Nested Microgrids: Operation and Control Requirements

SAM AL-ATTIYAH
Abstract

Nested Microgrids refers to the interconnection of multiple microgrids into one network. They are connected through the Nested Microgrid Network which forms the electrical link between them and facilitates power exchange.

In this thesis the concept of Nested Microgrids is investigated. This resulted in the conceptualization of three different implementation methods. Inter-microgrid interaction in terms of controllers and required communication is also analyzed. The functions would differ from a normal microgrid and they are discussed thoroughly in this report. Real life projects are also presented.

The efficacy and implementation of the proposed control functions are verified with time-domain simulations. Four microgrid control functions, islanding, resynchronization, feeder load shed on generator overload and black start are investigated in Nested Microgrid scenarios. Different control strategies and exchange of information among the microgrid controllers are proposed for stable Nested Microgrids operation. This project provides the ground work for future work to expand upon the theory provided and apply it into practical scenarios.
Sammanfattning

*Nested Microgrids* (nästlade mikronät) hänvisar till sammankoppling av flera mikronät i ett nätverk. De är anslutna via ett *Nested Microgrid Network* som bildar den elektriska kopplingen mellan dem och underlättar effektutbytet.

I denna avhandling undersöksbegreppet *Nested Microgrids*. Detta har resulterat i konceptualisering av tre olika integreringsmetoder. Interaktion mellan mikronät i form av styrenheter samt nödvändig datakommunikation analyseras också. Kontrollfunktionerna kommer att skilja sig från ett normalt mikronät, och dessa diskuteras grundligt i denna rapport. Verkliga projekt presenteras också.

Funktionaliteten och implementeringen av de föreslagna styrfunktionerna verifieras med tidsdomänsimuleringar. Fyra styrfunktioner för mikronät undersöks i scenarier med Nested Microgrids; *Islanding, Resynchronization, Feeder Load Shed on Generator Overload* och *Black Start*. Olika kontrollstrategier och utbyte av information mellan mikronätens styrenheter föreslås för stabil kapslade microgrids drift. Projektet ligger till grund för det framtida arbetet att utöka teorin och tillämpa den i praktiska situationer.
Acknowledgement

First and foremost I would like to give my deepest thanks to my supervisor Dr. Ritwik Majumder for selecting me for this great project. It was an honor to work under him and I have learnt a lot, from perfecting my technical writing to the many enlightening discussions we have had.

I would also like to thank Xue Wang for all the stimulating conversations we have had regarding microgrids, renewable energy and new technologies. Konstantina Bitsi as well for all the fun conversations we have had, reminding us that a healthy balance between work and play is always the best way to go.

To Hans Edin, Nathaniel Taylor and Luigi Vanfretti, I would also like to give a warm thank you. From all of you I have gained something to help me with this project, whether it is physical aid or an encouragement think deeply.

I am very thankful to have my girlfriend, Olga Koter, for being there beside me, pushing me to always keep going and not letting me slack off.

And finally, I would like to give my deepest and sincerest thanks to the Big Bang for making all of this possible.
Disclaimer

This report regarding microgrids uses ABB’s M+ System and the associated controllers, the MGC600, as a basis for analysis.

Although it uses the functionality from a high level perspective, this thesis does not bare semblance on the performance or the technical functionality of ABB’s system. This report is purely conceptual and only takes and inspiration from the solution.
Index

List of Figures ............................................................................................................................... XI
List of Tables............................................................................................................................... XIII
List of Acronyms......................................................................................................................... XIII

1 Introduction ............................................................................................................................... 1

1.1 Microgrids ........................................................................................................................................ 1
1.1.1 United States Department of Energy .................................................................................... 1

1.2 Microgrid Types ................................................................................................................................ 3
1.2.1 Military .................................................................................................................................. 3
1.2.2 Institutional & Campus .......................................................................................................... 3
1.2.3 Off-Grid.................................................................................................................................. 4
1.2.4 Commercial and Industrial .................................................................................................... 4
1.2.5 Community and Utility .......................................................................................................... 5

1.3 Microgrid Ownership Models ........................................................................................................... 5
1.3.1 Utility Model .......................................................................................................................... 5
1.3.2 Landlord Model ..................................................................................................................... 5
1.3.3 Co-op Model .......................................................................................................................... 5
1.3.4 Customer- Generator Model ................................................................................................. 6
1.3.5 District Heating Model .......................................................................................................... 6

1.4 Industrial Microgrid Systems ............................................................................................................ 6
1.4.1 ABB ........................................................................................................................................ 6
1.4.2 Siemens ................................................................................................................................. 7
1.4.3 Power Analytics ..................................................................................................................... 9
1.4.4 Green Energy Corp. ............................................................................................................. 10
1.4.5 S and C Electric .................................................................................................................... 11
1.4.6 Schneider Electric ................................................................................................................ 13
1.4.7 GE ........................................................................................................................................ 14
1.4.8 Encorp................................................................................................................................. 15
1.4.9 Blue Pillar ............................................................................................................................ 16
1.4.10 Other Microgrid Solution Manufacturers ............................................................................ 17
1.5 Thesis Objectives ............................................................................................................................ 17
1.6 Methodology .................................................................................................................................. 17

2 Nested Microgrids ............................................................................................................................ 19

2.1 Nested Microgrids Operation Theory ............................................................................................. 21
  2.1.1 Nested Microgrid Control Structure .................................................................................... 21
  2.1.2 Microgrid Network .............................................................................................................. 22
2.2 Nested Microgrid Types ......................................................................................................................... 24
  2.2.1 Nested Microgrids Configurations ....................................................................................... 24
  2.2.2 Nested Microgrid Structure ................................................................................................. 27
2.3 Real World Examples ...................................................................................................................... 38
  2.3.1 Bronzeville – Illinois Institute of Technology ....................................................................... 38
  2.3.2 Olney Town Center .............................................................................................................. 39
  2.3.3 Alstom Microgrid System for Philadelphia Navy Yard ......................................................... 40
  2.3.4 Oncor ................................................................................................................................... 42
  2.3.5 San Diego Navy Cluster ........................................................................................................ 43
  2.3.6 Yamagata Site Microgrid ..................................................................................................... 44

3 Control Functions ............................................................................................................................... 46
  3.1 Controller Functions ....................................................................................................................... 47
    3.1.1 Network Controller .............................................................................................................. 47
    3.1.2 Feeder Controller ................................................................................................................ 52
    3.1.3 Energy Storage System Controller ....................................................................................... 54
3.2 M+ System Operations in Nested Microgrids ................................................................................ 56
3.3 Functions Process ........................................................................................................................... 59
  3.3.1 Synchronization ................................................................................................................... 59
  3.3.2 Islanding .............................................................................................................................. 62
  3.3.3 Feeder Load-shed on Generator Overload .......................................................................... 65
  3.3.4 Black-Start Operation .......................................................................................................... 66

4 Test Cases ........................................................................................................................................ 67
  4.1 Case 1 – Planned Islanding ............................................................................................................. 68
  4.2 Case 2 – Islanding & Resynchronization ..................................................................................... 69
List of Figures

Figure 1: Control layout of a microgrid using the ABB MGC600 [13] 6
Figure 2: Microgrid layout with connections to the Power Spectrum [15] 8
Figure 3: Layers of the Siemens’ microgrid solution Spectrum Power [15] 8
Figure 4: The different Power Analytics tools joining together to manage different aspects [16] 9
Figure 5: Green Energy Corp’s Greenbus placement in a microgrid system [20] 11
Figure 6: Operation of the 5G Automatic Restoration System in a grid when a fault occurs [23] 12
Figure 7: S&C’s PureWave® Storage Management System single-line diagram [24] 13
Figure 8: Schneider Electric’s Prosumer microgrid solution with different component interaction [26] 14
Figure 9: Microgrid system with the IQ solution integrated [31] 15
Figure 10: Encorp’s Microgrid System Controller and how it sits in a microgrid [32] 16
Figure 11: GUI display for Blue Pillar’s Aurora solution [36] 17
Figure 12: Centralized and De-centralized Microgrid control structure 22
Figure 13: Microgrid components and communication 23
Figure 14: Components and communication of Nested Microgrids 24
Figure 15: Configuration of autonomous Nested Microgrids with a feeder bus 25
Figure 16: Nested Microgrids in a ring formation 25
Figure 17: Nested Microgrids in a meshed formation 26
Figure 18: Configuration of Dependent Nested Microgrids 26
Figure 19: Microgrid configuration with possibility of segmentation 27
Figure 20: Electrical layout for a type I Nested Microgrids 28
Figure 21: Internal communication within a microgrid for a type I Nested Microgrids 29
Figure 22: NMN Feeders connections for a type I Nested Microgrids 29
Figure 23: Type I’s network communication links for grid connection 30
Figure 24: Communication links between the various microgrids in a type I Nested Microgrids 31
Figure 25: Overall layout of a type I NM with the communication links and the electrical connection 31
Figure 26: A possible electrical layout for a Type II NM 32
Figure 27: Internal communication for the different microgrids in a type II Nested Microgrids 33
Figure 28: Feeder controllers and the associated communication links for a type II Nested Microgrids 33
Figure 29: Communication layout for the network connection in type II Nested Microgrids 34
Figure 30: Electrical layout of a separable microgrid 34
Figure 31: The internal communication in a Separable Microgrid 35
Figure 32: Feeder connection of a type III microgrid 36
Figure 33: Network feeder controller and communication connection to main grid for type III Nested Microgrids 36
Figure 34: The segmentation layout of a type III Nested Microgrids 37
Figure 35: Communication and electrical connections of a type III Nested Microgrid configuration 37
Figure 36: Location of IIT and Bronzeville Microgrids 38
Figure 37: The Nested Microgrid Network and connection for the IIT and ComEd microgrids 39
Figure 38: The different zones within the microgrid 40
Figure 39: Prioritization of loads 40
Figure 40: Different zones in Navy Yard before project [42] 40
Figure 41: Different Microgrids in the Navy Yard after project [42] 40
Figure 42: Communication network for the Nested Microgrids 41
Figure 43: Communication between the different components within the nested microgrid [44] 41
Figure 44: Lancaster Nested Microgrids electrical layout [46] 42
Figure 45: Map of San Diego area with the three microgrid locations 44
Figure 46: Yamagata Nested Microgrid site with the connections between the three microgrids [52]. 44
Figure 47: Yamagata's Nested Microgrids system layout [53]. 45
Figure 48: Different voltage synchronization options for Grid Resynchronization function 61
Figure 49: Different communication methods for performing islanding 63
Figure 50: A system with 2 Nested Microgrids and an issue occurring on load 4 feeder in NM 1 65
Figure 51: Issue on feeder in NMN in a 2 NM system 66
Figure 52: Layout of the test system 67
Figure 53: Layout of test system in Case 1 where the system is in Islanded NMN mode 70
Figure 54: Layout of the system in Case 1 following the disconnection of microgrid 2 70
Figure 55: Layout during case 2, Microgrid 2 is operating in Autonomous mode the rest are connected to NMN 71
Figure 56: Layout in Case 2 after Microgrid 2 resynchronizes to NMN 71
Figure 57: Case 3 initial system. All assets disconnected and lines de-energized 71
Figure 58: Case 3 figure showing black-start capable units started and lines are energized 73
Figure 59: Layout of system after Microgrids become energized and operational 73
Figure 60: Layout showing Microgrid 1 being energized through Microgrid 2 73
Figure 61: Layout of system with NMN energized and operational 73
Figure 62: Layout of system after process is completed 73
Figure 63: Layout of system after Main Grid 2 connection is lost 75
Figure 64: Layout of the system after feeders are she 75
Figure 65: Layout of system with 2 isolated operation zones 75
Figure 66: Case 1 - Real and reactive powerflow at PCC 1 & 2 76
Figure 67: Case 1 – System response in M2 77
Figure 68: Case 1 – System response in M3 77
Figure 69: Case 1 – System response of PCC1 and PCC2 78
Figure 70: Case 2 - The difference in synchronization signals on either side of the PCCs for PCC2 priority 79
Figure 71: Case 2 – System response in M1 when PCC2 is synchronized first 80
Figure 72: Case 2 – System response in M2 when PCC2 is synchronized first 80
Figure 73: Case 2 - Frequency at PCC1 (in NMN), PCC2 (in NMN) and that in M2 for PCC2 priority 81
Figure 74: Case 2 - The difference in synchronization signals on either side of the PCCs for PCC1 priority 81
Figure 75: Case 2 – System response in M1 for variant 2 82
Figure 76: Case 2 – System response in M2 for variant 2 82
Figure 77: Case 2 - The frequency at PCC1 (in NMN), PCC2 (in NMN) and that in M2 for variant 2 83
Figure 78: Case 2 - Comparison of the frequency mismatch at the PCC for both scenarios 84
Figure 79: Case 3 - System response in M1 for standard scenario 85
Figure 80: Case 3 - System response in M2 for standard scenario 85
Figure 81: Case 3 - Frequency within M1 and M2 for standard scenario 86
Figure 82: Case 3 – System response for M1 during PV connection priority scenario 87
Figure 83: Case 3 – System response for M2 during PV connection priority scenario 87
Figure 84: Case 3 - Frequency within M1 and M2 during PV connection priority scenario 88
Figure 85: Case 3 – System response for M1 during the critical load priority scenario 88
Figure 86: Case 3 – system response for M2 during the critical load priority scenario 89
Figure 87: Case 3 - Frequency within M1 and M2 during the critical load priority scenario 89
Figure 88: Case 3 - Frequency within M1 for the standard, PV priority and critical load scenarios 90
Figure 89: Case 4 – System response for M1 91
Figure 90: Case 4 – System response for M2
Figure 91: Case 4 - frequency within zone 1 (M1 & M2) and the rest of the NMN
Figure 92: Case 4 - frequencies within the isolated segment under different delays for load shedding and control modes

List of Tables

Table 1: Power Analytics solution functionality [18] 10
Table 2: Difference between a microgrid and a cluster of Nested Microgrids 20
Table 3: Different methods to control the Nested Microgrids 21
Table 4: Modes of operation for the different types of Nested Microgrid configurations 27
Table 5: Function list showing the hierarchy level, the urgency of it and what it does of NC in M-MG point 48
Table 6: Function list showing hierarchy level and how the functions is performed of NC in M-MG point 49
Table 7: Function list showing the hierarchy level, the urgency of it and what it does of NC in M-NMN point 50
Table 8: Function list showing hierarchy level and how the function is performed of NC in M-NMN point 50
Table 9: Function list showing the hierarchy level, the urgency of it and what it does of NC in NMN-MG point 51
Table 10: Function list detailing how the function is performed of NC in NMN-MG point 51
Table 11: Function list showing the hierarchy level, the urgency of it and what it does of FC at M level 52
Table 12: Function list showing hierarchy level and details about how the function is performed of FC at M level 53
Table 13: Function list showing the hierarchy level, the urgency of it and what it does of FC at NM level 53
Table 14: Function list showing hierarchy level and details about how the function is performed of FC at NM level 54
Table 15: Function list showing the hierarchy level, the urgency of it and what it does of ESC 55
Table 16: Function list showing hierarchy level and details about how the function is performed of ESC 55
Table 17: Function list of M+ system showing hierarchy level and details about how the function is performed 57
Table 18: Function list of M+ system showing hierarchy level and details about how the function is performed 58
Table 19: Maximum deviation in frequency, voltage and phase angle allowed for grid synchronization [54] 60
Table 20: The process for islanding using the different communication methods 64
Table 21: List of the assets of the system and their values 68

List of Acronyms

M: Microgrid  M+: M Plus system
μG: Microgrid  ES: Energy Storage
MG: Main Grid  SM: Synchronous Machine
NM: Nested Microgrid  PS: Power System
NMN: Nested Microgrid Network  P: Real Power
PCC: Point of Common Coupling  Q: Reactive Power
NC: Network Controller  f: Frequency
FC: Feeder Controller  V: Voltage
ESC: Energy Storage System Controller  φ: Phase
1 Introduction

1.1 Microgrids

There is a new drive to increase the amount of electrical generation from renewable energy. This is due to concerns over environmental damage, including the effects of CO₂ emissions. A challenge appears as a result of the increased renewable energy in the form of the unpredictability and controllability of sources such as photovoltaic cells and wind turbines. Since these are both based on the weather their electricity production can fluctuate significantly and combined with the lack of way of controlling the output, a tool to manage them is required. The Microgrid concept meets this requirement.

Historically microgrids served a different purpose, that of isolated distribution networks. Their goal was to support remote loads by providing islanded generation. The early start of microgrids was as small scale networks of <1 MW [1] capacity. Now their purpose has evolved and the common case scenario of microgrids is aimed at serving a new purpose.

Microgrids provide a way to manage large amounts of renewable energy by controlling them and the associated components to ensure that from the grid’s perspective the microgrid appears as a single controllable load. Microgrids are usually composed of a number of small electrical generation units and a number of loads. Some of the loads are critical loads such as hospitals, vital equipment in military bases or important equipment in universities, commercial campuses, and industrial plants. It is important that these critical loads remain operational when an outage occurs in the main grid.

With the growth of microgrids and microgrid applications the capacity and size have increased from the historically typical values of accommodating to loads of <1 MW to more common sizes of 2 MW to 10 MW, and this is expected to increase drastically in the future to large networks of 60 MW to 100 MW [1].

Furthermore, microgrids offer the advantage of being able to operate autonomously and supply the local region, which is crucial in the cases where there are grid-wide blackouts. This is typically the case when there are natural disasters. An example of this is the Sendai microgrid which continued to supply the region after the 2011 earthquake in Japan [2].

