MASTER’S THESIS 2018

Optimal Operation of Smart Distribution Systems

RELIABILITY CONSTRAINED OPTIMIZATION OF AN OPERATIONAL AUTONOMOUS MICROGRID SYSTEM

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ABSTRACT

The energy industry all over the world is undergoing a transformational change, a shift which would define the way how the future of the industry would look like. The awareness towards global warming and the damage caused by conventional methods of generation has led to huge investments in the research and deployment of renewable energy technologies and their integration into the current system. The technological advancements made in different non-conventional sources of energy is really commendable and the rate at which the more mature technologies like solar PV, wind energy, etc. are being put in to application is extravagant. One of the major challenges, which the industry faces now is to integrate these energy resources in to the grid. Since the renewable resources of energy are dependent on factors like topography, location, weather etc., they are more physically distributed and have a tendency to be intermittent. Hence, the current grid facilities built according to the conventional sources of generation, are not capable of handling the uncertainty and intermittency in generation, hence not suitable for renewable energy sources, putting a constraint on the integration of such sources into the grid. Since the current grid facilities have been built over many years with huge investments, changing it completely in neither possible physically or economically in the present day scenario. The concept of microgrids has hence been a great step towards introducing more renewable generation sources into the grid without having the need to change the utility grid.

Microgrids are being adopted and implemented all across the world due to different reasons and benefits. While it is being used to provide basic rural electrification with the help of available resources like PV or biomass in developing countries, on the other hand, it is being used to have a resilient electric distribution in areas prone to natural calamities and disasters. Along with the technology, various new business models related to microgrid organization are also coming up, benefitting the customers economically and creating more business opportunities.

Keywords: Microgrid, Optimization, Reliability, ENS, Unit Commitment

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1. INTRODUCTION

There has been a rapid growth in the installation of renewable energy sources throughout the world in the past few years. Figure 1 shows the investment of Germany in different renewable energy source from the year 2000 to 2016. Figure 2 shows the increased solar and wind capacity in United states by 2018. This growth in renewable energy around the globe has led to a change in the way we have been using the energy and our energy systems till date.

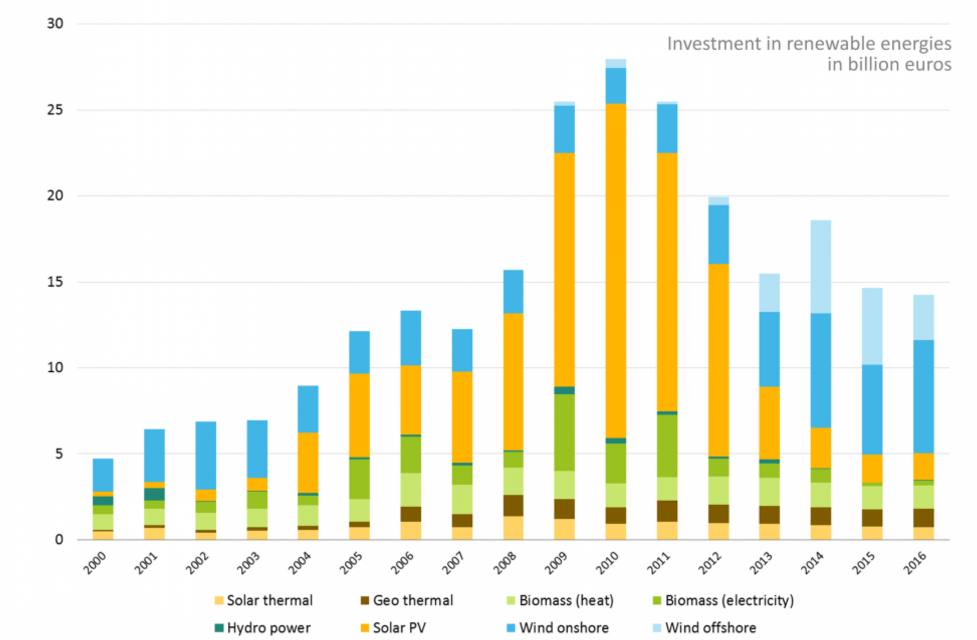

Figure 1 U.S. installed solar and wind capacity [1]

The way the energy transmission and distribution works with the conventional generators is completely different as compared to that in case of renewables. Conventional generators can be switched on and off according to the whims and fancies of the customers because they run on the burning of fossil fuels, which can be stored. On the other hand, most of the renewable energy resources like solar, wind, tidal energy etc. could be utilized only when they are available. It's not possible hence to use the fuel according to our wish in this case. But, it cannot be expected from the consumer to change behavior accordingly. Hence, there is a need of smarter system in order to make the efficient use of these free energy resources available to the humans in the nature.

