEED index can be used to assess generating capacity adequacy of microgrid, but they express by different parameters. The LOLE measures generation deficiency by the number of hours in a year in which the load exceeds the generation capacity, while the IEED measures the energy deficiency due to hours when the load exceeds the power generation.

2.9 EVALUATION OF OPERATION RELIABILITY INDICES

Microgrid has potential of improving the reliability of power supply by smoothly switching between the grid-connected mode and the islanded mode. That is, the power supply of the microgrid's loads would not be interrupted by the failures outside the microgrid, given that there is enough generation capacity in the microgrid. The ability of microgrids to switch uninterruptedly between islanded mode and grid-connected mode will influence the reliability of microgrid. If the microgrid fails switching to islanded mode, the islanding does not make sense, and the local loads of the microgrid would be interrupted by the failures on the main grid.

A positive impact on reliability requires that the microgrid is able to isolate itself successfully in the failure event on the main grid. This microgrid's ability of isolated operation in the emergency situation is an important aspect to consider in the reliability evaluation of microgrid. In order to include this operational characteristics in the reliability calculation, two reliability indices, IOSR (Island Operation Successful Rate) and the MIOP (Microgrid Islanded Operation

Probability) described in Section 2.3.3 are proposed to use for assessment of island switching operation. The formulae are given again below:

$$IOSR = \frac{Total\ number\ of\ forming\ island\ successfully}{Total\ number\ of\ outages\ on\ PCC}\ (pu) \quad (2.12)$$

$$MIOP = \frac{Microgrid\ hours\ in\ islanded\ mode}{Total\ microgrid\ operation\ hours}\ (pu) \quad (2.13)$$

Mathematically the indices IOSR calculates the probability of a microgrid to switch successfully from grid-connected operation mode to islanded operation mode, where PCC is point of common coupling of main grid at which microgrids is connected.

The MIOP is fraction of time that microgrid is operated in islanded mode with respect to the total microgrid operation time.

3 Case study

This section performs case study on a real microgrid, Arholma system, using the method described in Chapter 2. The case study will show reliability analysis process, illustrate assessment technique and numerical calculations.

3.1 ARHOLMA SYSTEM

Arholma microgrid is a pilot innovation project made by Vattenfall Distribution AB. Figure 3.1 shows the Arholma system. It locates on the island Arholma at Stockholm archipelago. It connects to main grid at 11 kV point of common coupling (PCC), but is expected to be able to operate in island mode for an hour. The island can be influenced hard by the outages on the main grid or by failures of the submarine cable connected to the main grid. In the failure events upstream the microgrid is expected to be disconnected from the main grid being seamless islanding and becomes self-sufficient to support its customers with its own power generation.

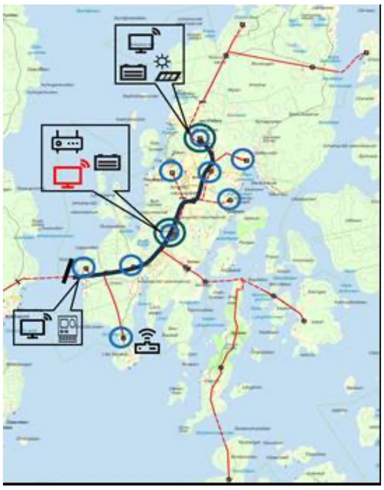

Figure 3.1: Arholma microgrid

The Arholma microgrid consists of photovoltaic system (PV), energy storage system (ESS), load and energy management system as shown in Figure 3.2. The PCC defines the separation point between the main grid and the microgrid. The energy management system is interfaced with all microgrid nodes using GOOSE communication for critical signals according to the IEC 61850 protocol. This communication is connected to the LV protection of the microgrid. The PV system and EES are integrated in the microgrid and controlled by low-level management.

On the island there are about 30 permanent households and 147 vacation houses. The Arholma system has 19 secondary substations, 199 customer connections with an annual consumption of 1.5 GWh. Two energy storage systems, ESS1 and ESS2, are identical, and each of them has a maximum active power of 160 kW and an installed energy capacity of 336 kWh. They are installed in standard containers and connected to the substations 10 and 15 respectively as shown in Figure 3.3. The

ESSs are connected to the LV side of the substations and have a maximum AC voltage of 400 V.

The PV system installed in the microgrid consists of 6 solar panels in series connected to the substation 15 with a total maximum power of 2.73 kWp. Figure 3.3 shows the single-line diagram of the microgrid.

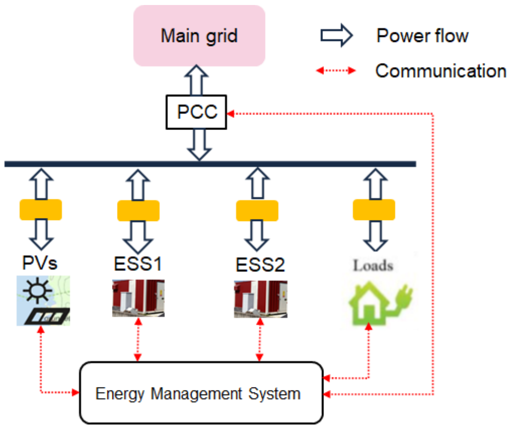

Figure 3.2: The structure of Arholma microgrid

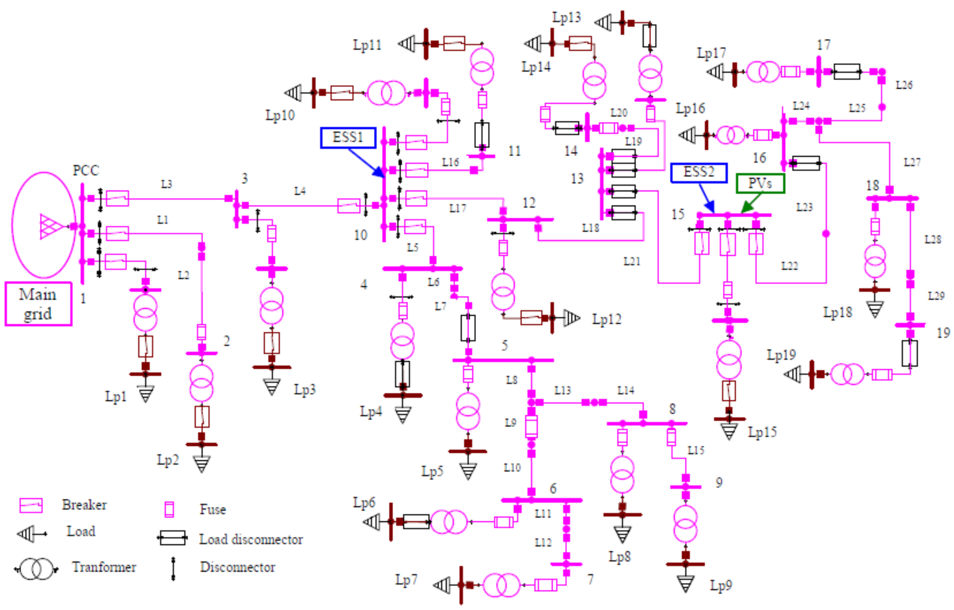

Figure 3.3: The single-line diagram of the Arholma microgrid

3.2 INPUT DATA

3.2.1 Power system data

The Arholma system comprises 19 secondary sub-stations, two main feeders and 19 load points. The line parameters are listed in Table 3.1. The lengths of the lines are in kilometers. The types of the lines are also given in the table, where UC stands for underground cable, HC hanging cable and OL overhead line.