1.1.1 United States Department of Energy

The Department of Energy (DOE) in the U.S. is one of the biggest driving forces behind research and projects in the microgrid and smart grid field, they are funding a number of projects some of which are mentioned in section 2.3.
The primary focus is “to develop commercial-scale microgrid systems (capacity <10 MW) capable of reducing outage time of required loads by >98% at a cost comparable to non-integrated baseline solutions (uninterrupted power supply [UPS] plus diesel generator-set), while reducing emissions by >20% and improving system energy efficiencies by >20%, by 2020.” This is why a lot of the projects in the microgrid field are being designed with high amount of renewable energy in mind, and with storage devices to improve the reliability.

According to DOE, modern microgrids offer the following benefits [1]:

- Increasing the resilience of the current grid
- Compensation for the aforementioned renewable energy supply fluctuation
- Volt-ampere reactive(var) and voltage support
- Providing UPS for critical loads
- Local power quality and reliability support
- Incorporating demand-side management leading to customer participation
- Modernizing the grid

The DOE plan to achieve the previously mentioned benefits as well as obtain the following objectives in their Advanced Microgrid Program.

- Improve the resilience of the nation’s grid infrastructure
- Operate and smoothly transfer between Islanded and Grid-connected mode
- Provides interconnection and interoperability for smart grids
- Provides cyber security for performance and data
- Improve the power quality for connected loads
- Provides two-way communications (frequency, verification, data latency)
- Provides data management and system predictions
- Provides volt/var/frequency controls and support for interconnectivity and island
- Enables dynamic configuration of local feeders
- Improves reliability for critical loads
- Provides outage management (i.e. number, duration and extent)
- Balances distributed and central control
- Enables price driven demand response
- Reduced peak loads for the interconnected grid
- Integrates with intermittent and variable output renewables
- Defers generation, transmission and distribution investments

With all of these points in mind it is evident why such a number of microgrid projects are being run. Most of the projects are designed to tackle a few of the above mentioned points.
1.2 Microgrid Types

Microgrids can be designed to serve many different purposes, with requirements that depend on their purpose. The reason for this is that when single party owns the local grid privately they may develop it as they need, whether this is to maximize reliability or to minimize costs.

1.2.1 Military

Military microgrids are those owned, run and funded by the military itself and as such have complete freedom on the all decisions regarding the microgrid and how to it is operated. These microgrids typically come with the option of operating autonomously or in grid-connected mode [3]. They are designed to be reliable first and foremost, but also to reduce costs and utilize sustainable resources.

For a military base it is important to keep operating at all times arguably it is even more necessary to continue operation during times of difficulty such as in case of outages in the region. This is because military operation is a matter of natural security and as such military bases need to ensure operation when the grid is unable to supply the required power. The answer in such a case is a self-sufficient region, and hence why microgrids are used [4].

Military microgrids value their reliability and autonomy [5] [6]. The microgrid should be operational at all times and be capable of running for an extended period of time. This is done through proper planning of the generation and assets to ensure supply is maintained while islanded.

At the same time, it is still desirable to reduce the cost of supplying power as well as the emissions produced. This is done through the increased integration of renewable energy in a manner that maintains the system security in terms of supply of energy, and this as such reduces the costs of power generation. Furthermore, the military microgrids typically would sell the excess generation to the grid and hence the desire for the grid connection. This would ensure that the microgrid is always running in the most optimal and cost efficient way. Most military microgrids are required to meet certain system goals such as efficiency levels as well as carbon footprint goals [7].

The three Nested Microgrids discussed in section 2.3.5 are an example of military microgrids as well as the NM concept.

1.2.2 Institutional & Campus

Institutional and Campus type microgrids are typically owned by a single party. They may be business, university or hospital campuses. What makes these microgrids interesting is that they usually have a tightly knit array of loads. And on top of that, geographically, the sources and loads are located close by. They usually also have many loads that can participate in demand
response or can be disconnected entirely. However, a high reliability is still desired due to the presence of critical loads [4].

These types of microgrids can range from 4-40 MW [8]. Their main focus is to ensure reliability while at the same time cutting down on costs and for the cases of university microgrids they are also utilized to provide a testing arena for research.

1.2.3 Off-Grid

Off-Grid microgrids are the classical case of microgrids, these are regions that are located at a great distance from the utility grid making it uneconomic to power off the main grid. As such a small grid is installed in the location with dedicated generation to ensure the loads are supplied without the extensive transmission line implemented in order to keep them connected. These small grids are hence named microgrids [4].

The main priority of these kinds of microgrids is to power remote locations in the most cost effective means. These microgrids are typically located in islands, remote villages or towns and in mining locations which are typically situated a fair distance away from inhabited areas.

There are a number of important factors in these kinds of microgrids. Firstly since these microgrids are situated away from utility grids they do not require the islanding, synchronization functionality or energy market interchange because they are seldom connected to the main grid. As such the controlling system may be greatly simplified with primary focus being protection. Secondly, as a consequence of lack of external supply, black start capability must be present within the microgrid to ensure it can initiate and energize the system in the case of post power outage scenarios [9].

1.2.4 Commercial and Industrial

Commercial and Industrial microgrids are typically owned by single private party, and they are typically responsible for all decisions regarding the microgrid aspects. Usually these types of microgrids are of the size of 1-10 MW generation capacity [10].

The number one factor of these kinds of microgrids is to ensure that they remain operational in the case of an outage in the grid. While performing that task they also can perform the useful function of reducing costs.

Costs are minimized through a number of key microgrid functions and this is done while connected to the grid or not. More options are available in grid connected mode. These are to reduce production costs, and to make the most of the market interchange.

On top of the previously mentioned factors there are some typical aspects of these kinds of microgrids, namely, renewable energy options as well as advanced technology. These factors increase their standing within their field by drawing attention.
Costs are reduced through the use of cost effective implementation strategy. This leads to the use of the cheapest generation options, namely renewable energy which benefits the operators as well as society. This would also fit into the advanced technology and modern technology usage factor as well as the carbon reduction factor.

1.2.5 Community and Utility

Community and Utility microgrids are as the name suggests microgrids that are built upon pre-existing sections of the grid. As such they utilize pre-existing infrastructure which can be limiting in some ways but also removes a lot of the extra work. On top of that they must strictly abide by the grid regulations and business model [11].

The advantage of these kinds of microgrids is that since they are sections of the utility grid these projects are normally government funded and make use of government incentive programs. Furthermore they serve an important role in research and trial programs in order to better understand and make changes for the future of electrical generation, transmission and consumption [12].

Lastly, with governments around the world implementing goals for harmful emission reduction and efficiency and reliability increases, this provides a method to achieve that and allow for the integration of renewable energy on large scale.

1.3 Microgrid Ownership Models

There are a number of different ownerships models for microgrids which is largely dependent on the type of microgrid it is, the level of investment as well as the ultimate purpose of the microgrid which can affect how the microgrid would be designed. This could be to reduce emissions, reduce costs or increase reliability [13].

1.3.1 Utility Model

Microgrids under this ownership model are typically owned by the utility. The purpose is for the utility to provide increased power reliability to certain parts of the grid.

1.3.2 Landlord Model

This model is usually a common case in private microgrids. Microgrids under this ownership can be created to suit a multitude of different purposes, from research to electricity usage cost reduction.

1.3.3 Co-op Model

Co-op model as the name suggests involves multiple parties cooperating together to fund and manage the microgrid in order to service their loads. Under this model, customers can join under contracted terms and be a part of the microgrid.
1.3.4 Customer-Generator Model

This type of model revolves around a single entity ownership. The owner provides the generation and management for its own load, but external contracts may be given to customers in surrounding area. This is in the case of excess generation.

1.3.5 District Heating Model

The microgrid is owned by an independent party, which operates the microgrid and provides power and heating to customers who wish to connect to the microgrid.

1.4 Industrial Microgrid Systems

1.4.1 ABB

The ABB solution for this application lies with the MGC600 Renewable Microgrid Controller. It is a decentralized solution that utilizes the individual controllers for the different microgrid assets to connect together through a local area network. The controllers broadcast valuable information to other controllers. Since it is a decentralized solution it offers a lot of scalability and allows for ease of plug & play solution which means that the system can be expanded as desired. Furthermore, should a controller fail, it won’t have a huge impact on the microgrid, as opposed to if a microgrid central controller fails which could disable the entire grid [14].

![Control layout of a microgrid using the ABB MGC600](image)

Figure 1: Control layout of a microgrid using the ABB MGC600 [14]

The system works as shown in figure 1 where the various controllers inside the microgrid interact through a LAN connection and they can transmit and receive data from the control room.
The ABB microgrid control solution can offer the following functions to the microgrid:

- Spinning reserve management
- Generator overload protection
- System step load capacity management
- Generator single contingency event management
- Manage load demand
- Feeder management in cooperation with protection relays
- Wind turbine or solar PV generator power/reactive power limitation
- Generator scheduling and configuration management based on various measures like runtime, hours, service, etc. This can be configured as desired
- Balance of plant management
- Feeder reclosing and feeder rotation
- Energy storage management of excess renewable energy
- Feeder shedding based on generator overload instead of under frequency
- Demand management
- Renewable energy maximization and stabilization

1.4.2 Siemens

Siemens offer two Microgrid Controller solutions, the advanced microgrid controller, Spectrum Power, and SICAM the basic microgrid controller.

The microgrids controller options are designed to improve the reliability of the microgrid by providing islanding capability as well a load shedding priority scheme and demand response. The controller also increases efficiency through optimal dispatch and renewable energy utilization with frequently updated long term forecasting. It is also designed to be secure and conform to the current standards. Finally, they provide sustainability through optimization of the output of the system, whether it is to maximize revenue, minimize emissions etc. [15].

The Spectrum Power Microgrid Management System is the more powerful of the two solutions. It is a SCADA system that allows for flexibility in its adaptation and can be tailored to the purpose of the microgrid and how it is to be operated for the eventual purpose of optimizing the system. On top of the previously mentioned functions it is used to provide the capability of peak shaving, increased power quality, and increased resilience of the microgrid [16].

How the controller would sit in the microgrid can be seen in Figure 2. It would connect the different microgrid components to the point of common coupling (PCC) and to the grid. These components range from controllable and non-controllable generation to storage units and
controllable loads, all interacting with the microgrid manager which also maintains a stable connection to the main grid.

Figure 2: Microgrid layout with connections to the Power Spectrum [16]

Figure 3: Layers of the Siemens’ microgrid solution Spectrum Power [16]

Figure 3 shows the different layers in the Siemens solution, ranging from the local assets such as protection and monitoring devices to sources and then into standard microgrid functions and advanced microgrid functions that are available through the controller solution.
The Power Spectrum controller works as a centralized control method and as such it communicates with all the components. It then performs decisions based on the inputs, and transmits the references and signals back to the components. The decisions could cover a wide range, from opening or closing circuit breakers, to rerouting the power flow, to setting power references for the devices so ensure the desired system parameters. It can also include starting functions such as demand response and so on.

On the other hand Siemens also offers the SICAM, it is the more basic of the two microgrid controllers but it still offers all the necessary microgrid features such as forecasting, automating tasks, modeling and optimization. It provides monitoring of the microgrid assets such as storage systems and loads and it provides the necessary analysis tools.

### 1.4.3 Power Analytics

Power Analytics offers a microgrid control solution in the form of the Paladin Microgrid Power Management System which acts as a central controller for monitoring and controlling all the microgrid components and for trading with the main grid. It acts in real-time to run the system in an optimal and economic manner, taking into account the current system situation, the limits, the demand and the electrical prices. This microgrid controller also factors in all the different aspects, such as weather and unexpected conditions such as fuel shortages or unexpected maintenance when optimizing the system.

Figure 4 shows the different Power Analytics solution interacting together in practice. Where the Paladin Microgrid Power Management System (previously named Paladin SmartGrid) acts on the actual hardware and operation and the other solutions offered sit at the control center. It is interacting and controlling all the microgrid assets.

![Figure 4: The different Power Analytics tools joining together to manage different aspects](image)

The Power Analytics controller is able to perform to optimization to focus on minimizing number of different factors such as [18]:

---

The Power Spectrum controller works as a centralized control method and as such it communicates with all the components. It then performs decisions based on the inputs, and transmits the references and signals back to the components. The decisions could cover a wide range, from opening or closing circuit breakers, to rerouting the power flow, to setting power references for the devices so ensure the desired system parameters. It can also include starting functions such as demand response and so on.

On the other hand Siemens also offers the SICAM, it is the more basic of the two microgrid controllers but it still offers all the necessary microgrid features such as forecasting, automating tasks, modeling and optimization. It provides monitoring of the microgrid assets such as storage systems and loads and it provides the necessary analysis tools.

### 1.4.3 Power Analytics

Power Analytics offers a microgrid control solution in the form of the Paladin Microgrid Power Management System which acts as a central controller for monitoring and controlling all the microgrid components and for trading with the main grid. It acts in real-time to run the system in an optimal and economic manner, taking into account the current system situation, the limits, the demand and the electrical prices. This microgrid controller also factors in all the different aspects, such as weather and unexpected conditions such as fuel shortages or unexpected maintenance when optimizing the system.

Figure 4 shows the different Power Analytics solution interacting together in practice. Where the Paladin Microgrid Power Management System (previously named Paladin SmartGrid) acts on the actual hardware and operation and the other solutions offered sit at the control center. It is interacting and controlling all the microgrid assets.

![Figure 4: The different Power Analytics tools joining together to manage different aspects](image)

The Power Analytics controller is able to perform to optimization to focus on minimizing number of different factors such as [18]:

---
• Annual cost
• Carbon footprint
• Peak load
• Importing

Overall the Power Analytics central microgrid controller, Paladin, aims to provide a system which offers the functionality provided in table 1. Furthermore, Power Analytics offers the option to dedicate a solution to your specific system building upon the existing Paladin product.

Power Analytics are also providing the master controller solution for the San Diego Navy Microgrid Cluster that is discussed in detail in section 2.3.5. The solution is to provide a controller that will sit above the other microgrid controllers and control them all as one.

Table 1: Power Analytics solution functionality [19]

<table>
<thead>
<tr>
<th>Paladin Microgrid Power Management System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Security Constrained Economic Dispatch</td>
</tr>
<tr>
<td>Security Constrained Optimal Power Flow</td>
</tr>
<tr>
<td>Weather, Market Prices, Forecasting</td>
</tr>
<tr>
<td>Energy Management System</td>
</tr>
<tr>
<td>Real-Time Power Flow Optimization</td>
</tr>
<tr>
<td>Near Real-Time Financial Settlements</td>
</tr>
<tr>
<td>Real-Time Arc Flash</td>
</tr>
<tr>
<td>State Estimator</td>
</tr>
<tr>
<td>Volt/VAR</td>
</tr>
<tr>
<td>Real-Time Iterations Against Model</td>
</tr>
<tr>
<td>DesignBase Integration of Vendor Elements</td>
</tr>
</tbody>
</table>

1.4.4 Green Energy Corp.

GreenBus is the microgrid controller solution from Green Energy Corp, and it is a software platform that enables interoperability and implementation of Smart Grid technologies [20] [21]. Green Energy Corp is a software company specializing Smart Grid technologies for power providers. The solution is an open source cloud based microcontroller that offers for customer modification and adaptability. It enables third party customization to expand upon the existing structure and implement new deployment strategies.

Green Energy Corp’s main aim with their provided product is to achieve the following:

<table>
<thead>
<tr>
<th>Interoperability</th>
<th>Security</th>
<th>Scalability</th>
</tr>
</thead>
</table>

The GreenBus system fits into the system as shown in figure 5 where it links the assets, the market data and the Microgrid Control System and acts to improve the operation of the microgrid.
Green Energy Corp. will be providing the GreenBus platform to the Olney Town Center microgrid project as well as providing research and development services along Schneider Electric and a number of other companies [22].

The Olney Town Center microgrid project discussed in section 2.3.2 is utilizing Green Energy Corp’s GreenBus solution to provide the control platform required to operate the system. They are leading the research and development team on the project.

1.4.5 S and C Electric

S&C do not offer a complete package as a standard product, but it offers a number of products to provide control over certain aspects of microgrid operation. One such product is the IntelliTeam® SG Automatic Restoration System which acts as the protection controller in the system. It provides self-healing, fault isolation, load management for fault scenarios, and prevents overloading in the system as well as a number of other functions.

The Automatic Restoration System is a decentralized solution and work to reconfigure the system after a fault so as to ensure that service is restored as quickly as possible by isolating the fault location and keeping the healthy lines in operation. It works using the monitoring equipment and
responds to abnormal conditions. It works with the ultimate goal of increasing the service reliability and maximizing system efficiency [23].

Figure 6 shows how S&C’s distribution grid protection solution would act in the case of a fault occurring and the process it takes to isolate the fault and resupply the sources.

![Figure 6](image)

**Figure 6: Operation of the SG Automatic Restoration System in a grid when a fault occurs [24]**

The other product provided by S&C is the PureWave® Storage Management System which would interface with the aforementioned package and create a system capable of islanding and autonomous operation. The storage device is designed to power the system during blackout scenarios but can also act as a support for renewable energy sources, compensating for fluctuations in solar and wind energy. Furthermore, the product provides peak shaving abilities, frequency regulation and spinning reserve [25].
The PureWave system, shown in figure 7, is composed of a number of batteries to a total 2 MW and can sustain such a load for 7 hours [25]. And it can also integrate with the IntelliTeam® DEM Distributed Energy Management System to allow for the management of multiple PureWave storage systems as well as improve the overall efficiency of the system and allow for further interaction with utility’s distribution management system to allow for distribution grid support on top of their microgrid support.