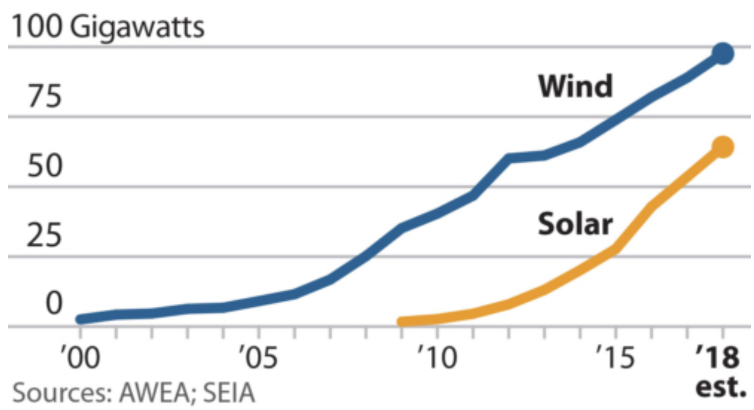

Figure 2 U.S. Installed capacity [2]

Considering the current energy scenario, moving more and more towards the green generation, it has become very important to develop the distribution system in a smart and greener way, in order to be competent and ready to be able to complement and apply the changes in our energy generation and distribution system. Microgrids are being researched and developed continuously as they can act a huge link for the higher share of renewable integration in the current grid system.

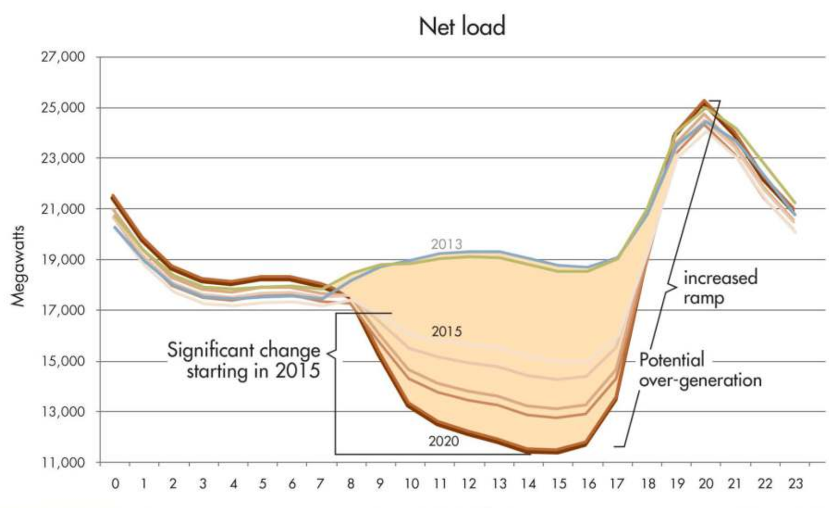

Figure 3 Duck Graph showing the growing need for flexibility [3]

Figure 3 represents a duck graph for California which shows the growing need of flexibility in the system. The graph represents the expected load in a system through the course of a day. With the increase in solar installations across the world, the load on the transmission and distribution system during the daytime is getting lower and lower. This leads to an increased ramp in the later part of the day, represented by the elongated neck of the duck curve for the year 2020. This could be met either by over-generation or increasing flexibility of the systems. The existing infrastructure for the whole transmission and distribution system is based on conventional sources of energy generation and hence lack flexibility required to include the unpredictable non-conventional energy sources. Microgrids are made up of several components and its very important for all these components to work in a synchronized way to obtain efficient and reliable results.

With all the different parts involved in a microgrid, there are different parameters influencing each other in different ways. The most reliable way of designing or operating the microgrid might not be the most economical solution. So it’s very important to find the optimal value of all the parameters involved in the functioning of a microgrid, in order to have get the best output from the system. The project focusses on the operational optimization of a microgrid with all its components under a practically constrained scenario. An optimization equation has been developed considering all the parameters present in a functioning microgrid and appropriate constraints have been applied. The equation is then subjected to four generation variation scenarios.

2. BACKGROUND

2.1 MICROGRIDS

According to the U.S Department of Energy Microgrid Exchange Group [4]:

"A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode."