Table 3.1: Line parameters

Line number	Type	Length (km)	Line number	Type	Length (km)
L1	UC	0,214	L16	UC	0,863
L2	OL	0,813	L17	UC	0,796
L3	UC	0,613	L18	UC	0,583
L4	UC	0,724	L19	UC	0,268
L5	UC	0,542	L20	HC	0,237
L6	UC	0,074	L21	UC	0,918
L7	HC	0,226	L22	UC	0,228
L8	UC	0,471	L23	OL	0,623
L9	UC	0,140	L24	OL	0,051
L10	HC	0,973	L25	OL	0,171
L11	HC	0,945	L26	UC	0,216
L12	UC	0,421	L27	OL	0,973
L13	UC	0,244	L28	OL	0,240
L14	HC	0,119	L29	UC	0,461
L15	HC	0,470			

3.2.2 Customer and load demand data

Table 3.2 lists the customer and load data for each load point. The load data are average customer demand during the period from Oct. 2015 to June 2019. The hourly load profile of Arholma during the period from Jan. 2016 to Dec. 2018 is displayed in Figure 3.4.

Table 3.2: Customer and load data of Arholma system

Load Point	Number of customers	Load (kW)
Load Point 1	4	6,14
Load Point 2	11	2,21
Load Point 3	10	6,77
Load Point 4	1	0,02
Load Point 5	5	3,84
Load Point 6	11	6
Load Point 7	3	1,67
Load Point 8	5	1,37
Load Point 9	1	2,01
Load Point 10	45	25,71
Load Point 11	30	20,43
Load Point 12	10	4,45
Load Point 13	21	8,25
Load Point 14	27	23,13
Load Point 15	19	10,35
Load Point 16	1	0,45
Load Point 17	5	36,48
Load Point 18	2	0,17
Load Point 19	2	0,01
Total	213	159,46

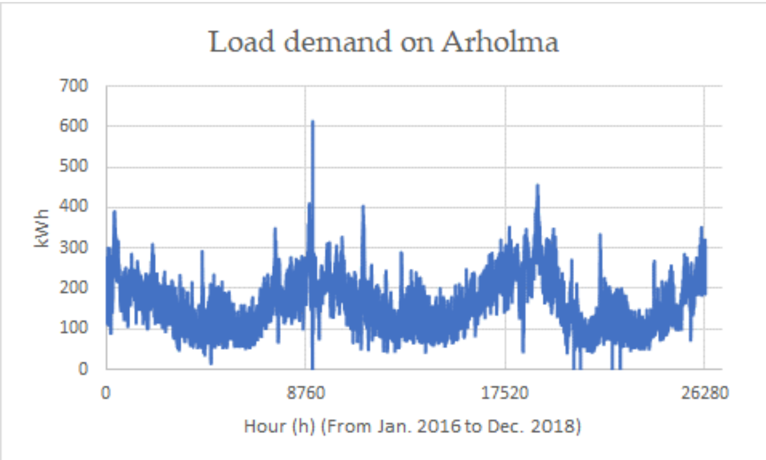

Figure 3.4: The hourly load demand of Arholma during Jan. 2016 – Dec. 2018

3.2.3 DGs data

As described in section 3.1, there are two types of DGs on the Arholma microgrid: PV system and ESS system (including ESS1 and ESS2). Table 3.3 summarizes their parameters.

Apart from the ESS1, ESS2 and the PV system newly installed, there exists the local PV generation from early installation by the customers with the total capacity of 80 kWp on Arholma network. Figure 3.5 shows the output power profile from the existing PV system during the period from Jan. 2016 to Dec. 2018.

Table 3.3: DGs nameplate data

Nummer of PV modules	6 connected in series
Maximum PV power (kWp)	2,73
Type of PV module	Longi Solar Hi-MO 4m LR4-72HPH 450
ESS maximum apparent power (kVA)	2x200
ESS available active power (kW) (at PF = 0,8)	2x160
ESS installed energy (kWh)	2x336

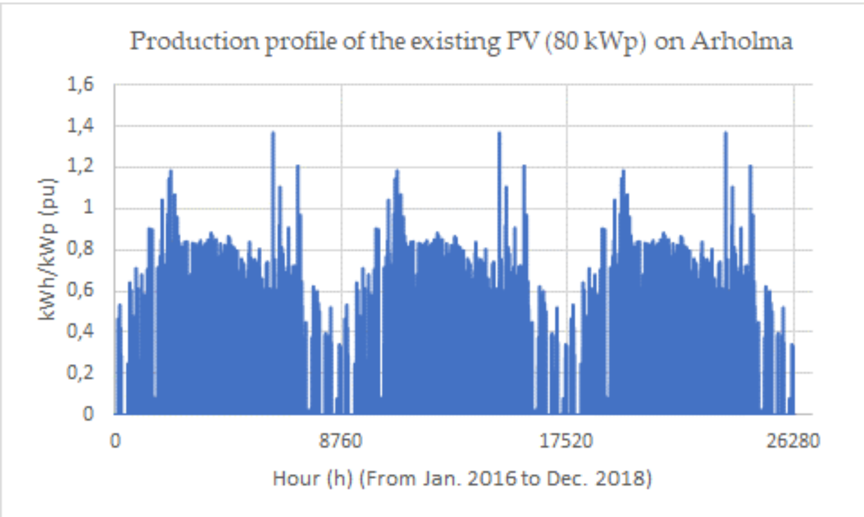

Figure 3.5: Output power profile of the existing local PV on Arholma

3.2.4 Component reliability data

The reliability input data used in the calculations are summarized in Table 3.4 below. The data were estimated based on the references and failure statistics available for the study. These data sources are also given in the table.

The reliability data used are considered only for sustained forced outages or permanent failures. The short-duration interruptions and component transient failures are not considered, since they are associated with undamaged faults and can be recovered quickly by reclosures or reconnections, besides there are no detailed information and statistics available for component transient failures.

The reliability of island isolation operation is determined by control method as well as reliability of communication and control equipment. Since the Arholma microgrid is still in building phase, there is no operation performance data available. The probability of unsuccessful isolation operation, P, due to failure of a controller or any other component in the communication and control system is estimated as 0,5%, based on some literatures [5, 48], and experience from the field control.

The reliability of battery energy storage system (BESS) can be affected by the reliability of battery packs, converter modules, BESS configurations and redundancy structure, as well as BESS dynamic operation [49]. However the battery storage systems are not yet installed on Arholma, these figures and information are not available at the present. The reliability data for the battery storage systems ESS1 and ESS2 are estimated based on the experience from performance of the existing battery storage system at Vattenfall, which are given in Table 3.5.