S&C are working on the Oncor project in section 2.3.4 along with Schneider Electric and S&C are providing the electrical groundwork on which the Schneider Electric controller solution will sit.

### 1.4.6 Schneider Electric

Schneider Electric offers a number of choices in terms of microgrid solutions. They offer a small scale pre-designed microgrid solution for off-grid purposes [26]. For grid connected microgrids, large and small, they offer a package which is in the form of the optimizing software, Prosumer. The purpose of this product is to manage and optimize generation through predicting load and weather conditions and the real-time pricing. It would then act to minimize the energy bill by adjusting the loads in the system and rescheduling non critical processes. It also aims to increase energy independence and provide supply during islanding. It enables the connection of storage into the system as well and implementing DR participation [27]. It constantly monitors the systems and local conditions and aims to provide an optimal operation plan.

Figure 8 shows how Schneider Electric’s Prosumer solution integrates into a small scale microgrid scenario where it is controlling a number of sources and storage units as well as managing the smart loads.
Figure 8: Schneider Electric’s Prosumer microgrid solution with different component interaction [27]

They also cater the solution to large scale projects that are designed for Campus, Military, Off-Grid and large commercial and industrial applications with higher focus on reliability and resilience than minimizing costs like in the small scale version, but while not disregarding it [27] [28] [29].

Furthermore, Schneider Electric has been an avid participator in microgrid projects, with a number of projects in the microgrid field having Schneider Electric participating in them. Most notably it is working on the microgrid central controller for the Oncor project in 2.3.4 that is being designed to control four microgrids. On top of that they are also a participator in the Olney project in 2.3.2.

1.4.7 GE

GE offers the Grid IQ Microgrid Control System, it is a system based on the U90 system at its core, which is also by GE, with a number of supplementary components creating a complete solution. It is used to integrate the microgrid assets into the system and optimize the power generation whilst also decreasing the costs. It enables the integration of conventional generation sources as well as renewable energy [30] [31] [32].

The IQ system is able to provide a number of different functions to the microgrid as a complete package solution. On top of the standard islanding, protection and unit commitment and starting/stopping functionality which are almost a standard, the system is also able to provide optimal dispatch functionality and demand optimization as well generator and storage efficiency.

Optimal dispatch is achieved through load forecasts and renewable energy forecasts. This includes wind, expected rain and weather patterns for hydro, solar and wind generation methods. And, it utilizes storage to add flexibility and give a margin to allow tweaks in the system to
ensure the most optimal operation conditions, this is all done through Model Predictive Control. The controller itself tracks the load and creates 24 hour forecasts to improve system operation with consistently updated forecast.

Demand optimization is achieved through a number of different ways, by the use of emergency load shedding which is invaluable during islanding scenarios. By using loads as resources, especially when using backup generator-sets the IQ system can contribute to demand optimization. It also does this by using energy management techniques in the loads including peak shaving as well as demand response.

Figure 9: Microgrid system with the IQ solution integrated [32]

Figure 9 shows how the IQ’s U90 controller sits in the microgrid with the various controllers and metering devices as part of the IQ Microgrid Control System solution.

1.4.8 Encorp

Encorp provides the Microgrid System Controller as a solution for microgrid control. It allows the interconnection of traditional generation methods with new renewable sources and controls them to maintain stability. The controller can be configured and, depending on the components of the microgrids, can be customized to provide the following functions [33]:

- Peak shaving/sharing
- Demand Response
- Cogeneration
- Full-load generator testing
- Prime-power generation
Figure 10: Encorp’s Microgrid System Controller and how it sits in a microgrid [33]

The controller provided by Encorp builds upon their previous generator power controller, the Gold Box, and uses it to incorporate the systems into the microgrid. The Gold Box itself provides monitoring and power sensing to be used to provide the following functionality [34]:

- Peak shaving/sharing
- Distributed Generation
- Soft loading closed-transition transfer
- Import/Export
- Energy Management
- Cogeneration
- Generator-set tested under load
- Real-time pricing
- Interruptible rates

1.4.9 Blue Pillar

Blue Pillar offers a management system designed for microgrid applications with the ability to operate a microgrid. This solution is the Aurora and it is a centralized control system. This option offers a way to monitor all the microgrid assets as well as provide operational and energy analytics and control over the microgrid [35] [36].

As a centralized control and monitoring platform it offers among other things fault detection. On top of that they provide a multi-management option. It can be used to manage different sites locally and around the world in a single location. Using this they can make energy saving changes.

Aurora also provides Data Visualization, providing real-time operation and energy data, monitoring health and readiness of equipment is another aspect of that. It also provides the
tools to analyze the energy trends and to observe and analyze the root cause of power events, so that key measures are taken to prevent issues or optimize the system with regard to the event. The Aurora system also aims to automate testing procedures and compliance, and to apply demand response in the system [37].

All of these are done with the ultimate goal of allowing the microgrid to run more efficiently and reliably, and can allow the use of islanding and demand response.

Figure 11: GUI display for Blue Pillar’s Aurora solution [37]

The GUI for the management system as seen in figure 11 is how the Blue Pillar solution allows the microgrid operators to manage the network connection and the protection system as well as the individual assets and analysis data.

1.4.10 Other Microgrid Solution Manufacturers

The manufacturers and solutions mentioned previously are only the brim of the pool, with many other companies creating their own solutions. Many of the solutions provided are being designed specifically to the required application due to the nature of the system being different from one microgrid to the other.

1.5 Thesis Objectives

This thesis aims to:

- Investigate the principles of Nested Microgrids which refer to the operation of multiple microgrids together.
- Identify different types of Nested Microgrids that could be implemented and how they could be implemented.
- Analysis of existing microgrid function operation and how they must be modified to be applicable in Nested Microgrid Operation
- Discuss Nested Microgrid operation through different microgrid functions

1.6 Methodology

To achieve the aforementioned objectives, the process is done as such:

- Study of microgrids is carried out, to understand existing technologies and operation strategies as well functionality.
Definition of the different types of nested microgrids is done. The controller interaction within the NMs as well as between the NMs and the NMN is analyzed to observe how communication would be exchanged.

Controller functionality is scrutinized and defined for NM operation to determine additional information required to perform the functions.

Nested Microgrid scenarios are created and tested in real-time using Matlab-Simulink software (version R2014a) the diagrams are created using Matlab for results and MS Visio for conceptualization.
2 Nested Microgrids

Microgrid projects are popping up all over the world and many countries from US to Japan to Australia are investing in these projects. And, with more and more microgrids being created and integrated into the grid, linking them becomes desirable. This phenomenon gives rise to a new concept, of the Nested Microgrid (NM).

Nested Microgrids refer to the operation of multiple interconnected microgrids. A single microgrid within the group is termed a Nested Microgrid (NM) whereas a group of them is referred to as Nested Microgrids (NMs).

There are a number of papers written regarding Nested Microgrids, under a variety of different synonyms such as Interconnected Microgrids, Microgrid Cluster, Aggregated Microgrids and Networked Microgrids, as well as the name chosen in this project, Nested Microgrids. The concept of NMs becomes important when there are adjacent microgrids present. Currently microgrids work independently, either connected to the main grid or operating autonomously depending on the conditions of the main grid. But, operating microgrids as NMs by connecting them together brings rise to a lot of benefits. This cooperation enables the microgrids to utilize the most efficient generation methods and run the system optimally. This is done whilst also improving security through generation deficit coverage. Grid support can also be provided externally by other NMs.

The main issue with microgrids is the complexity of the control system. Conventional sources are dispatchable and with near constant outputs but renewable sources are non-dispatchable fluctuating sources which have unpredictable behavior. This creates a management and control issue. On top of that, new technologies and flexible demand are also being added. This creates a requirement for new control and operation methods. This complexity further increases when combining multiple microgrids together to form a Nested Microgrid network.

As NMs, the system is expected to run more efficiently. It would produce fewer emissions, decrease generation cost as well as increase system reliability and stability. As such NMs become a valuable concept worth investigating. This is achieved through the optimization of the different assets within the system.

What makes a Nested Microgrid different from an ordinary microgrid is how the control functions as well as the operation complexity that is added as a result of the new system. These differences are highlighted in Table 2.

To address some of the points, a typical microgrid would be centrally controlled through the use of a microgrid controller or controlled in decentralized fashion. De-centralized control is done through a distributed controller scheme where each component would have its own controller with some kind of communication strategy to relay information between them (further discussed in section 2.1.1). When considering Nested Microgrids, an extra degree of controllability needs to be added. The Nested Microgrids can be controlled in a centralized or
decentralized case. Leading to an overall control structure that may be done in a number of different ways as can be seen in Table 3 in section 2.1.1.

**Table 2: Difference between a microgrid and a cluster of Nested Microgrids**

<table>
<thead>
<tr>
<th>Single Microgrid</th>
<th>Nested Microgrids</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single controller</td>
<td>Multiple Controllers</td>
</tr>
<tr>
<td>Mostly one PCC</td>
<td>Multiple PCC and PCC location</td>
</tr>
<tr>
<td>Operating modes – Grid-Connected, Islanded</td>
<td>Multiple Operating modes with multiple configurations</td>
</tr>
<tr>
<td>Complex system with multiple microgrid assets</td>
<td>Even more complex system with multiple regions and different assets</td>
</tr>
<tr>
<td>Centralized vs. Decentralized control</td>
<td>Centralized vs. Decentralized giving 4 different control options (see Table 3)</td>
</tr>
<tr>
<td>Difficult to manage power quality</td>
<td>Easier to manage power quality</td>
</tr>
<tr>
<td>Synchronization is simple</td>
<td>Synchronization becomes more complicated</td>
</tr>
<tr>
<td>Simple communication strategy</td>
<td>Complex communication strategy</td>
</tr>
<tr>
<td>Limited freedom in optimization</td>
<td>High degree of freedom in optimization</td>
</tr>
</tbody>
</table>

The second point is that, when considering a single microgrid the number of PCCs may be limited. This is due to lack of necessity for an extensive amount of connections. In the case of Nested Microgrids, however, it is preferable to have multiple PCC because the different microgrids may require or benefit from having a direct connection to the grid. This is presented more clearly with diagrams in section 2.2.1.

Managing all of the PCC points results in added operational complexity to the system. This becomes even more evident when it comes to the synchronization process and interaction between the Nested Microgrids. The synchronization process would in this case not only involve multiple microgrids but also multiple locations and options to synchronize.

Nested Microgrids would be able to operate in different modes, depending on the system configuration and controllability. They can operate in the standard grid connected mode and islanded mode similar to a single microgrid. They can also operate as connected to the NMN or islanded from it. These options lead to the ability of operating as part of a larger network for the majority of the time, to ensure the most optimal operation in terms of costs and resource usage.

By connecting multiple microgrids together, the operation of the system becomes more complicated as the number of assets within the system increases.

What can be achieved, however, is a larger network that is capable of a higher degree of optimization than is achievable with a single microgrid. On top of that, power quality control becomes easier to manage with multiple units present. The overall result is a stronger grid that is more stable and able to work more efficiently.
2.1 Nested Microgrids Operation Theory

To determine the operation of NMs a number of aspects are investigated. Firstly, different control structures are examined and then the different types of NMs are defined. Next, potential implementation strategies are presented.

2.1.1 Nested Microgrid Control Structure

Microgrids can be operated in a centralized and a decentralized way. Centralized control utilizes a central controller in the microgrid to manage all the resources and loads. The Microgrid Central Controller (MCC) manages the different assets to operate the system efficiently and reliably. In decentralized control the components are self-governing. However, the assets still maintain communication between each other through a network and acting accordingly. Hence, using a decentralized method, the central controller may not be a physical entity but still there is collaboration between all the controller units. The advantage of the latter method is that, as opposed to the centralized method, should a microgrid controller fail, the rest would continue to operate together. It also provides a higher degree of expandability, allowing the integration of new assets into the system with ease.

Furthermore, the management of the NMs adds another level in the control hierarchy with different control options (Table 3). As a result there are four different alternatives for the control of NMs. This newly added control level is represented as a Nested Microgrid Network Controller (NMNC) in a centralized solution or as a Communication Hub in a decentralized solution. It acts to monitor and govern the NM and provide the necessary management of the safe and reliable operation of the entire system.

Table 3: Different methods to control the Nested Microgrids

<table>
<thead>
<tr>
<th>Individual Nested Microgrid</th>
<th>Overall Nested Microgrids</th>
</tr>
</thead>
<tbody>
<tr>
<td>Option 1</td>
<td>Centralized</td>
</tr>
<tr>
<td>Option 2</td>
<td>Centralized</td>
</tr>
<tr>
<td>Option 3</td>
<td>Decentralized</td>
</tr>
<tr>
<td>Option 4</td>
<td>Decentralized</td>
</tr>
</tbody>
</table>
Figure 12 shows the control structure the centralized and decentralized control structure. In the case of centralized control, the microsources and loads are operated by the microgrid primary controller (MPC), which serves to monitor the parameters and transmit those to the Microgrid Central Controller (MCC). Based on those parameters and the data obtained from all the components within the microgrid, the MCC finds the optimal operating point for the different components, such that the demand is met and the system is operating efficiently.

Conversely, a de-centralized control unit gathers data from all the other microsources and loads within a microgrid to determine operating points through a Microgrid Controller (MGC). This leads to the ability of enhanced local condition sensing and acting accordingly, such as providing local voltage support. The communication is done through a communication hub or through an information distribution method. In this report it is referred to as the Microgrid Plus System (M+) reflecting ABB’s solution which acts as the communication network for the microgrid components. In this solution all of the asset controllers are contributing to the overall system operation and should one fail, the system goes on with using the rest of the controllers.

This project uses the de-centralized method utilizing ABB’s MGC and M+ System to monitor and govern the microgrid. Henceforth, the Nested Microgrid designs are based on this control structure. It is assumed that these M+ systems would interact with each other using communication links. This means that the control method utilized is option 4 in Table 3 which is a decentralized microgrid with decentralized Nested Microgrid Network control.

2.1.2 Microgrid Network

A microgrid is composed of a number of Microgrid Controllers each controlling an asset within the microgrid. Among those are the network controllers and feeder controllers. These are employed to control the network interface and feeders respectively.
All the controllers are connected together through a mesh of communication links using a Microgrid Plus System (M+ System) and this is shown in figure 13. The M+ System communicates using bidirectional communication with all the controllers within the microgrid. Using these controllers and the associated links, the microgrid is able to operate the protection components as well as manage the balance of supply and demand. The Network controller acts as the controller for the tie-line, the point of common coupling (PCC) between the microgrid and the Nested Microgrid Network or the main grid.

When the tie-line disconnected the Microgrid becomes islanded and the network controller ensures that the system parameters such as voltage and frequency are maintained. The other functions of the network controller are describer later.

Multiple microgrids can be connected together through the Nested Microgrid Network to act as a larger system sharing the loads and generation capacity between them, hence becoming Nested Microgrids. In this case, the M+ systems would communicate between each other and send information regarding the local conditions so that the other controllers may optimize their operation. Furthermore, as shown in Figure 14, the M+ systems would also communicate with the feeder controller through bidirectional communication to ensure the line is operational and receive status updates. It would also communicate with the network controller to receive information regarding the PCC and to disconnect from the main grid in the case of emergency or for other reasons. This is discussed thoroughly in section 3.1.

The system can be further expanded by adding more Microgrids to the NMN.
2.2 Nested Microgrid Types

Interconnection of microgrids can be done in a number of ways, all offering different properties and benefits. A number of different ways of operating multiple microgrids are possible and three of those are discussed.

2.2.1 Nested Microgrids Configurations

Three types of NMs are presented and the configuration for them is shown, the types depend on the application and objective of the NMs. In this report, the focus is on the AC Nested Microgrids as well as some simple configurations that could achieve generalized goals of power sharing and reliability.

The modes of operation to be investigated are as follows:

**Autonomous Mode:** In this mode the Nested Microgrid is islanded and all PCCs are open.

**Islanded NMN Mode (INMN):** The Nested Microgrid is connected to the Nested Microgrid Network and power exchange exists between NMs. All main grid connections are open.

**Grid Connected Mode (GCM):** The Nested Microgrid is connected to the main grid but not the NMN.

**Grid Connected NMN Mode (GNMN):** The Nested Microgrids are connected to the NMN and also to the Main Grid. This is the common scenario.

2.2.1.1 Type I: Autonomous Nested Microgrids

In this setup the interconnected microgrids may operate in Autonomous, INMN, GCM or GNMN mode depending on the conditions and requirements. There are a number of different configurations within this type, utilized to increase reliability and power supply and provide different operating options. The type I would be able to operate in all the previously defined modes.

This setup can be implemented in 4 different formations depending on the desired objective.
2.2.1.1 Feeder Bus Formation
The feeder bus formation is a very basic formation, shown in figure 15. The Nested Microgrids may choose to operate on any of the modes that were previously mentioned. This simple formation allows ease of expandability.

![Feeder Bus Formation Diagram](image)

Figure 15: Configuration of autonomous Nested Microgrids with a feeder bus

2.2.1.2 Ring Formation
Figure 16 shows the ring formation of Nested Microgrids. Using this setup, groups of microgrids can work together in smaller groups, allowing them to share resources. This increases the reliability and efficiency, utilizing surplus generation in one region to accommodate for the deficit in another.

![Ring Formation Diagram](image)

Figure 16: Nested Microgrids in a ring formation

2.2.1.3 Meshed Formation
In the Meshed formation the Nested Microgrids are able to work in smaller groups of Microgrids, contributing both to their collective demand and supply and supporting each other with frequency and voltage stability. All combinations of NM connection are possible.
2.2.1.1.4 Centrally Controlled Nested Microgrids
An additional level of control can be added to any of the aforementioned configurations. Through the utilization of a central controller, the system becomes capable of performing more advanced tasks. This includes further optimization of the system resulting in increased efficiency and reduced operation costs. The NMs in this case still retain the ability to disconnect from the NMN and operate autonomously.