Microgrids are LV distribution systems consisting of distributed energy generation and energy storage units included in the system, which can be operated in both autonomous and grid connected modes. The difference between a microgrid and a passive grid penetrated by micro-resources lies in the way of management and coordination of resources available. A microgrid operator has to perform the functions of an aggregator for small generators, a network service provider, a load controller as well as an emission regulator and could serve multiple objectives at once: technical, economic and environmental. Microgrids are, hence, beneficial for both the grid as well as the consumers. From the point of view of the grid, it can be operated like a single aggregated load, which could be a means of remuneration and could also act as a small power source for providing normal or ancillary services. For the customers, it improves local reliability, reduces emissions by allowing higher integration of renewables and enhances power quality by supporting voltage dips, hence reducing the cost of energy. The most important feature of the microgrid is its capability to isolate itself from the utility grid and operate in islanded mode during events effecting the grid like faults, black outs etc. Once the stability and the power quality are regained, the microgrid should be able to establish the connection with the utility distribution network without any interruption. There is also a possibility of intentionally disconnecting with the utility grid in case of maintenance or reduction in power quality from the grid. A typical microgrid consists of dispatchable and non-dispatchable generating units, a communication network for the exchange of information, a Microgrid Central Controller (MGCC), Local Controllers, local loads and a point of connection to the main grid called the Point of Common Coupling (PCC).

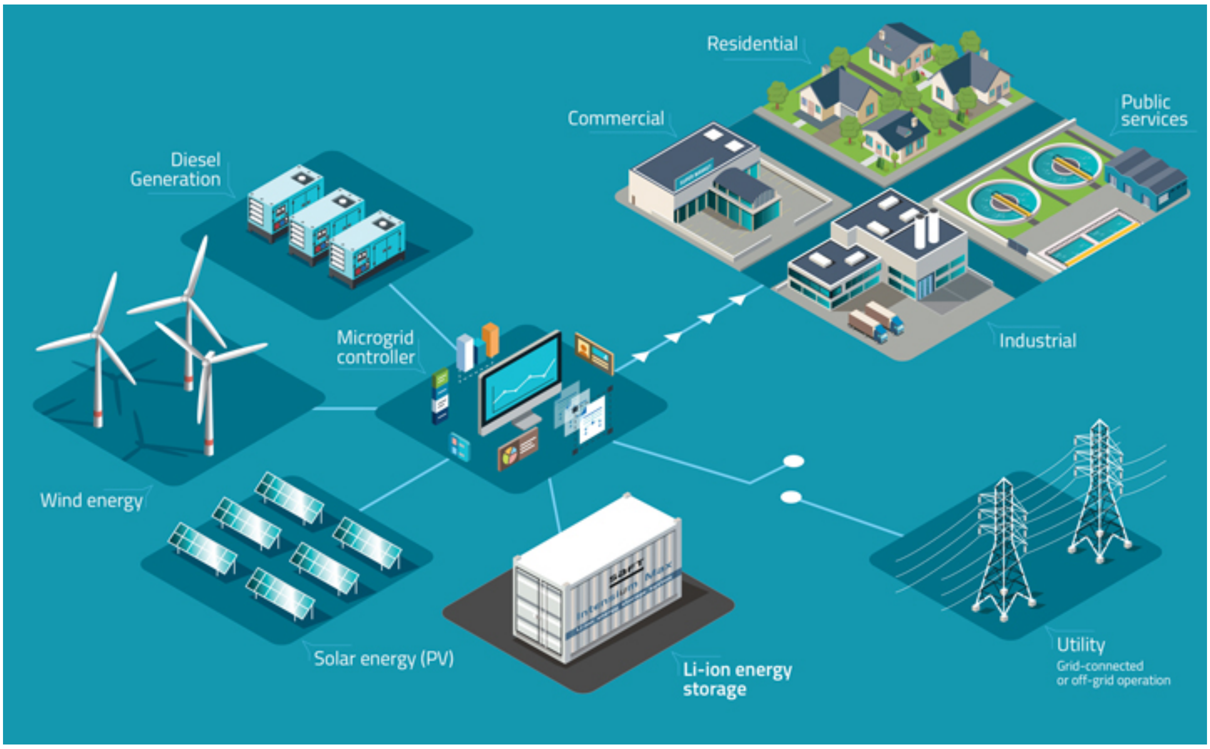

Figure 4 Example of a microgrid with Li-ion storage [42]

2.2 MICROGRID ARCHITECTURE

Microgrid architecture could be AC, DC or Hybrid based on the requirement, existing infrastructure of the grid and application.