Similar to any other electrical system, grid-connected PV system can fail due to accidental events and occasional failures of its components. A PV system is composed of many components, such as power electronic devices and solar cells, whose reliability is dependent on loads and ambient conditions. Since there is no performance data for the battery storage systems ESS1 and ESS2 available, their reliability data are estimated based on the experience from performance of the existing PV system, which are also given in Table 3.5.

Table 3.4: Component reliability input data

Component / Item	Failure rate λ (failure/year.km), (failure/year.unit)	Repair time r (Downtime) (hour/failure)	Unavailability U	Availability A	References / Sources
PCC	2,100	2,000	0,04795%	99,9521%	Estimated based on [42- 45, 47]
Power transformer 11/0,4 kV	0,012	10,000	0,0014%	99,9986%	Estimated based on [46]
Disconnector 11 kV	0,008	4,0	0,00037%	99,99963%	Estimated based on Vattenfall statistics
Load disconnector 11 kV	0,008	4,0	0,00037%	99,99963%	Estimated based on Vattenfall statistics
Load disconnector 0,4 kV	0,010	4,0	0,00046%	99,99954%	Estimated based on Vattenfall statistics
Circuit breaker 11 kV	0,011	4,0	0,00050%	99,99950%	Estimated based on [46]
Circuit breaker 0,4 kV	0,014	4,0	0,00064%	99,99936%	Estimated based on [46]
Underground cable 11 kV	0,020	5,0	0,00114%	99,99886%	Estimated based on [46]
Hanging cable 11 kV	0,040	6,0	0,00274%	99,99726%	Estimated based on [46]
Overhead line 11 kV	0,120	20,0	0,02740%	99,97260%	Estimated based on [46]

Table 3.5: Reliability data for isolation operation, ESS and PV system on Arholma

Item	Failure rate λ (failure/year)	Repair time r (hour/failure)	P
Isolation operation			0,5%
ESS1, ESS2	1,1	5	
PV	0,9	5	

3.3 CALCULATION OF LOAD POINT AND CUSTOMER ORIENTATED RELIABILITY INDICES

This section calculates load point and customer orientated reliability indices. The indices are calculated for three operational modes: grid-connected mode, islanded mode, and hybrid operation mode. For each operational mode the indices is analyzed at two levels: load points level and overall system level.

3.3.1 Grid-connected mode

In the first step, the reliability in grid-connected mode is calculated. In this operation mode, the microgrid is equivalently as a load connected at the PCC. It is operated radially as a part of the distribution network, and the energy storage system is subject to charging. A customer connected to a load point of the microgrid requires all components between himself and the supply point to be operating.

Consider the load point 11 of the system in Figure 3.3. Its single-line diagram from the supply point PCC to the load point is shown in Figure 3.6. It is seen that each failure on feeders L3, L4 and L16 will cause the breaker to trip to interrupt power supply to the load point. The failure must be repaired before the breaker can be reclosed. The failures on the other feeders can be isolated by the protection devices and will not cause outage of the load point 11. Based on the operating procedure the load point indices can be calculated by the equations (2.42) – (2.44). The results are given in Table 3.6.

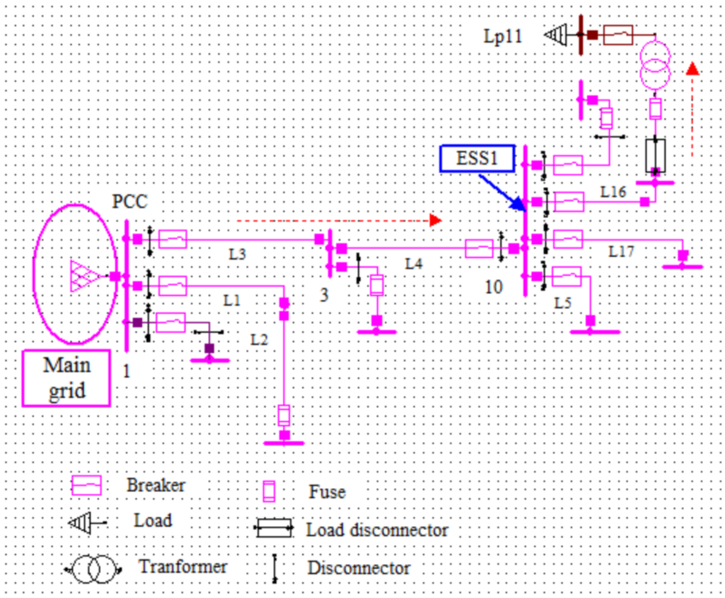

Figure 3.6: The load point 11 in grid connected mode

Table 3.6: Reliability indices of load point 11 in grid connected mode

Component	Failure rate λ_g (f/yr)	Repair time r_g (h/f)	Unavailability U_g (h/yr)
PCC	2,1	2	4,2
Disconnector 11 kV	0,008	4	0,032
Circuit breaker 11 kV	0,011	4	0,044
L3	0,01226	5	0,0613
L4	0,01448	5	0,0724
Circuit breaker 11 kV	0,011	4	0,044
Disconnector 11 kV	0,008	4	0,032
Disconnector 11 kV	0,008	4	0,032
Circuit breaker 11 kV	0,011	4	0,044
L16	0,01726	5	0,0863
Load disconnector 11 kV	0,008	4	0,032
Power transformer 11/0,4 kV	0,012	10	0,12
Circuit breaker 0,4 kV	0,014	4	0,056
Indices of load point 11	**2,235**	**2,173**	**4,856**

Similar to the calculation for load point 11, the reliability indices for all the other load points of the system can be assessed. The results are summarized in Table 3.7. It is seen that the load points 16- 19 have higher unavailability than the other load points. This is due to that the feeders to the load points, the overhead lines L23-L25, L27, L28 have higher failure rate and longer repair time, and hence higher unavailability.

Based on the load point indices, the reliability on system level can be evaluated by the equations (2.4)– (2.7). The system indices calculated are the most commonly used customer orientated indices, i.e., the system average interruption index (SAIFI), the system average interruption duration index (SAIDI), the average energy net supplied (AENS) and the average service availability index (ASAI). The results are presented in Table 3.8.