2.2.1.2 Type II: Dependent Nested Microgrids
In this case, the microgrids have a controller allowing them to control and monitor the local resources. However, they are unable to operate self-sufficiently and must at all times remain connected to the NMN. The network connecting all NMs is still capable of being islanded as a whole.

Using this type of Nested Microgrids formation the NM may operate in all the previously mentioned modes except for Autonomous mode.

This method of using the NM offers the benefits of simple cost effective controllers that do not require advanced controls for islanding; the main reason to implement this is in microgrids that have insufficient capability of accommodating for their own loads. Therefore, if the microgrid is disconnected for protection reasons that system goes into a blackout state.
2.2.1.3 Type III: Separable Microgrids
With this setup, the microgrid is able to segment itself into two or more parts, each of which maintaining isolated operation. Should the need arise, the M+ essentially creates virtual Nested Microgrids. The different Microgrid Segments or virtual Nested Microgrids would operate the same as in type I, however, they would only be controlled by a single M+ that would specifically designed to accommodate for such an event.

Figure 19 shows the structure of the type III: Separable Microgrids and how one microgrid can be segmented and become multiple islanded microgrids operating completely isolated electrically from each other.

![Separable Microgrids](image)

**Figure 19: Microgrid configuration with possibility of segmentation**

The type III configuration is able to operate in all of the aforementioned operation modes.

2.2.1.4 Type Summary
To summarize the modes of operation, type I and type III are capable of operating in every mode with type II being restricted to non-autonomous modes as shown in Table 4.

Table 4: Modes of operation for the different types of Nested Microgrid configurations

<table>
<thead>
<tr>
<th>Mode of Operation</th>
<th>Autonomous</th>
<th>Islanded NMN</th>
<th>Grid Connected</th>
<th>Grid-Connected NMN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I Nested Microgrids</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Type II Nested Microgrids</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Type III Nested Microgrids</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

2.2.2 Nested Microgrid Structure
In this section implementation and control structure of different Nested Microgrids are discussed. These structures are based on the Bus Feeder formation. The reason for this choice is its simplicity and effectiveness.
2.2.2.1 Type I: Autonomous Nested Microgrids

The Type I Nested Microgrid scenario can be implemented as shown in Figure 20. The electrical system is divided into zones. The system would be composed of a variety of electrical components, from different storage devices to different generation methods (termed as microsources) and loads.

The figure shows an example system that will be used to show how the different types of NMs can be implemented.

![Figure 20: Electrical layout for a type I Nested Microgrids](image)

The feeder for the individual microgrids can be disconnected for autonomous operation, allowing the microgrids to meet their own individual energy balance. The exact components inside the microgrid would typically vary from one microgrid to the next.

MGCs can be installed at the different system assets or components such as the generation sources, storage devices etc. The MGC aim to monitor and control the asset, ensuring that it is operating as expected, the health of the device as well as providing control for it. The MGC also provides the ability to link this asset with other assets for system-wide functionality.

To link these MGCs together an M Plus System is installed in each zone, forming individual microgrids as shown in Figure 21.

Figure 21 also shows the network controller that is internal to the microgrid which allows the microgrid to disconnect from the Nested Microgrid Network. The network controller sits at the PCC of the NMN controlling and monitoring the connection. There is also a Network Controller located at the PCC of the NM to the main grid.
**Type I: Autonomous Nested Microgrids**

Interaction between the microgrid controllers and the feeder controllers is shown in figure 22. In this configuration all of the microgrids have a connection to the feeder controller.

**Figure 22: NMN Feeders connections for a type I Nested Microgrids**

The feeder allows for the connection of segments in the NM or in the NMN. In the case of emergencies the feeder would shed those sections.
Finally, communication and the associated controllers are added for the main grid connection which is the point of common coupling (PCC) for the NMN. The network controller allows for the isolation of the NMN from the main grid and connection to the grid. This is shown in figure 23. The network controller provides not only islanding and resynchronization functionality, but also a range of other functions that are described later.

**Type I: Autonomous Nested Microgrids**

![Type I network communication links for grid connection](image)

In this design, the microgrids are expected to communicate together to optimize production and efficiency and reduce costs as well as provide increased reliability. Figure 24 demonstrates how this is done with the associated communication links. A communication hub is used to allow for this.
Type I: **Autonomous Nested Microgrids**

Figure 24: Communication links between the various microgrids in a type I Nested Microgrids

Figure 25 shows the final layout of the system with the controllers and communication links that would be present in the type I NM.

Type I: **Autonomous Nested Microgrids**

Figure 25: Overall layout of a type I NM with the communication links and the electrical connection
2.2.2.2 **Type II: Dependent Nested Microgrids**

The electrical network used to demonstrate the Type II Dependent Nested Microgrids configuration is the same as that in Type I. This is shown in figure 26.

**Figure 26: A possible electrical layout for a Type II NM**

Figure 27 shows the MGC controllers for differing components of the microgrid, the M+ system and the internal communication links.

In this case, the differing factor from the type I Nested Microgrids formation is that the local circuit breakers do not have an associated Network controller. This is because in this type, the circuit breaker is purely for protection. The microgrids cannot operate autonomously in this type. The Network Controller for the connection between the NM and the MG, however, is implemented.

Figure 28 and Figure 29 show the feeder and network controllers respectively, each with the required communication links. The network controller is connected at the PCC of the NMN to the main grid.
Type II: Dependent Nested Microgrids

Figure 27: Internal communication for the different microgrids in a type II Nested Microgrids

Type II: Dependent Nested Microgrids

Figure 28: Feeder controllers and the associated communication links for a type II Nested Microgrids
Type II: Dependent Nested Microgrids

$\text{Figure 29: Communication layout for the network connection in type II Nested Microgrids}$

2.2.2.3 Type III: Separable microgrids

Type III Nested Microgrids uses the same electrical layout as the previously mentioned types, i.e. a combination of electrical devices and feeder configuration. This can be seen in figure 30.

Type III: Separable Microgrids

$\text{Figure 30: Electrical layout of a separable microgrid}$

In this type of Nested Microgrids, there is only one microgrid control system or M+ system. This makes it distinctly different from the other two types as shown in figure 31. Similarly to
before, the networks have local MGC controllers managing them, and then they are interfaced with the M+ system. The M+ communication links allow for bi-directional communication. In this type, multiple Nested Microgrids are all controlled from one system. This makes the communication infrastructure extensive but offers a more centralized decision-making process.

**Figure 31: The internal communication in a Separable Microgrid**

The connection with the feeders is applied as was done in the previous two types leading to figure 32.

Communication and the corresponding controllers are shown in figure 33.

This type of Nested Microgrid formation can operate isolated microgrid segments with only one controller as shown in figure 34.

The final configuration with all the controllers, communication links and electrical components is shown in figure 35.
**Type III: Separable Microgrids**

Figure 32: Feeder connection of a type III microgrid

Figure 33: Network feeder controller and communication connection to main grid for type III Nested Microgrids
**Figure 34:** The segmentation layout of a type III Nested Microgrids

**Type III: Separable Microgrids**

The controller is able to segment the microgrid into isolated parts.

**Figure 35:** Communication and electrical connections of a type III Nested Microgrid configuration
2.3 Real World Examples

2.3.1 Bronzeville – Illinois Institute of Technology

The Bronzeville microgrid is an example of multiple microgrids working together as NMs. The initial stage is the design of a commercial microgrid controller capable of multi-microgrid management [38]. Initiated by ComEd and funded by the DOE, the test site for this project is the Bronzeville community. The aim of the project is to install a microgrid in a location that would allow for the interconnection with a nearby microgrid. This microgrid is the Illinois Institute of Technology microgrid which has already been implemented. Furthermore, the project has received funding to improve the solar generation capacity in the Bronzeville region. The project shows that there is a strong push for further microgrids projects, but also to commence the creation of nested microgrids. The initial funding was for the design and construction of the controller.

The Bronzeville Community Microgrid has a peak demand of 10 MW and the IIT Microgrid has a peak demand of 12 MW. It may operate as interconnected NMs or autonomously where they are islanded from each other and the main grid. The two microgrids are located adjacently as shown in figure 36. The system would allow power flow between the two microgrids so that they may support each other when possible.

Figure 36: Location of IIT and Bronzeville Microgrids

The two NMs are connected to the grid through different substations, however, they have a tie line allowing them to be connected electrically. The goal is to improve reliability, resilience and power quality through the use of NMs [39].
The Bronzeville microgrid in combination with the IIT Microgrid operates as a type I NMs formation with a central controller designed to govern the NMs. The single line diagram of the system is shown in Figure 37. The NMs have two PCCs each, allowing for grid connection at different points.

2.3.2 Olney Town Center

The Olney Town Center Microgrid received funding of $1.2 million USD from the DOE for research and development of the project. The final objective is increasing resiliency, reducing emissions and improving the efficiency [40].

The project involves the Microgrid Institute, Green Energy Corp., Schneider Electric and FREEDM Systems Center at N.C. State University to design and build the microgrid with the assistance of the local distribution company, Pepco Holdings Inc. [41].

The production consists of two phases, research and development and laboratory testing [40]. It will supply 33,000 residents and accommodate for a load of 7 MW of which there are a number of critical buildings such as schools, police stations etc.

Olney’s microgrid control system is designed such that it has a SAIDI (System Average Interruption Duration Index) of less than 2 minutes, a reduction in emissions of 20% and an improvement in efficiency of over 20%. Furthermore it is designed to be as a combination of six separate microgrid nodes [42].

The microgrid is arranged into different parts as shown in figure 38, based on the physical location of vital and critical loads shown in figure 39 [3]. The Olney microgrid could be categorized into the type II or type III NM formation, depending on whether the project is to have self-sufficient segments or not.
2.3.3 **Alstom Microgrid System for Philadelphia Navy Yard**

Alstom in combination with Pennsylvania State, and with funding from DOE, initiated a Microgrid project in the Philadelphia Navy Yard. It comprised of dividing the already split region into 4 microgrids (Figure 40, Figure 41). Previously, the region has a connection to two substations of 15 MW and 19 MW and has a peak demand of 27 MW. The Navy yard, houses 145 companies and 11,500 employees.

The purpose is to have the microgrids connected to 4 separate locations on the utility grid through differing substations and have them linked together. The goal of the DOE is to achieve 98% grid resilience, 20% emission reduction and 20% system energy efficiency. The local generation is 6 MW of distributed generation. It is composed of 1 MW of solar generation, a 600 kW fuel cell, 300 kW of storage and a 3 kW combined heat and power plant. Demand response is also utilized for the further improvement of the system [43].
The communication structure can be seen in figure 42. It shows the interconnection of the different NMs and the sources within. In this case PIDC 602 and PIDC 93 are in the same location/zone which is the reason for 5 controllers when only four microgrids are present.

The project is designed to interconnect the microgrid project with the Navy Yard infrastructure so that they may support each other. Furthermore, they are to work with Landis+Gyr which will work on the advanced metering and the communication side of the project [44]. The interaction is shown in figure 43.

Figure 42: Communication network for the Nested Microgrids

Figure 43: Communication between the different components within the nested microgrid [45]
The ultimate aim is to provide the Navy Yard with the following features [46]:

- Islanding
- Protection
- Voltage
- Frequency
- Synchronization
- Reconnection
- Power Quality Management
- Dispatch and System Resiliency

The Philadelphia Navy Yard can be classified as a type I or type III formation of Nested Microgrids. It depends on the specifics of the project and how it was designed and the control methods used.

### 2.3.4 Oncor

Texas distribution company, Oncor, is planning to build a microgrid in Lancaster, Texas. The primary focus is on energy storage, renewable energy and improving reliability of the grid in that location. This is an example of NMs. This Oncor microgrid is connected to the Oncor distribution network.

![Figure 44: Lancaster Nested Microgrids electrical layout](image)

The microgrid aimed to provide smoothing for renewable generation, demand management, peak shaving and load following [48]. The location was chosen because common power outages [49]. Further requirements were that the power supply would not be disrupted and for research of new equipment to be used in the network.
The project, being undertaken by S&C and Schneider Electric, was completed in nine months. It consists of 9 sources and has the possibility of operating 4 different microgrid segments all operated by a single microgrid controller making it a type III Nested Microgrid formation. This is shown in figure 44. In the figure the colored shades represent the different microgrid segments. The segments are able to work in different configurations as desired to supply a combined load of 1.25 MW [50].

The test site is prepped to be a location for a non-technical center for discussions of the future. It is designed to serve customers, developers, city leaders, officials and competitive market players. The center will also provide tours through the test site.

2.3.5 San Diego Navy Cluster

The NAVFAC with funding from the ESTCP has initiated a project to create a master microgrid controller that will be developed by Power Analytics. It would operate the microgrids in Point Loma, Coronado and San Diego as NMs. The project will receive $30 million USD. The Navy’s aim is to increase energy supply security, reduce costs and energy consumption. It would also act as a prototype for adoption into other military microgrids and form more NMs [51] [52].

Utilizing the Master Microgrid Controller the three individual microgrids would operate as a variant of the type I NM formation. The microgrids are expected to be able to operate autonomously to power the military bases. They should also ensure they are operational in the case of an outage in the main grid. This is done with the benefit of reducing operational costs when collaborating with other microgrids as NMs. When operating in NM formation, they would have an additional hierarchy of control in the form of the Master Microgrid Controller.

The three microgrids that the system would be composed of, as shown in figure 45, are of the following capacities [5]:

- San Diego – 42 MW
- Coronado – 26 MW
- Point Loma – 15 MW

This makes the proposed Nested Microgrid system a sizeable network, which could be grounds for an advanced system with breakthroughs for the future and a great example of the future of Nested Microgrids.
2.3.6 Yamagata Site Microgrid

NM have not been solely based in the U.S., at the same time projects are coming into the implementation phase in Japan. Spurred by recent natural disasters there that have created mass outages there has been a greater push for microgrids. One of these is a formation of three Nested Microgrids connected together located at the Yamagata site. It is a project that is funded by the Japanese Ministry of Environment (MOE) [2] [53].

Figure 46 shows how the three NM would connect together and the Energy Management System (EMS) governing them. This would make it a type I nested microgrid formation, where the primary aim is not only to investigate energy exchange between microgrid systems but to also focus on DC power. The eventual target is reducing storage battery capacity required by 40%. The reasoning behind this project is that by allowing power supply interchange between the microgrids it is possible reduce the power storage capacity required for safe and reliable operation of the NMs.
Batteries are used to accommodate for discrepancies between the power supply and demand. Power supply interchange is done over AC and DC links should the energy storage is insufficient.

The system layout is shown in figure 47 using a single line diagram: the AC and DC bus and components can be seen.

It is a small system with 15 kW of distributed generation divided evenly between the three NMs and 100 kW of storage divided as 50 kW in the first NM and 25 kW in each of the others. The system also contains dedicated units for power conditioning.

![Figure 47: Yamagata's Nested Microgrids system layout [53].](image-url)
3 Control Functions

In the previous chapter the concept of Nested Microgrids is discussed and different control schemes are described. Finally, the structure and possible layouts of the Nested Microgrids are scrutinized.

Building upon the theory discussed in the previous chapter, this chapter investigates the required control functions for the operation of NMs. These control functions are analyzed for the different controllers within the NMs. Variants of these functions based on controller location within the NMs are also scrutinized.

One of the main aims of this chapter is to categorize the functions at different levels of the control hierarchy within the NM scenario. Further on, actual implementation strategy is presented for selected functions that are considered important. The selected functions display an array of communication and interaction between the assets.

These levels of the control hierarchy are defined as follows:

**Nested Microgrids Level**
These functions require other NMs (outside the controller’s own microgrid) to also collaborate in the decision making or alter their behavior to perform the function. These functions are shown in a purple shade in the table.

- System level control
- Power scheduling and power management
- Emergency or islanding
- System wide stability issues
- Asset Optimization
- Etc.

**Microgrid Level**
Functions in this level involve control efforts from controllers/assets and/or communicate information to its own M+ system. These functions are shown in a blue shade in the table.

- Microgrid monitoring e.g. microgrid feeder status
- Setting control parameters for pre-decided modes e.g. Powerstore droop parameters
- Etc.

**Asset Level**
Asset level includes functions that perform a local action based on local parameters. These functions are shown in a grey shade in the table.

- Set-point tracking e.g. power or voltage control
- Automatic recharge
The purpose is to identify the changes required in the controller functions for implementing them in NMs as opposed to a single microgrid.

3.1 Controller Functions

Different controllers are employed within the NM. Each controller is dedicated to perform different control functions and to manage different assets within the system. Of particular interest are the Network Controllers, Feeder Controllers, Powerstore Controllers (storage controller) and the overall system integrator, the M+ system.

The function tables show for each function the following:

- The function name
- The control level it is implemented
- A brief description of what the function does
- The urgency, which determines the speed of the control action. It is classified as follows:
  - High: Action needs to be taken quickly and it is a matter of system stability, delay could cause a system collapse
  - Medium: Some delay is accepted, functions on this level are functions that maintain optimal operation of the system
  - Low: Necessary but not vital, things like communicating monitoring parameters for history or information fall under this category

With a second table to provide the following information:

- The function name
- The control level it is implemented
- An explanation of how the function is performed

3.1.1 Network Controller

The network controller (NC) is located at the PCC tie-lines and monitors and manages them. The tie-lines link:

- The microgrid to the main grid (M-MG)
- The microgrid to the NMN (M-NMN)
- The NMN to the main grid (NMN-MG)

The functions available in the controller would vary depending on the location/tie-line it is controlling as well as that the intercommunication requirements would also be dependent on this.