AC MICROGRID

An AC microgrid has all the generation, distribution and loads in the AC form. The interfacing of the distributed energy sources and energy storage systems to the AC network is done through inverters since all the energy produced need to be converted into AC within the frequency and voltage regulations of the utility grid. Majority of the microgrid systems existing currently are AC. A major reason for the situation is the existing grid infrastructure, which is AC and hence eases the design and implementation of AC microgrids. The fact that the technology has been in use for years makes it safe and reliable to implement makes it more convenient.

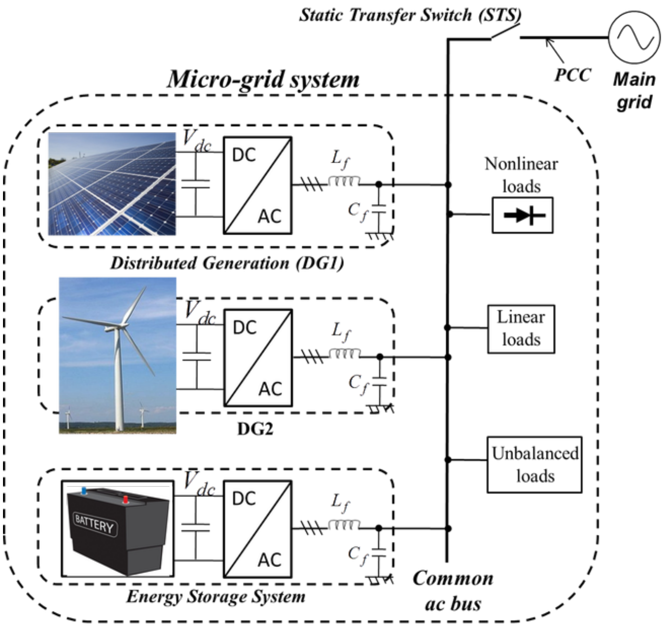

Figure 5 Example of an AC microgrid system [5]

DC MICROGRID

A DC distribution system is a better way of transmission as it has lesser losses and more efficiency as compared to the AC system. There is no reactive power in the system, hence the capacity of the system is enhanced and lesser conversion stages for all DC based generation units make it more efficient. The voltage control in these systems is simpler and there are less stability issues. The transmission losses in the system are reduced to a great extent and the need of synchronization is also eliminated. However, the drawback in such a microgrid could be the need of AC/DC conversion for all the AC sources and at the point of connection to the grid. The other disadvantages could be the requirement for over current and short circuit protection. This kind of microgrid is more beneficial if the majority loads in the system are DC. With the increasing number of DC devices in the energy sector, these microgrids could be the way to future.

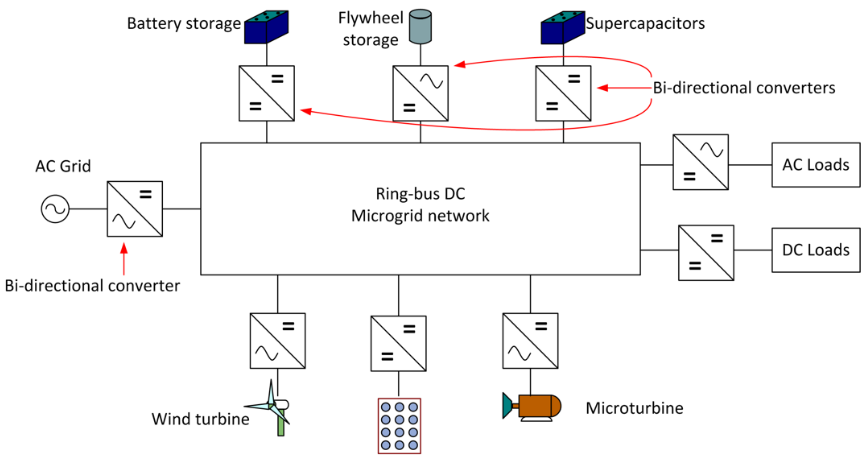

Figure 6a DC microgrid : Ring configuration [6]