Table 3.7: Load point indices of grid connected mode

Load point	Failure rate λ_g (f/yr)	Repair time r_g (h/f)	Unavailability U_g (h/yr)
Load point 1	2,153	2,083	4,484
Load point 2	2,247	2,859	6,425
Load point 3	2,165	2,099	4,545
Load point 4	2,243	2,185	4,902
Load point 5	2,244	2,197	4,930
Load point 6	2,296	2,272	5,217
Load point 7	2,332	2,335	5,446
Load point 8	2,244	2,197	4,930
Load point 9	2,263	2,228	5,042
Load point 10	2,218	2,151	4,770
Load point 11	2,235	2,173	4,856
Load point 12	2,253	2,192	4,940
Load point 13	2,249	2,189	4,924
Load point 14	2,276	2,221	5,055
Load point 15	2,318	2,250	5,215
Load point 16	2,577	3,967	10,221
Load point 17	2,577	3,967	10,221
Load point 18	2,577	3,967	10,221
Load point 19	2,585	3,967	10,253

Table 3.8: The system reliability indices of grid connected mode

Load point	Failure rate ƛ_g (f/yr)	Number of customers N	ƛ_g ·N	Repair time r_g (h/f)	Unavailability U_g (h/yr)	U_g ·N	Load La(kW)	La·U (kWh/yr)
Load point 1	2,153	4	8,612	2,083	4,484	17,936	6,140	27,532
Load point 2	2,247	11	24,715	2,859	6,425	70,671	2,210	14,198
Load point 3	2,165	10	21,653	2,099	4,545	45,453	6,770	30,772
Load point 4	2,243	1	2,243	2,185	4,902	4,902	0,020	0,098
Load point 5	2,244	5	11,221	2,197	4,930	24,648	3,840	18,930
Load point 6	2,296	11	25,255	2,272	5,217	57,388	6,000	31,303
Load point 7	2,332	3	6,996	2,335	5,446	16,338	1,670	9,095
Load point 8	2,244	5	11,221	2,197	4,930	24,648	1,370	6,754
Load point 9	2,263	1	2,263	2,228	5,042	5,042	2,010	10,135
Load point 10	2,218	45	99,798	2,151	4,770	214,637	25,710	122,629
Load point 11	2,235	30	67,050	2,173	4,856	145,680	20,430	99,208
Load point 12	2,253	10	22,533	2,192	4,940	49,396	4,450	21,981
Load point 13	2,249	21	47,236	2,189	4,924	103,396	8,250	40,620
Load point 14	2,276	27	61,456	2,221	5,055	136,493	23,130	116,929
Load point 15	2,318	19	44,036	2,250	5,215	99,093	10,350	53,979
Load point 16	2,577	1	2,577	3,967	10,221	10,221	0,450	4,599
Load point 17	2,577	5	12,884	3,967	10,221	51,106	36,480	372,866
Load point 18	2,577	2	5,153	3,967	10,221	20,442	0,170	1,738
Load point 19	2,585	2	5,169	3,967	10,253	20,506	0,010	0,103
Sum	44,052	213	482,071		116,596	1117,994	159,460	983,467
System indices	SAIFI (f/yr.cust)	SAIDI (h/yr.cust)	AENS (kWh/yr.cust)	ASAI				
	2,263	5,249	4,617	99,9401%				

3.3.2 Island mode

In the second step, the calculation focuses on the microgrid in island mode. Microgrid has a potential of improving the reliability of supplying its loads by smoothly switching between the grid-connected model and the island mode. That means that the power supply of microgrid's loads would not be interrupted by the failures outside the microgrid, given that there is enough power capacity available in the microgrid.

Assume that the microgrid has already successfully islanded from the main grid. It is in island mode and the loads are supplied by the local generation, which is constituted by two battery storage systems, ESS1 and ESS2, and the PVs. Figure 3.7 shows the system in island mode with the local generation.

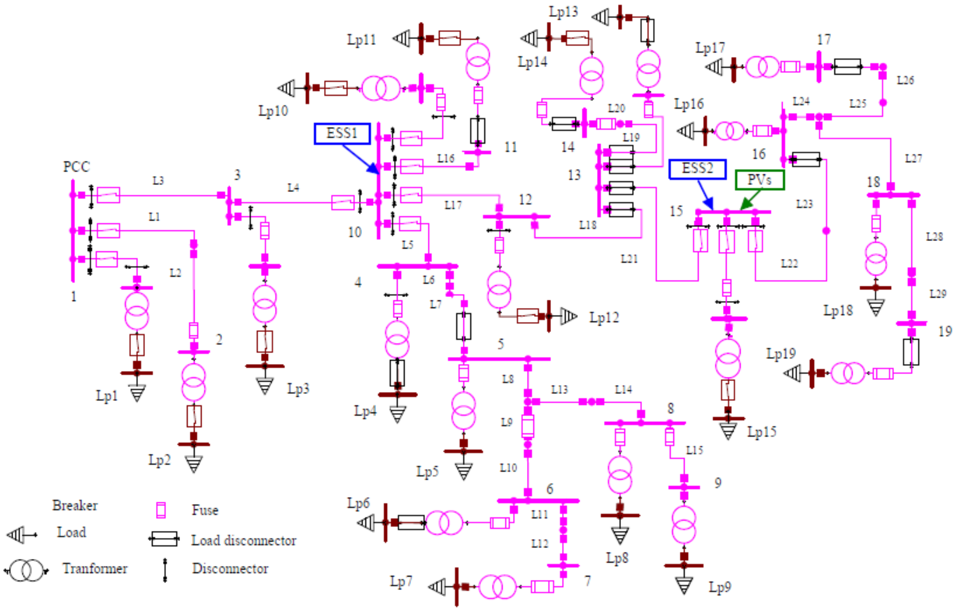

Figure 3.7: The Arholma system in island operation mode

As described in the section 2.7.2, three kinds of failure events can lead to failure of power supply. The load point indices in island mode can be accordingly evaluated by the equations (2.45)- (2.47). Consider again the load point 11 of the system in Figure 3.7. In island operation the load point is supplied by the battery storage system ESS1. The single-line diagram from the supply point ESS1 to the load point is shown in Figure 3.8.

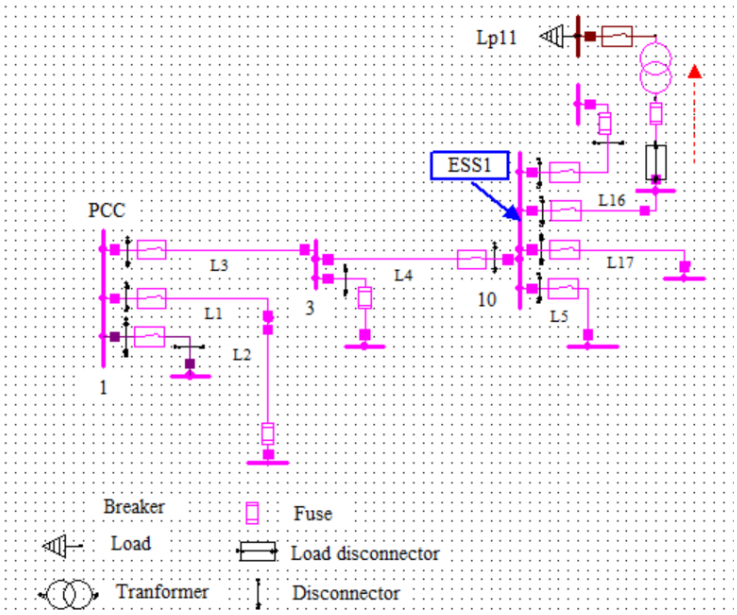

Figure 3.8: Power supply of the load point 11 in island mode

Using the reliability data for isolation operation, PV and energy storage system listed in Table 3.5, the load point indices are calculated, which are presented in Table 3.9. As seen in the table the load point indices in island mode reflect the reliability parameters of upstream system and the probability of an unsuccessful isolation. This will complement the reliability measure from island aspects. Comparing the values in Table 3.9 with that in Table 3.6, it shows that the reliability of load point 11 is improved significantly, the unavailability decreased by 48%. Due to the microgrid's ability to switch from grid-connected to grid-off operation in the emergency situation when fault event occurred on the main grid, the local energy storage has potential to enhance reliability of supply the local customers.