The Network Controller is vital for the operation of the microgrid and the NMs. It sits at the PCC and monitors the power flow and operational parameters of both the upstream and downstream systems. Furthermore, it provides islanding and synchronization capability to the
microgrid. Therefore it is vital to examine how it is impacted when additional microgrids are connected to form the NMs.

3.1.1.1 Network Controller: Microgrid – Main Grid Connection
This network controller sits at the PCC between a NM and the MG and offers the standard network controller functions.

Table 5 displays the functions for the Network Controller that connects the individual microgrid to the main grid.

Some of the functions listed in Table 5 would change in operation when moving from the classical microgrid system to a NM system.

Table 6 goes further into how these functions would work in the Nested Microgrid system. The column, change, shows if the function changes in its behavior because of the other Nested Microgrids from a normal case of a single microgrid.

Table 5: Function list showing the hierarchy level, the urgency of it and what it does of NC in M-MG point

<table>
<thead>
<tr>
<th>Function</th>
<th>Level</th>
<th>Purpose</th>
<th>Urgency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resynchronization</td>
<td>NM</td>
<td>Adjust the voltage at the PCC and the frequency of the system as well as the phase to achieve synchronization and grid connection (f, V, ϕ measure and publish)</td>
<td>Medium</td>
</tr>
<tr>
<td>Islanding</td>
<td>NM</td>
<td>Disconnect from the grid and inform the NM of the action so that stability is maintained</td>
<td>High</td>
</tr>
<tr>
<td>Planned Islanding</td>
<td>NM</td>
<td>Inform NM and reduce the power flow at PCC to zero and disconnect</td>
<td>Medium</td>
</tr>
<tr>
<td>Measure P, Q, V, f, ϕ to maintain setpoints</td>
<td>NM</td>
<td>Coordinate system parameters</td>
<td>Low</td>
</tr>
<tr>
<td>Overloading alarm</td>
<td>NM</td>
<td>Inform NM of overloading situation to alleviate the problem or prepare for islanding</td>
<td>Medium</td>
</tr>
<tr>
<td>Black-Start Operation</td>
<td>μG</td>
<td>Coordinate generators for black start</td>
<td>Medium</td>
</tr>
<tr>
<td>Voltage Droop</td>
<td>μG</td>
<td>Voltage droop coordination</td>
<td>Medium</td>
</tr>
<tr>
<td>Publish Nest status to PS</td>
<td>μG</td>
<td>Obtain status of NMN from M+ system then publish to the PS operator</td>
<td>Low</td>
</tr>
<tr>
<td>Receive status from PS</td>
<td>μG</td>
<td>Obtain status from the PS operator and send details to the M+ system, highly critical information is sent to NMs directly i.e. alarms</td>
<td>Low</td>
</tr>
</tbody>
</table>
Table 6: Function list showing hierarchy level and how the functions is performed of NC in M-MG point

<table>
<thead>
<tr>
<th>Function</th>
<th>Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resynchronization</td>
<td>NM</td>
<td>Synchronization is done by utilizing all of the assets of a microgrid(^1) to achieve the desired voltage, frequency and phase angle. Once the reference values are achieved the circuit breaker is closed and power flow between the main grid and microgrid commences.</td>
</tr>
<tr>
<td>Islanding</td>
<td>NM</td>
<td>Islanding is done. Then NM(^2) is informed as quick as possible so that steps are taken to ensure system stability. The loss of a connection to the main grid may have a strong effect.</td>
</tr>
<tr>
<td>Planned Islanding</td>
<td>NM</td>
<td>Islanding is done proactively. The NMs are informed and coordinate to reduce the power flow at the tie-line to zero. It is done through the M+ level communication.</td>
</tr>
<tr>
<td>Measure P, Q, V, f, (\phi) to maintain setpoints</td>
<td>NM</td>
<td>The NM controllers work together to maintain system parameters through a combined control effort. I.e. control (P) &amp; (V) at the tie line</td>
</tr>
<tr>
<td>Overloading alarm</td>
<td>NM</td>
<td>This function would inform all of the NM as opposed to just the microgrid in the normal condition.</td>
</tr>
<tr>
<td>Black-Start Operation</td>
<td>(\mu G)</td>
<td>During black-start operation the microgrids would be islanded from the grid and the NM.</td>
</tr>
<tr>
<td>Voltage Droop</td>
<td>(\mu G)</td>
<td>Coordinate the microgrid assets to achieve desired droop level and communicate that to the NM.</td>
</tr>
<tr>
<td>Publish Nest status to PS</td>
<td>(\mu G)</td>
<td>This function transmits the status of the downstream connection which would comprise of the NM. Since the transmission is received from the M+ system it is considered internal level function, however, the M+ would have information already obtained regarding all the NM</td>
</tr>
<tr>
<td>Receive status from PS</td>
<td>(\mu G)</td>
<td>Obtain status from the PS operator and send details to the M+ system. The M+ system would then distribute the necessary information or all the information to the other NM</td>
</tr>
</tbody>
</table>

3.1.1.2 Network Controller: Microgrid – Nested Microgrid Network Connection

A Network Controller can also be implemented at the connection between the NM and the NMN. It monitors and controls the tie-line power flow and voltage and it is vital in the islanding and synchronization process.

The functions of this variant are similar to the previous one at the Microgrid-Main grid connection but with some modification in how the functions are implemented. The functions can be seen in Table 7.

---

\(^1\) It may involve the assets of all the NMs. This is explained in detail in section 3.3.1

\(^2\) How the communication to the other NM for the islanding case is done is discussed in section 3.3.2
Table 7: Function list showing the hierarchy level, the urgency of it and what it does of NC in M-NMN point

<table>
<thead>
<tr>
<th>Function</th>
<th>Level</th>
<th>Purpose</th>
<th>Urgency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resynchronization</td>
<td>NM</td>
<td>Same as table 1</td>
<td>Medium</td>
</tr>
<tr>
<td>Islanding</td>
<td>NM</td>
<td>Same as table 1</td>
<td>High</td>
</tr>
<tr>
<td>Planned Islanding</td>
<td>NM</td>
<td>Same as table 1</td>
<td>Medium</td>
</tr>
<tr>
<td>Measure $P, Q, V, f, \phi$ to maintain setpoints</td>
<td>NM</td>
<td>Same as table 1</td>
<td>Low</td>
</tr>
<tr>
<td>Overloading alarm</td>
<td>NM</td>
<td>Same as table 1</td>
<td>Medium</td>
</tr>
<tr>
<td>Black-Start Operation</td>
<td>$\mu$G</td>
<td>Same as table 1</td>
<td>Medium</td>
</tr>
<tr>
<td>Voltage Droop</td>
<td>$\mu$G</td>
<td>Same as table 1</td>
<td>Medium</td>
</tr>
</tbody>
</table>

Similar to the previous case, the functions are described and it is noted whether they have become NM functions. This is shown in Table 8.

Table 8: Function list showing hierarchy level and how the function is performed of NC in M-NMN point

<table>
<thead>
<tr>
<th>Function</th>
<th>Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resynchronization</td>
<td>NM</td>
<td>Synchronization is done by utilizing all of the assets of all the NMs to achieve the desired voltage, frequency and phase angle. Once the reference values are achieved the circuit breaker is closed and power flow between the NMN and microgrid commences.</td>
</tr>
<tr>
<td>Islanding</td>
<td>NM</td>
<td>When issues are detected on the main grid, the NMN would disconnect and become islanded. It would then transmit the status to all the M+ systems so that modes of the assets are changed to maintain stability.</td>
</tr>
<tr>
<td>Planned Islanding</td>
<td>NM</td>
<td>Same as table 2</td>
</tr>
<tr>
<td>Measure $P, Q, V, f, \phi$ to maintain setpoints</td>
<td>NM</td>
<td>Same as table 2</td>
</tr>
<tr>
<td>Overloading alarm</td>
<td>NM</td>
<td>All of the NMs are informed in the case of alarm</td>
</tr>
<tr>
<td>Black-Start Operation</td>
<td>$\mu$G</td>
<td>Same as table 2</td>
</tr>
<tr>
<td>Voltage Droop</td>
<td>$\mu$G</td>
<td>Same as table 2</td>
</tr>
</tbody>
</table>

3.1.1.3 Network Controller: Nested Microgrid Network – Main Grid Connection

The next variant of the network controller is of that placed at the connection point between the NMN and the MG. At this position it ensures the safe operation and connection of the NMN to the MG. The functions at this point are all on the NM level. This can be seen in Table 9.
Table 9: Function list showing the hierarchy level, the urgency of it and what it does of NC in NMN-MG point

<table>
<thead>
<tr>
<th>Functions</th>
<th>Level</th>
<th>Purpose</th>
<th>Urgency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resynchronization</td>
<td>NM</td>
<td>Same as table 1</td>
<td>Medium</td>
</tr>
<tr>
<td>Islanding</td>
<td>NM</td>
<td>Same as table 1</td>
<td>High</td>
</tr>
<tr>
<td>Planned Islanding</td>
<td>NM</td>
<td>Same as table 1</td>
<td>Medium</td>
</tr>
<tr>
<td>Measure $P, Q, V, f, \phi$ to maintain setpoints</td>
<td>NM</td>
<td>Same as table 1</td>
<td>Low</td>
</tr>
<tr>
<td>Overloading alarm</td>
<td>NM</td>
<td>Same as table 1</td>
<td>Medium</td>
</tr>
<tr>
<td>Publish NM status to PS (A range of information)</td>
<td>NM</td>
<td>Publish that status of the NMN to the PS operator</td>
<td>Low</td>
</tr>
<tr>
<td>Receive status from PS (A range of information)</td>
<td>NM</td>
<td>Receive information from PS operator and transmit to all the NM</td>
<td>Low</td>
</tr>
</tbody>
</table>

This controller would be a new addition since it does not sit within the defined NM region but within the NMN. However, the operation would be almost identical to the classical PCC controller connection. The function descriptions are provided in Table 10.

Table 10: Function list detailing how the function is performed of NC in NMN-MG point

<table>
<thead>
<tr>
<th>Functions</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resynchronization</td>
<td>Resynchronization is achieved through the coordination of all NMs. Once the reference values are achieved the circuit breaker closes and power flow between the main grid and microgrid would commence.</td>
</tr>
<tr>
<td>Islanding</td>
<td>Disconnect from the grid and inform all the NMs of the action so that stability is maintained.</td>
</tr>
<tr>
<td>Planned Islanding</td>
<td>Islanding is done proactively. The NMs are informed and coordinate to reduce the power flow at the tie-line to zero.</td>
</tr>
<tr>
<td>Measure $P, Q, V, f, \phi$ to maintain setpoints</td>
<td>Same as table 2</td>
</tr>
<tr>
<td>Overloading alarm</td>
<td>Inform all the NMs of an alarm</td>
</tr>
<tr>
<td>Publish NM status to PS (A range of information)</td>
<td>This function transmits the status of the NMs to the PS operator</td>
</tr>
<tr>
<td>Receive status from PS (A range of information)</td>
<td>Obtain information from the PS operator and transmit to all the NM</td>
</tr>
</tbody>
</table>
3.1.2 Feeder Controller

The feeder controller (FC) is employed in the microgrid feeders for monitoring and control functionality. These controllers can be placed in the NMN or within the NMs and as a result there are two variants respectively.

Some of the functions in this controller are operation mode specific. They depend on whether the system is islanded or operating in grid-connected mode.

3.1.2.1 Feeder Controller: Microgrid Level

This feeder controller sits on the feeders within the microgrid. The functions of this controller are as shown in Table 11. The table details the functions performed, the level on which the function is executed, the process involved in performing the function and the urgency level which is related to the timing requirements of the system.

Table 11: Function list showing the hierarchy level, the urgency of it and what it does of FC at M level

<table>
<thead>
<tr>
<th>Feeder Controller - Microgrid Level</th>
<th>Level</th>
<th>Purpose</th>
<th>Urgency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station Spinning Reserve Management</td>
<td>NM</td>
<td>Ensure that sufficient spinning reserve and step load capacity is available within the microgrid</td>
<td>Medium</td>
</tr>
<tr>
<td>Priority Based Feeder Connection</td>
<td>NM</td>
<td>Coordinate closure priority &amp; delay for different feeder connections within NMN</td>
<td>High</td>
</tr>
<tr>
<td>Automatic Feeder Reconnection</td>
<td>NM</td>
<td>Signals for additional generating capacity if required in order to close the circuit breaker</td>
<td>Medium</td>
</tr>
<tr>
<td>Microgrid Peak Power Lopping</td>
<td>NM</td>
<td>Reroute power flow on feeder during overloading</td>
<td>Medium</td>
</tr>
<tr>
<td>Feeder Shedding on Generator Overload / Proactive load shedding</td>
<td>NM</td>
<td>Shed sections of grid if required (islanded function)</td>
<td>High</td>
</tr>
<tr>
<td>Protection Group Switching</td>
<td>μG</td>
<td>Ensure proper protection setting for the feeder to close/open i.e. inrush current</td>
<td>High / Medium</td>
</tr>
<tr>
<td>Operation Modes</td>
<td>μG</td>
<td>Selection of control mode for the feeder within the microgrid</td>
<td>Low</td>
</tr>
<tr>
<td>Automatic Station Black Start</td>
<td>Asset</td>
<td>When sufficient power is available the breaker would close</td>
<td>Medium</td>
</tr>
</tbody>
</table>

The microgrid level feeder controller for the NM concept changes in some aspects, and they are related to the overall operation. This is especially so in regards to the protection and management, where communication is required to account for the whole NMN condition. How the functions would be performed is given in Table 12.
Table 12: Function list showing hierarchy level and details about how the function is performed of FC at M level

<table>
<thead>
<tr>
<th>Functions</th>
<th>Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station Spinning Reserve Management</td>
<td>NM</td>
<td>Calculate the available spinning reserve &amp; step load capacity. Factors in capacity that other NMs can provide. Communication is performed through M+.</td>
</tr>
<tr>
<td>Priority Based Feeder Connection</td>
<td>NM</td>
<td>Communicate with other feeders through M+ system to coordinate the controllers. Set and coordinate the priority and delay time to ensure that when a different feeder has closed, a countdown timer initiates before another feeder can close.</td>
</tr>
<tr>
<td>Automatic Feeder Reconnection</td>
<td>NM</td>
<td>Signals to M+ level for additional capacity which would then be transmitted to all the other M+ systems in the network.</td>
</tr>
<tr>
<td>Microgrid Peak Power Lopping</td>
<td>NM</td>
<td>If overloading occurs in the feeder, transmit the load and parameters data to M+ and then other NMs to control the generation to eliminate the overloading</td>
</tr>
<tr>
<td>Feeder Shedding on Generator Overload/Proactive load shedding</td>
<td>NM</td>
<td>If there is overloading or insufficient generation commence shedding of grid functions. It would inform the M+ system which would then transmit to the other NMs. (Islanded mode function)</td>
</tr>
<tr>
<td>Protection Group Switching</td>
<td>μG</td>
<td>Based on the grid conditions and operation mode, the M+ system would ensure that the protection settings within its domain are configured accordingly</td>
</tr>
<tr>
<td>Operation Modes</td>
<td>μG</td>
<td>Operation mode is designated by the M+ system based on the information it already has from the system</td>
</tr>
<tr>
<td>Automatic Station Black Start</td>
<td>Asset</td>
<td>Check the system conditions and if sufficient power is available in the microgrid to close the circuit breaker and allow power flow</td>
</tr>
</tbody>
</table>

### 3.1.2.2 Feeder Controller: Nested Microgrid Level

Feeder controllers are also implemented in the NMN where they connect multiple sections together. This feeder controller acts to provide the necessary control and monitoring to feeders located in the NMN linking the NM together. The functions, level, process and urgency are given in Table 13.

Table 13: Function list showing the hierarchy level, the urgency of it and what it does of FC at NM level

<table>
<thead>
<tr>
<th>Functions</th>
<th>Level</th>
<th>Purpose</th>
<th>Urgency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station Spinning Reserve Management</td>
<td>NM</td>
<td>Ensure that sufficient spinning reserve and step load capacity is available within the NMN</td>
<td>Medium</td>
</tr>
<tr>
<td>Priority Based Feeder Connection</td>
<td>NM</td>
<td>See Table 11</td>
<td>high</td>
</tr>
<tr>
<td>Automatic Feeder</td>
<td>NM</td>
<td>Signals to relevant NMs for additional generating</td>
<td>Medium</td>
</tr>
</tbody>
</table>
Table 14 shows the processes for executing the functions that were shown in in Table 13. These functions involve all of the NM because of the location of the controller.