Table 3.9: Reliability indices of load point 11 in island mode

Item	Failure rate λ_is (f/yr)	Repair time r_is (h/f)	Unavailability U_is (h/yr)
D	0,008	4,000	0,032
B	0,011	4,000	0,044
L16	0,017	5,000	0,086
LD	0,008	4,000	0,032
T	0,012	10,000	0,120
B0,4	0,014	4,000	0,056
P·λup	0,011	0,010	0,000
(1-P)*λup, ESS	1,507	1,421	2,142
Indices of load point 11	**1,587**	**1,582**	**2,512**

In the similar way the reliability for all the other load points can be calculated. The results are summarized in Table 3.10. By comparing the results of the indices of grid-connected mode in table 3.7, it is seen that the reliability of power delivery to respective load points in island mode is generally improved, the unavailability decreases in the range of 27% - 53%. The ability of microgrid with flexible operation modes could increase the local reliability of power supply.

Based on the load point indices the system indices can be calculated by the equations (2.4) – (2.7), the results are given in Table 3.11. By comparison of the results with the values for grid-connected mode in Table 3.8, it is seen that the system indices are improved in island mode. SAIFI and SAIDI decrease by 29% and 45% respectively. The results demonstrate the reliability improvement brought by the microgrid with its flexible operation strategy.

Table 3.10: Load point indices of islanded mode

Load point	Failure rate λ_is (f/yr)	Repair time r_is (h/f)	Unavailability U_is (h/yr)
Load point 1	1,635	1,658	2,711
Load point 2	1,729	2,691	4,652
Load point 3	1,585	1,576	2,498
Load point 4	1,595	1,603	2,557
Load point 5	1,597	1,619	2,586
Load point 6	1,648	1,743	2,873
Load point 7	1,684	1,842	3,102
Load point 8	1,597	1,619	2,586
Load point 9	1,615	1,670	2,698
Load point 10	1,570	1,545	2,426
Load point 11	1,587	1,582	2,512
Load point 12	1,606	1,616	2,596
Load point 13	1,592	1,591	2,533
Load point 14	1,619	1,646	2,665
Load point 15	1,570	1,545	2,426
Load point 16	1,829	4,063	7,431
Load point 17	1,829	4,063	7,431
Load point 18	1,829	4,063	7,431
Load point 19	1,837	4,062	7,463

Table 3.11: System reliability indices of islanded mode

Load point	Failure rate λ_is (f/yr)	Number of customers N	λ_is ·N	Repair time r_is (h/f)	Unavailability U_is (h/yr)	U_is ·N	Load La(kW)	La·U (kWh/yr)
Load point 1	1,635	4	6,539	1,658	2,711	10,845	6,140	16,648
Load point 2	1,729	11	19,016	2,691	4,652	51,171	2,210	10,281
Load point 3	1,585	10	15,846	1,576	2,498	24,981	6,770	16,912
Load point 4	1,595	1	1,595	1,603	2,557	2,557	0,020	0,051
Load point 5	1,597	5	7,983	1,619	2,586	12,928	3,840	9,929
Load point 6	1,648	11	18,131	1,743	2,873	31,604	6,000	17,238
Load point 7	1,684	3	5,053	1,842	3,102	9,306	1,670	5,180
Load point 8	1,597	5	7,983	1,619	2,586	12,928	1,370	3,542
Load point 9	1,615	1	1,615	1,670	2,698	2,698	2,010	5,424
Load point 10	1,570	45	70,655	1,545	2,426	109,154	25,710	62,364
Load point 11	1,587	30	47,621	1,582	2,512	75,359	20,430	51,319
Load point 12	1,606	10	16,057	1,616	2,596	25,956	4,450	11,550
Load point 13	1,592	21	33,442	1,591	2,533	53,202	8,250	20,901
Load point 14	1,619	27	43,722	1,646	2,665	71,959	23,130	61,644
Load point 15	1,570	19	29,832	1,545	2,426	46,087	10,350	25,105
Load point 16	1,829	1	1,829	4,063	7,431	7,431	0,450	3,344
Load point 17	1,829	5	9,146	4,063	7,431	37,157	36,480	271,096
Load point 18	1,829	2	3,658	4,063	7,431	14,863	0,170	1,263
Load point 19	1,837	2	3,674	4,062	7,463	14,927	0,010	0,075
Sum	31,555	213	343,398		71,178	615,113	159,460	593,866
System indices	SAIFI_is (f/yr.cust)	SAIDI_is (h/yr.cust)	AENS_is (kWh/yr.cust)	ASAI_is				
	1,612	2,888	2,788	99,9670%				

3.3.3 Hybrid operation mode

Microgrid is flexible in the operation mode, it can operate as an integrated part of distribution system or an islanded network. Depending on the operation situation and control strategy, microgrid must switch smoothly among different operation modes at different time periods. This hybrid operation mode may affect the reliability of the microgrid.

In the third step, the calculation focuses on the microgrid in hybrid operation mode. Assumed that the microgrid operates in grid-connected mode with a probability of 60% and in island mode with a probability of 40%. The load point indices in hybrid mode can be calculated by the equations (2.48) – (2.50), where P_g=60%. Table 3.12 lists the results of the calculations.

Based on the load point indices the system indices are evaluated, which are given in Table 3.13. For comparison purpose Table 3.14 summarizes the system indices in different operation modes. It shows that the system in hybrid operation is more reliable than in grid-connected operation. In hybrid operation the SAIFI is improved by 11.5%, SAIDI reduced by 18%, and AENS reduced by 15.8% compared with grid-connected operation mode. The function of microgrid to isolate the loads from the main grid during the system failure upstream can lead to the improvement of power supply reliability of internal customers in the microgrid. It is observed that under the same operation mode the customers experience different reliability. The customers far away from the local power supply sources, as load points 2, 6, 7, and 16- 19 have higher unavailability than those close to the local power supply, as load points 3-5, 10 and 13.

Table 3.12: Load point indices of hybrid mode

Load point	Failure rate λ_h (f/yr)	Repair time r_h (h/f)	Unavailability U_h (h/yr)
Load point 1	1,946	1,940	3,775
Load point 2	2,040	2,802	5,716
Load point 3	1,933	1,928	3,726
Load point 4	1,984	1,998	3,964
Load point 5	1,985	2,011	3,992
Load point 6	2,037	2,101	4,280
Load point 7	2,073	2,175	4,508
Load point 8	1,985	2,011	3,992
Load point 9	2,004	2,048	4,105
Load point 10	1,959	1,956	3,832
Load point 11	1,976	1,983	3,918
Load point 12	1,994	2,007	4,002
Load point 13	1,987	1,997	3,968
Load point 14	2,013	2,036	4,099
Load point 15	2,019	2,031	4,100
Load point 16	2,278	3,998	9,105
Load point 17	2,278	3,998	9,105
Load point 18	2,278	3,998	9,105
Load point 19	2,286	3,998	9,137

Table 3.13 System indices of hybrid mode

Load point	Failure rate λ_h (f/yr)	Number of customers N	$\lambda_h \cdot N$	Repair time r_h (h/f)	Unavailability U_h (h/yr)	$U_h \cdot N$	Load La(kW)	La·U (kWh/yr)
Load point 1	1,946	4	7,783	1,940	3,775	15,100	6,140	23,178
Load point 2	2,040	11	22,435	2,802	5,716	62,871	2,210	12,631
Load point 3	1,933	10	19,330	1,928	3,726	37,264	6,770	25,228
Load point 4	1,984	1	1,984	1,998	3,964	3,964	0,020	0,079
Load point 5	1,985	5	9,926	2,011	3,992	19,960	3,840	15,329
Load point 6	2,037	11	22,405	2,101	4,280	47,075	6,000	25,677
Load point 7	2,073	3	6,219	2,175	4,508	13,525	1,670	7,529
Load point 8	1,985	5	9,926	2,011	3,992	19,960	1,370	5,469
Load point 9	2,004	1	2,004	2,048	4,105	4,105	2,010	8,251
Load point 10	1,959	45	88,141	1,956	3,832	172,444	25,710	98,523
Load point 11	1,976	30	59,279	1,983	3,918	117,551	20,430	80,053
Load point 12	1,994	10	19,943	2,007	4,002	40,020	4,450	17,809
Load point 13	1,987	21	41,718	1,997	3,968	83,318	8,250	32,732
Load point 14	2,013	27	54,362	2,036	4,099	110,679	23,130	94,815
Load point 15	2,019	19	38,354	2,031	4,100	77,891	10,350	42,430
Load point 16	2,278	1	2,278	3,998	9,105	9,105	0,450	4,097
Load point 17	2,278	5	11,389	3,998	9,105	45,526	36,480	332,158
Load point 18	2,278	2	4,555	3,998	9,105	18,210	0,170	1,548
Load point 19	2,286	2	4,571	3,998	9,137	18,274	0,010	0,091
Sum	39,053	213	426,602		98,429	916,842	159,460	827,627
System indices	SAIFI (f/yr.cust)	SAIDI (h/yr.cust)	AENS (kWh/yr.cust)	ASAI				
	2,003	4,304	3,886	99,9509%				

Table 3.14 System indices of different operation modes

	Grid concected mode	Islanded mode	Hybrit mode
SAIFI (f/yr.cust)	2,263	1,612	2,003
SAIDI (h/yr.cust)	5,249	2,888	4,304
AENS (kWh/yr.cust)	4,617	2,788	3,886
ASAI	99,9401%	99,9670%	99,9509%

3.4 CALCULATION OF GENERATING CAPACITY ADEQUACY RELIABILITY INDICES

The reliability of microgrid includes two facts: security and adequacy. Security is related to the ability of the system to respond to the sudden disturbances arising within the system, while adequacy refers to the existence of sufficient power capacity within the system to satisfy the customer demand. The power output of DGs used by microgrid is random and intermittent, which is different from the conventional power supply. When analyzing microgrid reliability it is necessary to take generation adequacy into account.

The primary concern in generating adequacy evaluation is to assess whether the capacity of the generation facilities satisfies the load demand. The power output of microgrid with PV system and ESS may be insufficient in the following situations: (1) absence of light at night, (2) insufficient light during the day, (3) insufficient energy in battery storage system. When microgrid is in island mode, occurrence of these situations may lead to failure state and loss of load occurs. When the generation capacity cannot meet load demand, this system failure state is not caused by sudden disturbance due to component failure, but due to no sufficient generation.

As described in section 2.3.2, three indices, LOLE, LOEE and LOLP are the most commonly utilized to measure the overall adequacy of system. When microgrid operates in island mode its generation needs to be consumed in order to maintain the system power balance as expressed by equation (2.51). The power available from all the generation facilities are combined and compares with the total load demand. The system is in failure state if the total power supply cannot serve the load. The adequacy indices can then be calculated by identify the total number of hours in which the load surpasses the available generation capacity, and the energy not supplied at each loss of load duration.

3.4.1 Load demand on Arholma

To determine whether the local generation is sufficient, it is necessary firstly to examine the load demand on individual load point. The hourly time series load data on each load point for at least one year are preferred. The actual hourly load data on each load point are obtained from the system owner of Vattenfall Distribution AB for the period from Oct. 2015 to June 2019. These load data at load points are then aggregated to get the total load demand on system level. Figure 3.9 shows the actual load curve for Arholma for the time period from Jan 2016 to Dec. 2018.

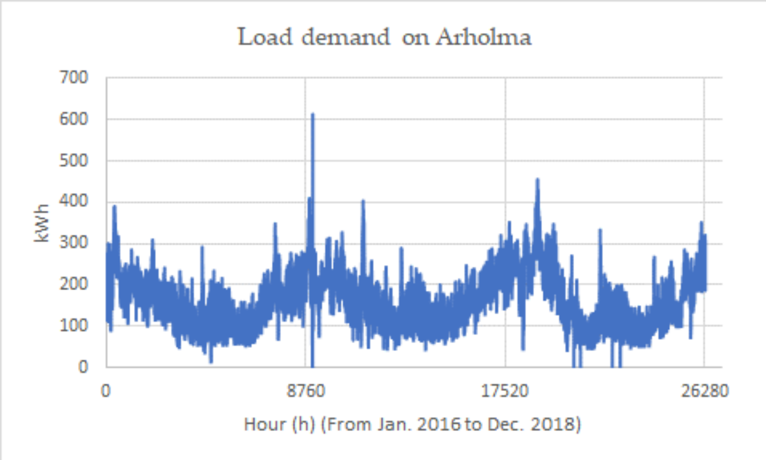

Figure 3.9: Hourly load demand on Arholma

3.4.2 Local Generation on Arholma

As described in section 3.2.3, the local generation on Arholma consists of PV system and ESS system. The solar panel is the central element of a PV system, its output depends on several factors, such as solar radiation received by the panel, temperature, and relative humidity. To estimate the power supplied by the solar panels, the hourly output pattern from the existing solar panel of 80 kWp on Arholma is used. The pattern was measured by Vattenfall Distribution AB from Oct. 2015 to June 2019. Figure 3.5 shows the PV output pattern from Jan, 2016 to Dec. 2018.