**Table 14: Function list showing hierarchy level and details about how the function is performed of FC at NM level**

<table>
<thead>
<tr>
<th>Functions</th>
<th>Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station Spinning Reserve Management</td>
<td>NM</td>
<td>Calculate the available spinning reserve and capacity available in the system by communicating to all the M+ systems.</td>
</tr>
<tr>
<td>Priority Based Feeder Connection</td>
<td>NM</td>
<td>See Table 12</td>
</tr>
<tr>
<td>Automatic Feeder Reconnection</td>
<td>NM</td>
<td>Signals to all the M+ systems for additional capacity. When achieved the circuit breaker would close.</td>
</tr>
<tr>
<td>Microgrid Peak Power Lopping</td>
<td>NM</td>
<td>If overloading occurs in the feeder, transmit the parameters to all M+ system to reroute power flow.</td>
</tr>
<tr>
<td>Feeder Shedding on Generator Overload/Proactive load shedding</td>
<td>NM</td>
<td>If there is overloading or insufficient generation it can start shedding sections of grid (islanded function). It would then inform all the M+ system.</td>
</tr>
<tr>
<td>Protection Group Switching</td>
<td>NM</td>
<td>Based on the grid conditions and operation mode the protection settings within are configured accordingly. This is a collaboration of all the NMs.</td>
</tr>
<tr>
<td>Operation Modes</td>
<td>NM</td>
<td>Operation mode is designated by all the NMs based on the conditions of system</td>
</tr>
</tbody>
</table>

### 3.1.3 Energy Storage System Controller

An essential part of microgrids is the storage system. It is vital to the concept and must be analyzed to observe the impact of NMs on the behavior of this controller's functions. Table 15 shows the function name of the Energy Storage System Controller (ESC), the level, process and urgency of the functions that can be performed.
Table 15: Function list showing the hierarchy level, the urgency of it and what it does of ESC

<table>
<thead>
<tr>
<th>Functions</th>
<th>Level</th>
<th>Purpose</th>
<th>Urgency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scheduling</td>
<td>NM</td>
<td>Storage can be activated or scheduled to activate</td>
<td>Low</td>
</tr>
<tr>
<td>Operation Modes</td>
<td>NM</td>
<td>Set the operation mode for the storage device</td>
<td>Low</td>
</tr>
<tr>
<td>Peak Lopping</td>
<td>NM</td>
<td>Engage in peak lopping</td>
<td></td>
</tr>
<tr>
<td>Peak Shaving [I/G]</td>
<td>NM</td>
<td>Engage in peak shaving</td>
<td>High</td>
</tr>
<tr>
<td>Step Load Capacity</td>
<td>μG</td>
<td>Calculate step load capacity and provide information to local M+</td>
<td>Low</td>
</tr>
<tr>
<td>Spinning Reserve Capacity</td>
<td>μG</td>
<td>Calculate available spinning reserve capacity and provide information to local M+</td>
<td>Low</td>
</tr>
<tr>
<td>P,Q Setpoints</td>
<td>μG</td>
<td>Operate at defined setpoints</td>
<td>Low</td>
</tr>
<tr>
<td>Frequency Droop Control[A/I]</td>
<td>μG</td>
<td>M+ system can select this mode and sends the operation parameters.</td>
<td>Low</td>
</tr>
<tr>
<td>Voltage Droop Control[A/I]</td>
<td>μG</td>
<td>M+ system can select this mode and sends the operation parameters.</td>
<td>Low</td>
</tr>
<tr>
<td>Power Factor Correction [I/G]</td>
<td>μG</td>
<td>M+ system can select this mode and sends the operation parameters.</td>
<td>Low</td>
</tr>
<tr>
<td>Anti-Islanding [I/G]</td>
<td>μG</td>
<td>Monitor grid and provides anti-islanding protection if required and inform M+</td>
<td>High</td>
</tr>
<tr>
<td>Battery lifetime optimization</td>
<td>Asset</td>
<td>Optimize the storage lifetime</td>
<td>Low</td>
</tr>
<tr>
<td>Automatic Recharge</td>
<td>Asset</td>
<td>Recharge during optimal time</td>
<td>Low</td>
</tr>
</tbody>
</table>

Table 16 shows how much of an impact NM has on the functions of the storage controller, showing what functions have changed a description of how it would work in the new system of NM as opposed to ordinary microgrids.

Table 16: Function list showing hierarchy level and details about how the function is performed of ESC

<table>
<thead>
<tr>
<th>Storage</th>
<th>Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scheduling</td>
<td>NM</td>
<td>Scheduling can be done using M+ system but it is decided upon using the collective data from all the M+ systems</td>
</tr>
<tr>
<td>Operation Modes</td>
<td>NM</td>
<td>M+ systems collaborate to designate the operation mode for the storage systems.</td>
</tr>
<tr>
<td>Peak Lopping</td>
<td>NM</td>
<td>Participate in peak lopping if required in order to avoid overloading by rerouting power</td>
</tr>
</tbody>
</table>
### 3.2 \( M^+ \) System Operations in Nested Microgrids

With the controller functions investigated the next step is determine the system wide functions. In a typical scenario these functions would be NM-wide, requiring the collaboration of the assets of all the NMN in order to achieve the microgrid’s objective.

The \( M^+ \) functions are listed in Table 17 with an outline of the purpose of the functions. These functions range from power management, the protection capability as well as market

<table>
<thead>
<tr>
<th>Function</th>
<th>Type</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Shaving ([I/G]^3)</td>
<td>NM</td>
<td>( M^+ ) system can designate the storage device to provide power during times of high peak so as to avoid starting new generators. The ( M^+ ) system would collaborate to activate this.</td>
</tr>
<tr>
<td>Step Load Capacity ( \mu G )</td>
<td>( \mu G )</td>
<td>Based on the conditions of the storage the Step Load Capacity is calculated and the ( M^+ ) is informed. The capacity is then published to all the ( M^+ ) systems.</td>
</tr>
<tr>
<td>Spinning Reserve Capacity ( \mu G )</td>
<td>( \mu G )</td>
<td>Based on the conditions of the storage the Spinning Reserve Capacity is calculated and the ( M^+ ) is informed. The capacity is then published to all the ( M^+ ) systems.</td>
</tr>
<tr>
<td>P,Q Setpoints ( \mu G )</td>
<td>( \mu G )</td>
<td>( M^+ ) system can designate points to the storage at operate at. These setpoints can be communicated to the ( M^+ ) from the NMN</td>
</tr>
<tr>
<td>Frequency Droop Control[A/I]^3 ( \mu G )</td>
<td>( \mu G )</td>
<td>Activate Frequency Droop Control through ( M^+ ) system and receive operation parameters and values. The droop values would be decided on by all the ( M^+ ) systems but received through local ( M^+ )</td>
</tr>
<tr>
<td>Voltage Droop Control[A/I/G]^3 ( \mu G )</td>
<td>( \mu G )</td>
<td>Activate Voltage Droop Control through ( M^+ ) system and receive operation parameters and values. The droop values would be decided on by all the ( M^+ ) systems but received through local ( M^+ )</td>
</tr>
<tr>
<td>Power Factor Correction [I/G]^3 ( \mu G )</td>
<td>( \mu G )</td>
<td>Activate PF correction through ( M^+ ) system and receive operation parameters and values. The droop values would be decided on by all the ( M^+ ) systems but received through local ( M^+ )</td>
</tr>
<tr>
<td>Anti-Islanding ([I/G]^3) ( \mu G )</td>
<td>( \mu G )</td>
<td>Monitor grid status such as voltage, frequency etc. and provide anti-islanding protection if islanding occurs inform the ( M^+ ) which would then inform the other ( M^+ ) systems</td>
</tr>
<tr>
<td>Battery lifetime optimization Asset</td>
<td>Asset</td>
<td>Storage system optimizes its operation based on parameters received from the ( M^+ ) system.</td>
</tr>
<tr>
<td>Automatic Recharge Asset</td>
<td>Asset</td>
<td>Based on current conditions the storage device would act to charge itself in order to make use of periods of excess generation</td>
</tr>
</tbody>
</table>

\[3 \ [I/C/G] -> \ A: \text{Autonomous Microgrid} \quad I: \text{Islanded NMN mode} \quad G: \text{Grid Connected Mode}\]
interfacing and dispatch. For each function the level of operation is identified which in this case is either ‘μG’ to signify that it is a local function to the microgrid or ‘NM’ level to signify that it is a function that has expanded to involve all the NMs.

Table 17: Function list of M+ system showing hierarchy level and details about how the function is performed

<table>
<thead>
<tr>
<th>Function</th>
<th>Level</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Renewable Energy Integration</td>
<td>NM</td>
<td>Ensure sufficient capacity is available in NMN for renewable energy integration</td>
</tr>
<tr>
<td>Storage / Stabilizing Integration</td>
<td>NM</td>
<td>Designate available assets for smoothing. As well as synchronizing sources</td>
</tr>
<tr>
<td>Integration of automated demand response systems;</td>
<td>NM</td>
<td>Enable demand response in NMs if required</td>
</tr>
<tr>
<td>Archiving</td>
<td>NM</td>
<td>Log important and significant events and occurrences</td>
</tr>
<tr>
<td>Managed load demand</td>
<td>NM</td>
<td>Monitoring and managing connected loads</td>
</tr>
<tr>
<td>Single contingency analysis</td>
<td>μG/NM</td>
<td>Determine critical elements in the NMN</td>
</tr>
<tr>
<td>Generator scheduling/ dispatch/ start-stop</td>
<td>μG</td>
<td>Maintains generator status and operation commands</td>
</tr>
<tr>
<td>Generator Power Sharing (Active &amp; Reactive Power)</td>
<td>μG</td>
<td>Sets P &amp; Q setpoints for supplying loads and the NMN</td>
</tr>
<tr>
<td>Generator configuration management</td>
<td>μG</td>
<td>Configure generator settings and parameters</td>
</tr>
<tr>
<td>Generator overload capability</td>
<td>μG</td>
<td>Calculate the overload capability and set value in generator</td>
</tr>
<tr>
<td>Feeder proactive load shedding and automatic microgrid black start;</td>
<td>μG</td>
<td>Managing feeder automation parameters for shedding and reconnection.</td>
</tr>
<tr>
<td>Control of V, f in standalone/isolated grids (Time drift correction);</td>
<td>μG</td>
<td>Maintain desired operating parameters</td>
</tr>
<tr>
<td>Wind turbine or solar PV generator power limitation setpoint</td>
<td>μG</td>
<td>Power generation in wind turbines and solar PV can be limited</td>
</tr>
<tr>
<td>Determine and manage the energy storage system state of charge</td>
<td>μG</td>
<td>Monitoring capacity and managing the energy storage systems within the microgrid</td>
</tr>
<tr>
<td>Power Management</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Renewable energy availability</td>
<td>NM</td>
<td></td>
</tr>
<tr>
<td>Unit commitment (priority, sizes and availability);</td>
<td>NM</td>
<td>Manage availability, prioritization and system capacity (spinning reserve, step load and storage) and requirements</td>
</tr>
<tr>
<td>Economic dispatch;</td>
<td>NM</td>
<td></td>
</tr>
<tr>
<td>Spinning reserve requirements</td>
<td>NM</td>
<td></td>
</tr>
</tbody>
</table>
Table 18 explains what each function does and indicates whether this function has evolved to a NM level or not. It becomes evident then that when considering a NM system the functions would be changed and as such it is important to investigate them and how their implementation and operation would change.

Table 18: Function list of M+ system showing hierarchy level and details about how the function is performed

<table>
<thead>
<tr>
<th>Function</th>
<th>Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Renewable Energy Integration</td>
<td>NM</td>
<td>Ensure sufficient capacity exists in the NMN to provide power balance and stability for renewable energy integration to compensate for power fluctuations</td>
</tr>
<tr>
<td>Storage / Stabilizing Integration</td>
<td>NM</td>
<td>Coordinate the available assets to ensure that some participate in power quality and droop to maintain system stability. Also synchronize sources for connection</td>
</tr>
<tr>
<td>Integration of automated demand response systems;</td>
<td>NM</td>
<td>Communicate with other NMs in order to engage in the required demand response</td>
</tr>
<tr>
<td>Archiving</td>
<td>NM</td>
<td>Log important and significant events and occurrences in the NMs in order to monitor reoccurring events or utilize the data to optimize future production</td>
</tr>
<tr>
<td>Managed load demand</td>
<td>NM</td>
<td>Monitor the demand levels and ensure that adequate generation is available as well as necessary capacity required for increases.</td>
</tr>
<tr>
<td>Single contingency analysis</td>
<td>µG/NM</td>
<td>Perform powerflow analysis on the system to determine critical elements and reconfigure system to achieve the required conditions of N-1</td>
</tr>
<tr>
<td>Generator scheduling/ dispatch/ start-stop</td>
<td>µG</td>
<td>Monitors the status of microgrid assets such as availability, conditions as well as maintenance and creates a schedule as well as dispatching generation units. Involves direct comm. with asset.</td>
</tr>
<tr>
<td>Generator Power Sharing (Active &amp; Reactive Power)</td>
<td>µG</td>
<td>Distributes the required P &amp; Q among available units to ensure that they are operating within limits and the load is supplied. Also manages the export to the NMN</td>
</tr>
<tr>
<td>Generator configuration management</td>
<td>µG</td>
<td>Configure generator settings and parameters to achieve desired operating conditions. It may inform other NM of the configuration for information purposes.</td>
</tr>
<tr>
<td>Function Description</td>
<td>Unit</td>
<td></td>
</tr>
<tr>
<td>-------------------------------------------------------------------------------------</td>
<td>------</td>
<td></td>
</tr>
<tr>
<td>Generator overload capability</td>
<td>μG</td>
<td></td>
</tr>
<tr>
<td>Calculate the overload capability based on variables such as weather and generator component conditions and set limit which is transmitted to the asset.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feeder proactive load shedding and automatic microgrid black start;</td>
<td>μG</td>
<td></td>
</tr>
<tr>
<td>Managing the feeder controller in order to eliminate generator overload through the use of proactive load shedding. Whether the feeder is in NM or NMN the action is still taken by the microgrid.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control of V, f in standalone/isolated grids (Time drift correction);</td>
<td>μG</td>
<td></td>
</tr>
<tr>
<td>Provide voltage and frequency control. Even in the NMN the task would be assigned to one of the NMN hence it would be a microgrid level task.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind turbine or solar PV generator power limitation setpoint</td>
<td>μG</td>
<td></td>
</tr>
<tr>
<td>Wind and solar power generation can be limited in order to achieve desired objective. I.e. avoiding overloading or reduce fluctuations.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Determine and manage the energy storage system state of charge</td>
<td>μG</td>
<td></td>
</tr>
<tr>
<td>Monitor the state of charge and manage the state of charge in storage devices in the microgrid</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Power Management</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Renewable energy availability</td>
<td>NM</td>
<td></td>
</tr>
<tr>
<td>Determine the amount of renewable energy available and inform the NMNs so that it can be utilized.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unit commitment (priority, sizes and availability);</td>
<td>NM</td>
<td></td>
</tr>
<tr>
<td>NMs collaborate in order to set the priority levels based on the sizes and availability of the combined sources of the NMN.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Economic dispatch;</td>
<td>NM</td>
<td></td>
</tr>
<tr>
<td>NMs collaborate to dispatch the cheapest sources in the NMN in order to reduce operation cost.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spinning reserve requirements</td>
<td>NM</td>
<td></td>
</tr>
<tr>
<td>Determine the required spinning reserve capacity in order to ensure that changes are accommodated for and this is done as the total between all the NMNs.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step load requirements</td>
<td>NM</td>
<td></td>
</tr>
<tr>
<td>Determine the required step load capacity in order to ensure that changes are accommodated for and this is done as the total between all the NMNs.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dispatchable loads available</td>
<td>NM</td>
<td></td>
</tr>
<tr>
<td>Identify the dispatchable loads available in the NMN between all the NMNs in case of emergency.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Storage/Stabilizing available</td>
<td>NM</td>
<td></td>
</tr>
<tr>
<td>Identify the available capacity in the NMN for providing stabilization and power quality support between all the NMNs.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 3.3 Functions Process

#### 3.3.1 Synchronization

For Grid synchronization the sinusoidal signals on either side of the PCC are matched to within a mismatch margin provided in Table 19. This matching in the case of NMs can be
between the NM and the NMN, the NM and the MG and the NMN and the MG. This is performed by ensuring that the difference in the voltage, frequency and phase on either side of the PCC are minimized and within the specified deviation limits. This helps avoid stability issues and limit transients during the connection process. It also ensures the inrush current is minimized to within the limits of the system. Table 19 shows the maximum deviation allowed in the aforementioned parameters according to the IEEE standard for the interconnection of distributed sources to the main grid.

Table 19: Maximum deviation in frequency, voltage and phase angle allowed for grid synchronization [54]

<table>
<thead>
<tr>
<th>Aggregate rating of DR units (kVA)</th>
<th>Frequency difference (Δf, Hz)</th>
<th>Voltage difference (ΔV, %)</th>
<th>Phase angle difference (Δϕ, °)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-500</td>
<td>0.3</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>&gt;500-1500</td>
<td>0.2</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>&gt;1500-10000</td>
<td>0.1</td>
<td>3</td>
<td>10</td>
</tr>
</tbody>
</table>

To initiate the synchronization process, the network controller located at the PCC must first detect an active grid with a healthy voltage and frequency. It would then begin the synchronization process by broadcasting its intention to synchronize. The required frequency, voltage and phase angle parameters are then transmitted to the local M+ system (that it is a part of) in order to connect.

The synchronization of frequency requires the adjustment of active power in the system, increasing active power generation corresponds to an increase in the frequency and vice versa.

To achieve the required frequency, the NMs collaborate and adjust their power generation accordingly. The Network controller would obtain the upstream frequency and broadcast it to all the M+ systems through the local M+ system. A new frequency reference is determined corresponding to the desired frequency value. According to this value, the sources participating in control would increase/decrease the power injection. The final result is the adjustment of the frequency of the NMN to match that of the MG.

The voltage matching is done by adjusting the voltage at the local point of the PCC in order to match that of the voltage on the other side of the PCC. Voltage synchronization can be achieved in three different ways:

1. Power injection at the point
2. Adjusting local power generation
3. Adjusting Nested Microgrid power generation

The different methods for voltage synchronization are shown in Figure 48.

The first method controls the voltage using a local storage that would either inject or absorb power at the downstream PCC point. This directly affects the voltage and increases or decreases it respectively to the value of the upstream voltage. This method is the simplest and

---

4 If the PCC sits at the Nested Microgrid and the Main Grid tie-line
does not require the coordination of other NM assets. Rather, it can be managed within the microgrid. In Figure 48 it is represented as the green line and it can be seen that minimal coordination is required. But it does require a dedicated storage at the PCC. The storage device in question would change its mode to voltage control mode.

![Diagram showing different voltage synchronization options for Grid Resynchronization function](image)

**Figure 48: Different voltage synchronization options for Grid Resynchronization function**

The second method utilizes the local sources. Their output is adjusted such that the voltage at the downstream point of PCC is the same as the upstream voltage. This is accomplished by performing calculations to obtain new reference values for the power based on the voltage set point required at the PCC. The local M+ system would designate the real and reactive power reference values for all of the microgrid assets so that the desired voltage is achieved at the PCC. Should the capacity prove to be insufficient then the M+ must request additional power supply from other NMs.

The second method is shown using the red arrow in Figure 48. The network controller communicates to the M+ then the M+ system coordinates the assets within the microgrid.

The third method involves the utilization of all the NMs. An extensive analysis is performed over the entire system such that the desired voltage set point is found and power reference values are set for the different assets. Then with the different power output references, the power would be rerouted in order for the voltage at the PCC to be the desired value for resynchronization.
In order to establish the coordination, the M+ system (in which the network controller resides) informs the other M+ systems of the voltage level needed at which point the other M+ systems would participate in the rerouting of the power.

Each method has its advantages and disadvantages. The first method is the easiest but also requires dedicated storage device at the specific point to provide the power injection. This is costly solution. Existing storage devices can be relocated to that point to achieve this purpose. No additional resources are required for the second method, it requires sufficient capacity however, and some computing power. Collaboration of all the nested microgrids is required for the third method which requires a complex power flow analysis but it would have sufficient capacity to achieve the desired voltage level.

Finally the phase angle needs to be synchronized as well. This can be done through two different methods. One of these uses frequency mismatch to connect at the instant of phase angle synchronization. If the frequencies differ slightly the synchronization process is not affected because it has a higher degree of tolerance than phase mismatch. The phase angle would change however, at the frequency difference between the upstream and downstream frequencies. Then when the two signals are close to each other the circuit breaker would close and create the connection.

The other method to achieve phase synchronization is through the use of a phase locked loop to synchronize the voltage signal of the NMN to that of the main grid signal by using the grid voltage as a reference.

With all of the parameters brought close to the values of the main grid the connection can be created easily by closing the circuit breaker.

### 3.3.2 Islanding

Islanding is the case when the NMs are isolated electrically from the MG. This can occur for a number of reasons such as natural disasters or electrical faults.

The network controller located at the PCC would be continuously monitoring the upstream system. When an issue on the main grid is detected that could pose serious problems for the NMN or NM, it would open the circuit breaker. Once the circuit breaker is opened, the connection is severed and, if this is the only connection to the main grid, the NMN becomes islanded.

In islanded mode the NMN is expected to manage its own operational parameters, which are the frequency and the voltage of the system. This is done by switching the micro sources within the system to droop mode and designating some to provide voltage and frequency control. This is done by determining the amount of droop required in the system based on current conditions and setting those in the sources.

Some assets are capable of providing frequency and voltage control. These maybe introduced into the system to ensure that it is operating at the desired level, i.e. 1 p.u. voltage and 50/60 Hz frequency.
When islanded, the system loses the connection to a strong grid which would provide frequency and power supply stability. The NMs must react immediately or risk a system collapse within the NMN. Since the reaction of NMs is important, the inter-NM communication becomes an important matter as well.

There are many ways of informing and managing the NMs during islanding, however, the three cases shown in Figure 49 would be the ones investigated.

The green line (option 1) shows the information being communicated from the network controller (NC) sitting at the PCC to the M+ systems of all the NMs directly. This way the M+ then takes care of the asset coordination. This method is reasonably effective because it can relay the information quickly and does not require additional communication links. It utilizes the available infrastructure.

Another option, option 2, is that shown in the blue line which is to communicate the information to the Network Controllers sitting in NMN outside of the NMs. These network controllers which are already linked to all the systems can then take care of the transfer. This method could be quicker but requires additional communication links to be added, between the NC controllers.

Lastly, the network controller can communicate directly to the assets and switch them to the required modes as shown in option 3, the red line. This method is by far the fastest solution. The communication is directly to the sources but it requires extensive communication infrastructure in order to achieve this method.

The steps performed for the different communication methods can be seen in Table 20. Method 3 can be seen to have very few steps, because it is a direct method. On the other hand, method 2 has a lot steps required to get the signal across even though it is a quick method.
Islanding can also be done on an individual microgrid in some of the types mentioned in section 2.2.1. In this case the microgrid disconnects from the NMN, it would island the same way and inform the other Nested Microgrids using one of the three methods above. However, it is even more vital to ensure that within the autonomous microgrid there are units providing droop control as well as controlling the voltage and frequency.

Table 20: The process for islanding using the different communication methods

<table>
<thead>
<tr>
<th>Method 1</th>
<th>Method 2</th>
<th>Method 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perform islanding by disconnecting from grid</td>
<td>Perform islanding by disconnecting from grid</td>
<td>Perform islanding by disconnecting from grid</td>
</tr>
<tr>
<td>Inform all M+ systems of status</td>
<td>Transmit status to Network controller in NMN</td>
<td>Change some of the assets to droop &amp; control mode</td>
</tr>
<tr>
<td>M+ systems performs action to adjust the local asset control modes to droop modes</td>
<td>NMN NC transmits status to the NM NC</td>
<td>Collaborate with other M+ to maintain control</td>
</tr>
<tr>
<td>Collaborate with other M+ to maintain control</td>
<td>NM NC changes some of the assets to droop</td>
<td>Collaborate with other M+ to maintain control</td>
</tr>
</tbody>
</table>

3.3.2.1 Planned Islanding

The NMs can also perform planned islanding. It could be used to avoid foreseeable grid problems that could affect NMN, such as incoming storms or natural disasters or a number of other things that could cause outages. The NMN would aim to island beforehand so that the impact is minimized.

The islanding part is done as is previously mentioned, however, to perform planned islanding it is preferred that the power flow through the tie-line is reduced to zero before the connection is severed.

To achieve this, a local or system wide calculation is performed in order to obtain the power references required. This would be performed inside the M+ system then the references communicated to the assets. With the new operating points, the power is rerouted to ensure no power is imported or exported through the tie-line. Once this is achieved the circuit breaker would open and the NMN becomes disconnected from the main grid. The reason to reduce power flow in tie-line is to reduce stress on the circuit breaker as well as eliminate the stability and power quality issues that arise from islanding case, such as power oscillations and transients.

In the event of a NM disconnecting from the NMN there is a small difference, the M+ systems must collaborate together to reduce the power flow at the tie-line.

Once the power flow is reduced to zero and the tie-line disconnected, the Nested Microgrids would designate additional droop mode settings if required or change some modes from droop to constant power if there is an excess. Furthermore, if the control unit was removed a new one is selected to maintain the voltage and frequency.
3.3.3 Feeder Load-shed on Generator Overload

In the case of fault or issues with a load or feeder line, the generator would begin overloading. If this persists for an extended period of time the generator could be disconnected or worse, damaged. Thus, the issue would need to be resolved quickly. There are number of ways to accommodate for this issue, one way is the rerouting of the power flow. If that does not work, the feeder which is drawing the excess power is removed. This is done to relieve the stress from the generator.

To remove the correct feeder, the M+ system would determine where the faulty component lies. This is done by assessing the loads on all the feeders. When it is determined which feeder is causing the overloading issue, a signal is sent to feeder controller to disconnect the feeder line.

An example of the procedure is shown in Figure 50. An issue occurs somewhere on feeder 2 but it was not detected by the control system. The generator begins to increase the power supply to the point where it begins to overload. The MGC-G controller located at the generator signals to the M+ system that it is overloading. The M+ system determines that there is an issue somewhere. It analyses the two feeders for the four loads to determine the feeder that is drawing an abnormally large amount of power. Once the feeder with the issue is identified, which in this case it is feeder 2, it would be disconnected to bring the generator back within normal operating limits.

The feeder responsible for the overload could be identified outside the NMs in theNMN. To resolve this, the M+ system would communicate with the other M+ systems to identify the feeder causing the issue. When it is discovered and confirmed, it is then disconnected.

![Figure 50: A system with 2 Nested Microgrids and an issue occurring on load 4 feeder in NM 1](image-url)
Figure 51 shows a case of an issue occurring in NMN. Like before, the MGC-G signals that there is overloading in the generator, and the M+ System 1 begins the investigation. It determines that the excess power demand is coming from outside the microgrid. The M+ systems collaborates with other M+ systems to determine which feeder is the one drawing the excess power, at which point they disconnect the offending feeder.

![Diagram of microgrid system](image)

**Figure 51: Issue on feeder in NMN in a 2 NM system**

### 3.3.4 Black-Start Operation

During a blackout within a NM, the NM completely is disconnected from the system. Similarly if the blackout is in the NMN all the NM would completely de-energize and disconnect from the NMN and the main grid. During this state the NM are completely islanded. In order to restart the systems, each individual NM would have to energize itself then connect to the NMN if possible. The process of energizing the network to raise the voltage to the desired level and energize the network is called a black-start.

The NC coordinates black-start restoration, but the process is initiated from the M+ system. The operation is done by first activating a micro source within the microgrid that is capable of black-starting. This generator would then energize the NM and bring the voltage up. Then a small load is selected to connect in order to absorb the supplied power. The process is continued until it has created a stable system with generation capacity for spinning reserve and step load and some operational loads.

At this point the microgrid becomes fully operational and it is safe for it to connect to the NMN to energize it. After the NMN becomes stable and there is excess generation capacity in the system, the NM without black-start capability would then proceed to slowly connect some loads to the NMN.
4 Test Cases

Potential functions within NMs are discussed and analyzed in the previous chapter. Based on these functions, and using the theorem discussed in Chapter 2, test cases are created for time-domain simulations of NMs.

These test cases aim to verify the system stability of microgrid functions presented in Chapter 3. The proposed test system is displayed in Figure 52. This system is composed of a number of sources and loads that are listed in Table 21.

![Figure 52: Layout of the test system](image)

Based on this system four cases are created to test different functions that are mentioned in section 3.3. Important functions are chosen and to execute these major functions requires the utilization of others. For example, in order to ensure the system is operating in a safe manner after islanding occurs, the M+ system must communicate to assets to change to droop mood and assign reference values if necessary.
The four test cases are:

- Case 1 – Planned Islanding
- Case 2 – Islanding and Resynchronization
- Case 3 – Black-start Operation
- Case 4 – Feeder Shedding due to Overload

**Table 21: List of the assets of the system and their values**

<table>
<thead>
<tr>
<th>Asset</th>
<th>P (MW)</th>
<th>Q (Mvar)</th>
<th>S (MVA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microgrid 1 (M1)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PV</td>
<td>1.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>L1</td>
<td>0.4</td>
<td>0.2</td>
<td>-</td>
</tr>
<tr>
<td>L1a</td>
<td>1.4</td>
<td>0.27</td>
<td>-</td>
</tr>
<tr>
<td>L2</td>
<td>1.8</td>
<td>0.87</td>
<td>-</td>
</tr>
<tr>
<td>Microgrid 2 (M2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SM1</td>
<td>-</td>
<td>-</td>
<td>5.0</td>
</tr>
<tr>
<td>ES1</td>
<td>1.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>L3</td>
<td>0.4</td>
<td>0.2</td>
<td>-</td>
</tr>
<tr>
<td>L3a</td>
<td>1.4</td>
<td>0.27</td>
<td>-</td>
</tr>
<tr>
<td>L4</td>
<td>1.8</td>
<td>0.87</td>
<td>-</td>
</tr>
<tr>
<td>Microgrid 3 (M3)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SM2</td>
<td>-</td>
<td>-</td>
<td>10.0</td>
</tr>
<tr>
<td>ES</td>
<td>1.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>L5</td>
<td>1.8</td>
<td>0.87</td>
<td>-</td>
</tr>
<tr>
<td>L7</td>
<td>1.8</td>
<td>0.87</td>
<td>-</td>
</tr>
<tr>
<td>L8</td>
<td>1.8</td>
<td>0.87</td>
<td>-</td>
</tr>
<tr>
<td>Microgrid 4 (M4)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SM2</td>
<td>-</td>
<td>-</td>
<td>2.0</td>
</tr>
<tr>
<td>L9</td>
<td>0.297</td>
<td>0.162</td>
<td>-</td>
</tr>
<tr>
<td>L10</td>
<td>0.297</td>
<td>0.162</td>
<td>-</td>
</tr>
<tr>
<td>L11</td>
<td>0.297</td>
<td>0.162</td>
<td>-</td>
</tr>
<tr>
<td>L12</td>
<td>0.297</td>
<td>0.162</td>
<td>-</td>
</tr>
<tr>
<td>L13</td>
<td>0.297</td>
<td>0.162</td>
<td>-</td>
</tr>
<tr>
<td>L14</td>
<td>0.297</td>
<td>0.162</td>
<td>-</td>
</tr>
<tr>
<td>Lumped Load</td>
<td>0.9</td>
<td>0.43</td>
<td>-</td>
</tr>
</tbody>
</table>

### 4.1 Case 1 – Planned Islanding

In Case 1, two major functions are investigated, Islanding and Planned Islanding. The aim is to observe the system behavior when the NMN is intentionally islanded. Subsequent to the planned islanding of the whole NMN, an occurrence causes a NM to disconnect abruptly. The effects on the autonomous microgrid as well as the NMs would be evaluated in this event.

In order to perform the Planned Islanding as described in Section 3.3.2, a signal (operator input) is sent to the M+ system to initiate the process. Then, all of the systems assets are assigned new power reference values. These reference values would ensure that the powerflow in the corresponding tie-line is reduced to zero for **Main Grid 1 (MG1)**. It is then disconnected. The same is done for **Main Grid 2 (MG2)** to disconnect it.

The operation modes of the sources are adjusted if necessary to a regulation mode (droop) to provide the necessary ancillary support for Islanded NMN mode operation. In this case only
**ES1** would change to droop mode. The **PV** and **ES** would continue operating in constant power mode.

Furthermore, to ensure system stability and the continued operation of the critical loads, some of the non-critical loads are shed.

After a period of time, a fault occurs and causes **M2** to disconnect from the NMN.

The process is as follows:

1. **Expected blackout on the main grid due to a heavy storm.**
   - Planned Islanding is initiated

2. **Cooperation between NMs to disconnect at the different PCC with main grid**
   - Power reference values set in assets
   - Power in tie-line for PCC1 reduced to 0
   - Tie-line disconnected
   - New power reference values set in assets
   - Power in tie-line for PCC2 reduced to 0
   - Tie-line disconnected

   **ISLANDED NMN MODE (Figure 53)**

3. **Droop must be added to system**
   - **ES1** is set to droop mode

4. **Disturbance occurs in NMN**
   - Islanding is initiated in **M2**

5. **M2** performs islanding
   - Tie-lines to NMN disconnected

   **M2: AUTONOMOUS MODE (Figure 54)**

6. **Droop is added to M2**
   - **M2** has sufficient droop, no more is added

### 4.2 Case 2 – Islanding & Resynchronization

Case 2 is designed to showcase how Islanding and Resynchronization of a NM is performed and the effects it has on the NMN as a whole. These two functions are performed for **M2**. The NM is expected to remain stable when operating in islanded state as well as be capable of synchronizing and connecting to the NMN.

Following the detection of an issue, the tie-lines at both PCC in **M2** are disconnected. The M+ system then sets **ES1** into droop mode to provide support and regulation. Loads may or may not be shed and that would depend on the capability of the generators present at the time. Normally, **M2** is able to support all of its load.
When it is safe to reconnect to the NMN the resynchronization phase begins. The PCC2 located at the tie-line to M3 is chosen as the first point of connection. The frequency is then adjusted through generation increase/decrease using a new reference frequency, $\omega_{ref}$.

The grid voltage is adjusted and the phase is matched. Once synchronization is achieved the link is connected and powerflow commences. To connect the second PCC to the NMN, the voltage is matched at PCC1 which links to M1. Since it is the same grid the frequency and the phase are the same and hence do not require additional effort.

The process is performed in the following way:

1. Disturbance in NMN detected by M2.
   - Tie-line to M1 and M3 disconnected

   **Autonomous Mode (Figure 55)**

2. Droop is added to system
   - ES1 is set to droop mode
3. Healthy Grid detected.
   - Resynchronization initiated
4. Frequency, phase and voltage at PCC to M3 is adjusted
   - New $\omega_{ref}$ set in ES1
     - Voltage is matched using one of methods presented in section 3.3.1
5. Synchronization achieved
   - Close circuit breaker when phase is matched

**GRID CONNECTED NMN MODE (Figure 54)**

6. Connect tie-line to M1
Voltage is matched again at the new PCC

NORMAL OPERATION (Figure 56)

4.3 Case 3 – Black Start Operation

For this case all the grid components are de-energized and disconnected, as seen in Figure 57. All the microgrids are islanded and the NMN is disconnected from the main grid. The feeder connections are also open.

Then, in each microgrid the units capable of black-starting are started. This would energize the network and bring up the voltage. SM1 would start up to initiate Microgrid 2. Microgrid 3 and 4 are energized by SM2 and SM3 respectively. M1, however, is incapable of black-
starting and must be energized by another microgrid after the other NMs have been brought online.