Energy storage system is a significant component in microgrid, especially in island operation. The major function of energy storage is to smooth out the power fluctuation and improve the power generation availability. In microgrid operation, energy storage system sometimes serves as generation providing power to the load, and sometimes it is charged as a load when connected to main grid. In islanding mode, the available renewable energy is firstly utilized to serve the load. If it is not enough to cover the load, the energy stored in ESS is discharged to avoid or minimize load curtailment.

The battery storage system may have different output levels. In this case study it is simply considered as a unit. Its maximum active power of 320 kWp is discharged when the microgrid is switched to island operation. Since one hour is considered for the microgrid to be able to operate as one period in island mode, the discharging energy is equal to 320 kWh (320 kW multiplied by one hour).

3.4.3 Calculation of the indices

The power available from all the generation units, PVs, ESS1 and ESS2, are combined to form the total system power supply in island operation, which is compared with the total load according to the power balance equation (2.51). Hourly time series load and generation data are used for the comparison. The load data are chronological hourly load pattern. As data in three years are available, these data are used for the calculations. For every hour from Jan, 2016 to Dec. 2018 the difference between the total system power generation and the total load demand is identified. A positive margin indicates power sufficiency, while a negative margin means power insufficiency indicating a capacity outage. By counting the number of occurrences of power insufficiency and the total load curtailment, the desires adequacy indices can be calculated based on the equations (2.52) and (2.53).

The calculation shows that 130 hours a year in average during the three years the load demand exceeded the available system generation in island operation. It illustrates the loss of load duration when the hourly load demand surpasses the available power generation. Any generating capacity outage will result in a load curtailment (or loss of load supply). Figure 3.10 represents the system load demand that could not be supplied due to insufficient power generation in island operation. The value of loss of energy expectation is evaluated as 4613 kWh/year. Based on the number of hours of capacity outage, the loss of load probability can be calculated. The calculation indicates that the available generation is unable to meeting the load with a probability of 1.5%. Table 3.15 summarizes the calculated generating capacity adequacy reliability indices.

Table 3.15 Adequacy indices

LOLE(h/yr)	LOEE(kWh/yr)	LOLP
130	4613	1,5%

The evaluation of the adequacy indices illustrates that energy storage system plays an important role in microgrid island operation, it can significantly enhance the reliability of power supply. The results of the capacity adequacy evaluation can also provide insights on how battery storage capacity affects the reliability. The quantified values of these indices could also be helpful in determining the prober capacity of energy storage to achieve desired reliability level in building microgrid.

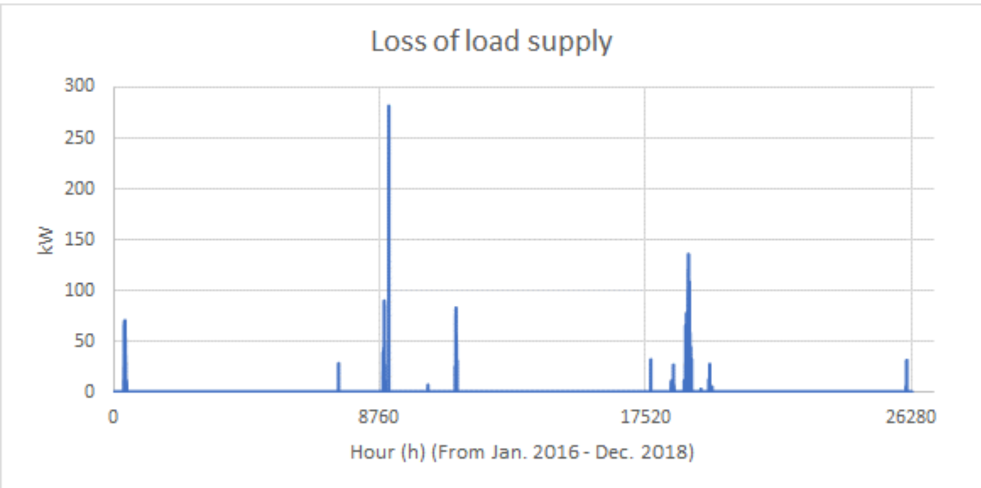

Figure 3.10: Loss of load supply

3.5 CALCULATION OF OPERATION RELIABILITY INDICES IN ISLANDED MODE

Intentional islanding, also called as “microgrid islanding operation”, plays an essential role in providing the reliability enhancement for local customers of the microgrid. An important issue during the islanding operation is to determine the probability of islanding to be a success or a failure. As mentioned in section 2.3.3 the paper [16] proposed to calculate this probability by the equation (2.12). It is suggested to measure operation reliability of microgrid by the indices of IOSR (Island Operation Successful Rate) and MIOP (Microgrid Island Operation Probability), the equations are given again below.

$$IOSR = \frac{Total\ number\ of\ forming\ island\ successfully}{Total\ number\ of\ outages\ on\ PCC} \quad (2.12)$$

$$MIOP = \frac{Microgrid\ hours\ in\ islanded\ mode}{Total\ microgrid\ operation\ hours} \quad (2.13)$$

Since Arholma microgrid is still in building phase, the operation performance data do not exist, the number of forming island successfully and microgrid operating hours are currently unavailable, the calculation of these operation indices could not be performed. After the Arholma microgrid is set on operation, the practical field performance data are collected, such as number of incorrect operations, these indices can then be evaluated straight forwards.

4 Recommendation of method for reliability analysis of microgrid

Based on the literature study and the case study described in the previous chapters, an applicable method for reliability evaluation of microgrid is recommended. The overall structure of the method is presented by block diagram in Figure 4.1. The basic workflow of the method is described further below.

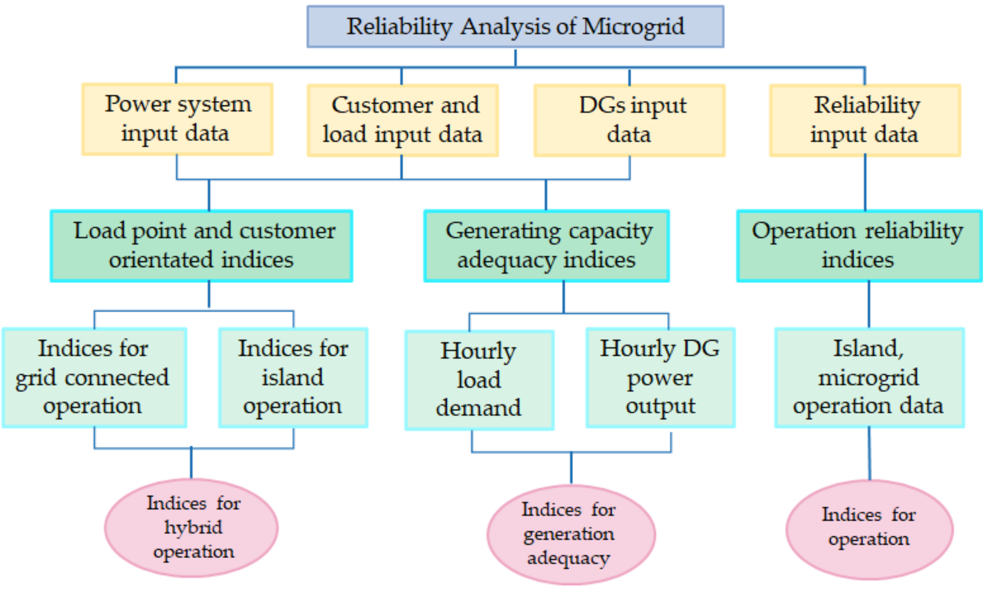

Figure 4.1: Method of microgrid reliability analysis

Workflow of the method:

Step 1: Start with preparing input data necessary for the analysis, which include the following four types of data and parameters as exemplified given in section 3.2:

- Power network data
- Customer and load demand data
- DGs data
- Component reliability data.