After the network in each microgrid is energized, loads are added to absorb the injected power. The generation is then further increased if possible. **M2** and **M3** would connect additional generation whilst M4 does not have additional generation. The load is again increased further and this process is repeated until the network is brought up. When **M2** is energized, it would connect to **M1** to energize its network and establish a voltage so that the **PV** may connect.

Following the energization of all the microgrids capable of black-starting, one would connect to the NMN to energize it. Once the NMN has been energized the remaining microgrids are connected.

This case is implemented as follows:

1. Grid can be restored
   - *Initiate blackout function*
2. Black-start capable generators are started (Figure 58)
   - *SM1 is started*
   - *SM2 is started*
   - *SM3 is started*
3. Load & Generation is added slowly
4. Microgrids brought up (Figure 59)

**AUTONOMOUS MODE**

5. Connect to the NMN/Energize NMN
   - *Synchronize/Energize*

**ISLANDED NMN MODE**

6. Nested Microgrid Network brought up
   - Energize other microgrids
   - **M1** is brought up (Figure 60)
7. Ensure NMN is healthy
8. Check if main grid is healthy
   - Synchronize

**GRID CONNECTED NMN MODE**
Figure 58: Case 3 figure showing black-start capable units started and lines are energized

Figure 59: Layout of system after Microgrids become energized and operational

Figure 60: Layout showing Microgrid 1 being energized through Microgrid 2

Figure 61: Layout of system with NMN energized and operational

Figure 62: Layout of system after process is completed
4.4 Case 4 – Segmentation of NMN due to overload

Case 4 begins with a fault at the PCC of MG2 causing the tie-line to disconnect. The NMN is then only connected to MG1. Overloading occurs in the system and it is determined that the issue occurs on Feeder1 which is promptly disconnected. The system remains as it is (in constant power mode) because it is operated in Grid Connected NMN mode.

After this the NMN is segmented into two parts. M3 and M4 (zone 2) are connected to the main grid and thus continue operation in the same mode. M1 and M2 (zone 1), however, are now islanded. The two microgrids would designate ES1 to droop mode in order to provide the required droop capacity.

The listed steps show the case implementation:

1. An issue causes the system to disconnect at PCC2
   o Tie-line to MG2 is disconnected (Figure 63)
2. Overload alarms activates and the issue is in NMN
   o Feeder1 is shed
3. Overload alarms activates again because the issue remains
   o Feeder2 is shed
4. NMN becomes segmented (Figure 64)

SEGMENTED OPERATION (Figure 65)

ISLANDED NMN - ZONE 1           GRID CONNECTED NMN – ZONE 2

5. Zone 1 adds droop
   o ES1 is set to droop mode
Figure 63: Layout of system after Main Grid 2 connection is lost

Figure 64: Layout of the system after feeders are she

Figure 65: Layout of system with 2 isolated operation zones
5 System Simulation and Results

Different scenario cases are designed in the previous chapter. The operational steps for these scenarios are determined and the setup is finalized. The next step is to simulate these designs for verifying system stability. It is also crucial to assess the system’s ability to stay in desirable operating conditions, i.e. the system voltage and frequency are within limits. This chapter focuses on the results of the simulations and draws conclusions on NM operation in general based on different variants of the four cases.

The simulations of the cases are done in the same sequence as the cases were presented in Chapter 4.

5.1 Case 1: Planned Islanding

This case demonstrates planned islanding as described in section 4.1. The whole NMN is islanded from both MG connections by ensuring the power import and export is reduced to zero then disconnected.

Figure 66 shows the regulation of the power flowing through the tie-lines. Firstly, loads are shed in preparation of islanding (a) to reduce the power imported. This is to ensure that available generation is sufficient for the demand in the islanded grid. Next, sources are assigned new real and reactive power references to create zero power flow at tie-line for PCC1 (b). It is then disconnected (c). The same is done for PCC2 (d) (e).

![Figure 66: Case 1 - Real and reactive powerflow at PCC 1 & 2](image)

The majority of the power and control contribution to the planned islanding is done by M2 and M3 which have the largest generation. The system parameters within M2 are shown in Figure 67, where ES1 and SM1 are contributing to the planned islanding operation.
In M3, ES and SM are contributing to the planned islanding operation and the overall system response is shown in Figure 68.
Figure 69: Case 1 – System response of PCC1 and PCC2

Figure 69 shows the real and reactive powerflow through the tie-lines which is reduced to zero before islanding.

5.2 Case 2: Islanding and Resynchronization

Using the setup designed in section 4.2 testing is done to analyze the ability of the system to maintain stability. Furthermore, a variant of the case is created in order to compare the system behavior and analyze the optimal sequence for synchronization to the NMN. In both variants of the case Islanding is performed in the same way. M2 is islanded through the disconnection of both the tie-lines at the same time. The two variants show the result of synchronization at PCC1 first vs. PCC2. The PCCs are shown in Figure 52.

5.2.1 Variant 1 – Synchronizing PCC2 First

This variant deals with the synchronization of M2 through PCC2 (connected to MG/M3) first. Then, PCC1 (connected to M2) is synchronized.
Figure 70: Case 2 - The difference in synchronization signals on either side of the PCCs for PCC2 priority

Figure 70 shows the frequency, voltage and phase angle of both sides of PCC1 and PCC2. The voltage is different at both PCCs (on the NMN side) as expected because it is a local parameter. The frequency is the same with a small steady-state error.

The frequency synchronization is done with a mismatch of 0.1 Hz with the islanded microgrid operating at a lower frequency. This error in the frequency synchronization is to allow for the phase mismatch to continuously change in the range of $-\pi < \phi \leq \pi$. The time period for the phase synchronization is longer than synchronizing time required for the voltage or frequency as can be seen and thus it is the determining factor in the synchronization timing. Once the phase mismatch is $\leq 2^\circ$, the frequency and voltage are checked to ensure that they are within the limits before the circuit breaker is closed to form the connection at PCC2 (a).

After this point, the frequency would continue to be in synch because it is a system-wide parameter. The phase would, as a consequence, also remain in synch because it can only vary if there is a frequency mismatch. The only synchronization requirement for subsequent PCC connections is the voltage synchronization. Thus, the voltage is controlled at PCC1 and once the error is within the limits, the circuit breaker at PCC1 is closed after a time delay (the delay is incorporated to ensure the system reaches steady-state) (b).

Figure 71 shows the system response in M1. The parameters are unaffected until M2 is synchronized then linked. At this point there is a small system transient and a slight change in the steady-state voltage.

Figure 72 shows the system response in M2. The response shows the islanding, transition from GNMMN mode to Autonomous mode, resynchronization process and reconnection.
Figure 71: Case 2 – System response in M1 when PCC2 is synchronized first

Figure 72: Case 2 – System response in M2 when PCC2 is synchronized first

Figure 73 shows how the frequency changes within M2 compared to the frequency in the NMN at both PCCs.
Figure 73: Case 2 - Frequency at PCC1 (in NMN), PCC2 (in NMN) and that in M2 for PCC2 priority

5.2.2 Variant 2 – Synchronizing PCC1 First

In this variant M2 is first synchronized to M1. This is done to compare the system behavior and how the choice of PCC for synchronization affects the system stability. ES1 is used for the frequency and voltage control as it is only source capable of doing so within the NM. This storage, however, is located at a distance from the PCC.

Figure 74: Case 2 - The difference in synchronization signals on either side of the PCCs for PCC1 priority
The difference in the values on either side of PCC1 and PCC2 for the voltage, frequency and phase is shown in Figure 74. With the exception of the operation sequence, a similar behavior to variant 1 is seen. One observable difference, in this case, is the larger oscillations in the phase mismatch that can be found on the PCC2 NM-side signal as opposed to PCC1 NM-side in Figure 70. The connection at PCC1 is formed at (a) and that at PCC2 is formed at (b).

Figure 75: Case 2 – System response in M1 for variant 2

Figure 76: Case 2 – System response in M2 for variant 2
The system response in M1 is shown in Figure 75. One significant impact is the connection of M2 with a weaker system. It can be observed that system responses in M1 remain very similar with exception of a slight voltage transient and a small frequency transient.

The system response in M2 is shown in Figure 76. It can be seen that system handles the synchronization without any significant transients.

![Graph showing frequency at PCC1, PCC2, and M2](image)

**Figure 77: Case 2 - The frequency at PCC1 (in NMN), PCC2 (in NMN) and that in M2 for variant 2**

Of particular interest is the frequency synchronization shown in Figure 77. It is evident that due to the location of the storage in the system, there is some difficulty in maintaining a smooth frequency compared to that observed in variant 1, where the controlling source was located near the PCC. The frequency is slowly dropping from the desired value. This could have dire consequences with the frequency dropping outside the specified limits causing inability to synchronize and re-connect.

### 5.2.3 Performance Comparison

The frequency mismatch for the two different variants is particularly highlighted in Figure 78. It is evident that the mismatch at PCC1 is not consistent and difficult to control. The oscillations vary and at some point eliminated entirely but at the wrong steady-state value. This causes phase-matching at that point to fail the frequency matching criterion. This can lead to a significant delay in the connection process.

The voltage is also difficult to control. It can be affected but not matched due to the location of the storage being far from PCC2.
Figure 78: Case 2 - Comparison of the frequency mismatch at the PCC for both scenarios

5.3 Case 3 – Black-start Operation

A black-start is simulated to demonstrate cooperation between NMs and assess the system stability under such conditions. The impact of the execution sequence on the system stability and steady-state behavior is also examined.

Three variants are created:

1. M2 is fully started up, then M1 is energized and connected
2. Priority is to connect the PV
3. Critical loads are given priority

The first scenario examines a normal situation where NMs give priority to themselves. Second scenario demonstrates a case where the objective is reducing costs and PV has low operation costs. Third scenario is if the primary objective of the system is energy security, hence, critical loads are connected as soon as possible.

5.3.1 Variant 1 – Standard Black-start

A standard black-start operation scenario was designed where the NM prioritizes itself. Thus, M2, first brings all of its loads online, adding generation if required. Then and only then does it connect to M1 to energize it. With a voltage present, M2 begins to connect its loads and sources. This is done because M2 is capable of black-starting whereas M1 is not.
Figure 79: Case 3 - System response in M1 for standard scenario

Figure 79 shows the system response for M1. M1 is not energized until M2 is fully restored. At this point M1 is connected and the voltage in M1 is brought up. This is evident by the presence of a voltage at the load terminals at 10 seconds. Once M1 is energized the PV is connected to provide power into the system since it has low operation costs. Load 1 is then connected. Load 2 remains disconnected because the network cannot support anymore loads.

Figure 80: Case 3 - System response in M2 for standard scenario

Similarly, the system response for M2 is shown in Figure 80. SM1 is started to energize the microgrid at (a). With the presence of a source, a voltage and frequency becomes present in the
NM. Progressively, loads and a storage unit are added with the SM1 increasing or decreasing its output accordingly. ES1 is connected at (b).

![Figure 81: Case 3 - Frequency within M1 and M2 for standard scenario](image)

The frequency during the simulated period is shown for both NMs. At 10 seconds the two microgrids are connected and the frequency begins to synchronize (c). The PV is connected at (d), the frequency drops temporarily as a result of this. After a period of time the two microgrid frequencies begin to follow the same response. There is a steady-state error; however, this is expected to diminish with time.

### 5.3.2 Variant 2 – Black-start with PV priority

The same case is tested with a different sequence of operation to observe the behavior. In this variant, following the energization of M2 at (a), M1 is connected to be energized at (b). The PV is then connected at (c). This is done because PV offers power at a low production cost so it is economically desirable to run PV as much as possible. As done previously, the system response for M1 and M2 is analyzed. M1 and M2 are represented by Figure 82 and Figure 83 respectively. ES1 is connected at (d)

A comparison is drawn between the frequencies of the two grids shows that the steady-state value is similarly stable with a smaller offset between the two NMs. This is due to the fact that the PV has been synchronized to SM1 for a longer period of time allowing for the gradual elimination of the steady-state error.
Figure 82: Case 3 – System response for M1 during PV connection priority scenario

Figure 83: Case 3 – System response for M2 during PV connection priority scenario
5.3.3 Variant 3 – Black Start with Critical Load priority

The last variant created is the simulation of Black Start with the priority of connecting critical loads first. The critical loads are present in M1 and M2. Therefore, the first step after energizing M2 at (a) and connecting the critical load is to energize M1, (b), and then connect the critical load within that NM. The PV is then connected at (c) followed by the rest of the loads and storage.
The system response of M1 and M2 can be seen in Figure 85 and Figure 86 respectively. Figure 87 shows the frequency within M1 and M2. ES1 is connected at (c).

![Graph showing system response for M1 and M2](image)

**Figure 86: Case 3 – system response for M2 during the critical load priority scenario**

![Graph showing frequency within M1 and M2](image)

**Figure 87: Case 3 - Frequency within M1 and M2 during the critical load priority scenario**

### 5.3.4 Comparison of Execution Order

The frequency of M1 is compared for the different variants in Figure 88. The different execution sequences provide the same results. The steady-state value in the end is identical as expected, due to the overall generation and load being the same. The only difference is the system level
transients. A large dip in frequency can be observed following the integration of the PV into the system. It can be concluded that the early integration of the PV would result in less system transients. Furthermore, there are no drawbacks from prioritizing cheaper energy or more critical loads when executing a black-start sequence.

5.4 Case 4 – Segmentation of NMN

As designed in section 4.4, a sequence of faults causes several of the feeders to disconnect. M1 and M2 eventually become islanded as a result. Figure 89 and Figure 90 show the system response of M1 and M2 during segmentation.

PCC2 disconnects at (a) and feeder 2 at (b). At the 7 second mark (c), complete islanding occurs. ES1 changes its mode from PQ to Droop mode 10 ms later and loads are shed 100 ms after islanding. This is done to improve stability within the system. The frequency stabilizes to a value of 59.6 Hz as shown in Figure 91 which is within the expected margin.
Figure 89: Case 4 – System response for M1

![Figure 89](image)

Figure 90: Case 4 – System response for M2

![Figure 90](image)
5.4.1 Effects of Communication Delay

For the sake of comparison, the system is tested for different delays in load shedding and control operation to represent communication delays found in real life. A major note is that the control of the ES has no impact on the stability in this case. The load shedding on the other hand has a significant impact on the system frequency and stability. If the delay is increased by a further 100 ms to a total of 200 ms delay the frequency stabilizes to a much higher value of 61.7 Hz and if increased further there is a risk of transient instability.
Whilst the storage does not impact the stability in this case its presence still provides increased transient stability.

5.5 Discussion

From the various test cases it can be seen that a NM system can be created with different microgrids. It offers greater operation flexibility and different control options depending on the desired priorities.

Furthermore, the functions implemented are all stable within the system. Collaboration is key to achieve the designated goals of the NMs and it is its greatest advantage over traditional microgrids.
6 Conclusion

This thesis was initiated with the aim of conceptualizing Nested Microgrids, to describe them and evaluate potential strategies for implementation. This is accomplished with a variety of different implementation strategies and alternatives presented.

This thesis divided into multiple parts, first the term nested microgrids is introduced and defined. A number of projects were found around nested microgrids in USA and Japan.

An analysis of the control structure is then carried out followed by actual implementation options. Decentralized control is chosen as the control method to be utilized in the thesis. Decentralized control methods are found to be more practical and applicable to real-life projects, because they offer “plug-n-play” ability; ABB’s M+ system and MGC600 controllers were chosen to fulfill this role. It is theorized that the NMs can be categorized into three types: Autonomous, Dependent and Separable NMs, of which multiple configurations are possible. But it would greatly depend on the project that it is being implemented in.

A number of controllers which would be of importance to the concept are highlighted and discussed. These were the Network, Feeder and Storage Controller and the M+ System. The functions for these controllers are investigated and the ones which would change in their behavior are identified. It is found that changing from a microgrid to a Nested Microgrid alters most of the functions but some remain the same. This means, that new communication links would have to be implemented and new procedures to execute them.

Finally, test cases are created and simulated in time domain to verify the system stability as well as observe the impact of operation sequence on the system. Interesting conclusions are also drawn such as the impact of the storage droop when placed next to a large source and the impact of phase synchronization on the time required for completing the process. Another aspect, and one vital to the concept, is the cooperation of the NM such as using different NMs to provide black-start support.

In the end, one must consider what type of NM best suits the situation: for example, whether a combination of the different types is best utilized, and how that would affect the execution of certain functions. In this thesis a combination of Autonomous and Dependent NM is used for the test system.
7 Future Work

Future work should involve the communication aspect of the NM. It plays a vital role in the operation of the NM, with more assets and the addition of another layer of control for all the NM within the NMN.

Optimization of the NM operation is another important aspect. When considering multiple microgrids connected together, the operation becomes more complicated and operation sequences can be developed. This would ensure that the NMs are operating optimally, reducing cost and improving efficiency and electrical security.

Another possibility for expansion is the implementation of NMs using real-life systems to ensure feasibility in practical situations.

The effects of distributed energy storage in this system can be analyzed with emphasis on the effects on planned islanding and resynchronization and how it impacts the system stability.
8 Bibliography


   http://www.greentechmedia.com/articles/read/the-military-microgrid-as-smart-grid-asset


https://wpweb2.tepper.cmu.edu/ceic/pdfs/CEIC_05_08.pdf


http://www.poweranalytics.com/paladin-software/paladin-smartgrid/

https://dbxi.poweranalytics.io/shop/microgrid-power-management-system/


http://www.greenenergycorp.com/solutions/microgrid-as-a-service/

http://www.greenenergycorp.com/solutions/green-bus-software-platform/