Step 2: Calculate load point and customer orientated reliability indices.

Calculate the indices for three operational modes at two levels: load points level and overall system level.

- Firstly suppose the microgrid is connected to the PCC of the distribution network, treat the microgrid as a section of the network, perform the reliability calculations as described in section 3.3.1. Calculate load point indices by equations (2.42) - (2.44) and calculate system indices by equations (2.4) – (2.7).

- Suppose then the microgrid is islanded from the distribution network by disconnecting from the PCC. The loads of microgrid is fully supplied by the local energy resources. Carry out reliability calculations as described in section 3.3.2. Calculate load point indices by equations (2.45) - (2.47) and calculate system indices by equations (2.4) – (2.7).

- Assume that the microgrid operates in grid connected mode with a probability of P_g and in island mode with a probability of (1- P_g), calculate load point indices in hybrid mode by combining the indices for grid connected mode and the indices for island mode as described in section 3.3.3. Calculated the indices by the equations (2.48) – (2.50), and calculate system indices by equations (2.4) – (2.7).

Step 3: Calculate generating capacity adequacy reliability indices.

This step involves the following three aspects:

- Determine hourly load demand during a period of at least a year

- Determine hourly power output from all distributed generation units. The time period considered is normally at least a year, so that the indices calculated are year based.

  The best power output data are production data measured on the DG units, since all related attributes should be contained and reflected in the data. When real production data are unavailable, it is necessary to calculate the production data using DG output models, as described in sections 2.4 and 2.5. Choose an appropriate model based on the available data and parameters required for the model.

  Some web sides provide possibility to run simulations of generating hourly power output data from wind and solar generation units located anywhere in the world. These web sides can be used to produce DG production data if there are no better data available. Appendix A shows PV production data on Arholma generated by simulation tool at web side Renewables.ninja, https://renewables.ninja/.

- Combine the load data and DG production data to produce the generating capacity adequacy reliability indices. The power output from all the generating units are added together and then compared with the load demand based on the power balance equation (2.51). Proceed this chronologically from one hour to the next repeated for the whole time period. At each time point identify the difference between the total available output power and the total load demand. Perform the reliability evaluation as described in section 3.4 and calculate the indices by equations (2.52) – (2.54).

Step 4: Calculate operational reliability indices

If operation performance data are available, carry out the reliability evaluation as described in section 3.5 and calculate the operational reliability indices by equations (2.12) and (2.13).

5 Conclusion

This report proposes a method for practical reliability analysis of microgrid. The method is able to deal with uncertainty and significant failure modes of a microgrid, and can be used as an applicable method for microgrid reliability evaluation. The method is analytical and incorporates power output characteristics of intermittency and randomness of local renewable energy sources as well as the flexible operation modes of microgrid so that their influence on the reliability are included in the reliability assessment.

The work of the project is made up of the following parts:

- ➢ Literature study: to search, review and capture existing developed models and methods for reliability evaluation of practical microgrid. The following predominant themes are considered in the study. The results of the study are described in Chapter 2.
  - ✓ Microgrid structure and operation
  - ✓ Reliability evaluation method categories
  - ✓ Reliability indices used for microgrid
  - ✓ Wind and solar power output modelling
  - ✓ Energy storage system reliability modelling
  - ✓ Evaluation of reliability of microgrid
- ➢ Based on the literature study, a set of reliability indices are proposed for evaluating reliability of microgrid. These indices describe reliability of microgrid from the following three aspects that would influence the reliability:
  - ✓ Load point and customer orientated reliability indices
  - ✓ Generating capacity adequacy reliability indices
  - ✓ Operation reliability indices

  The definition and evaluation method of these indices are described in detail in Chapter 2.
- ➢ Using the evaluation method a case study on a real Swedish microgrid, Arholma system, are performed. The analysis process, illustration of assessment technique, and numerical calculations are detailed in Chapter 3.
- ➢ Based on the literature study and case study an applicable method for reliability analysis of microgrid is recommended. The overall structure and the workflow of the method are described in Chapter 5.

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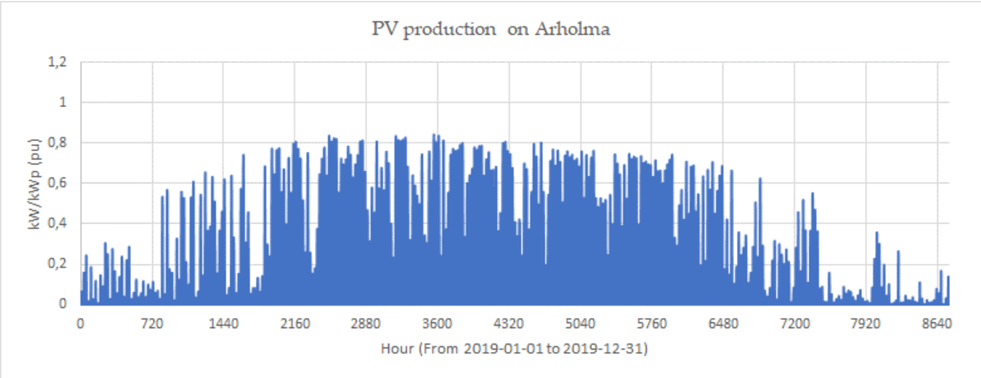
Appendix A: PV production data on Arholma generated from web side Renewables.ninja



RELIABILITY ANALYSIS OF MICROGRID

Microgrid is a part of distribution system that contains local distributed generation as wind and solar power, and energy storage. It has become an important component of distribution systems and has been increasingly implemented in building future smart grid. Microgrid has a potential of improving reliability of local power supply by smoothly switching between the grid-connected mode and the islanded mode.

The reliability evaluation of microgrid is, however, one of the most important challenges that system planners encounter due to random and instable characteristics of the local power generation and the flexible operation features of microgrid.

This report proposes a method for practical reliability analysis of microgrid. The method is able to deal with uncertainty and significant failure modes of microgrid and can be used to evaluate reliability of practical microgrid. The method incorporates power output characteristics of intermittency and randomness of local renewable generation as well as the flexible operation modes of microgrid so that their influence on the reliability are included in the reliability assessment.

Using the method that is proposed, a case study on a real microgrid, Arholma system, are performed. The case study shows reliability analysis process, illustrates numerical calculations, and explains how to account for significant failures of microgrid and how to use the method to judge reliability of microgrid.

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