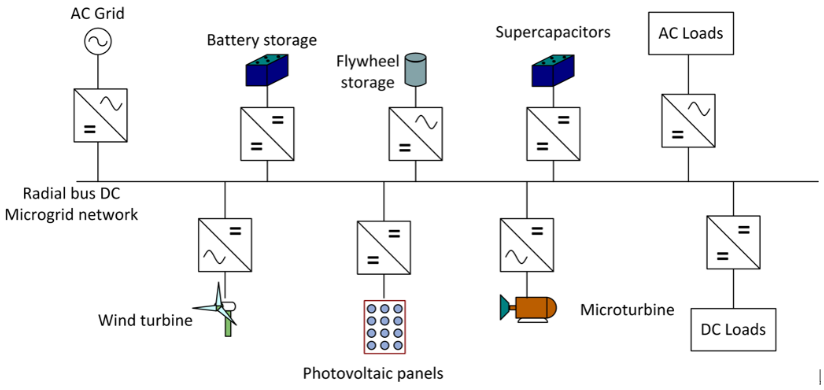

Figure 6b DC microgrid : Radial configuration [6]

Two different configurations of the DC microgrid are shown in the figures above. The first depicts a ring configuration of the microgrid whereas the second is a radial formation.

HYBRID MICROGRID

These microgrids contain both AC and DC sections, separated according to the generation sources and the loads. The energy conversion between AC and DC sections is optimized to reduce the conversion loss and hence utilize the concepts of AC and DC in the way to have an improved efficiency. It provides a perfect path in between the two systems and hence integrate the reliability of the existing AC infrastructure, to the more productive DC infrastructure with lesser losses.

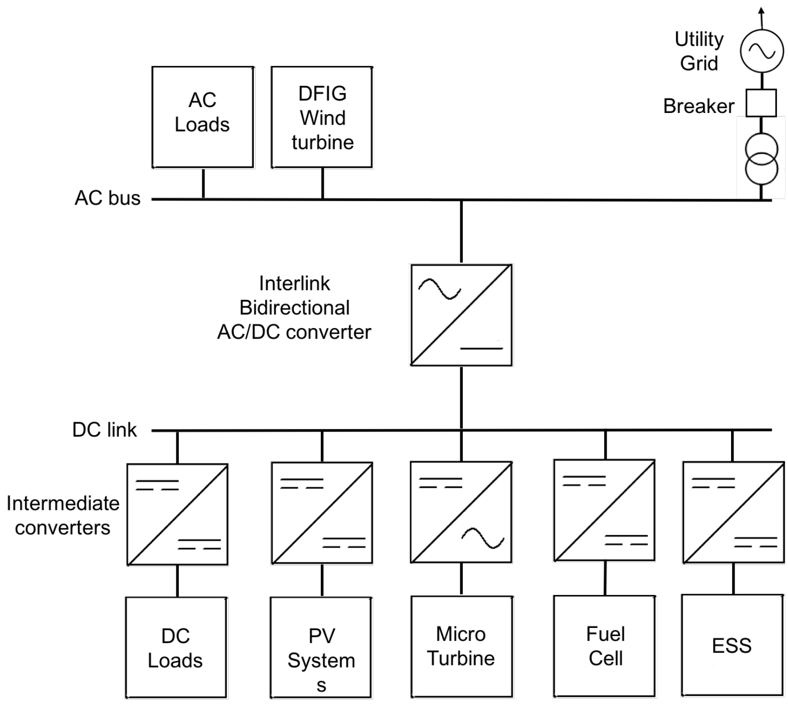

Figure 7 Structure of a Hybrid Microgrid [7]

As it can be clearly observed from Figure 7, the AC and the DC parts of the microgrid system are connected to two different buses, AC and DC respectively and similar types of loads or generators are connected to each bus. The two buses are linked by a bidirectional AC to DC converter, hence ensuring the synchronization in the system. The AC bus in the system is then connected to the utility grid facility. The intermediate converters in the DC link are required to maintain the uniform voltage level in the DC link bus.

2.3 MICROGRID CLASSIFICATION

There could be different types of microgrids based on their application. The Berkeley Lab supported by the U.S Department of Energy classifies microgrids into four categories [8]:

1. CUSTOMER/ TRUE MICROGRIDS:
   The most of the known demonstrations of microgrids belong to this category. These microgrids are self-governed and are connected to the grid through a single point of common coupling (PCC). They work in accordance to the customer requirement and there are fewer regulatory restrictions imposed on these microgrids. These microgrids could be easily integrated into our current electrical grid and regulatory structure.
2. UTILITY/ COMMUNITY MICROGRIDS:
   These microgrids are similar to the True microgrids in the technical aspects, but have a completely different regulatory and business model. A segment of the microgrid is regulated and hence the utility grid is incorporated in the system in a more established way. The regulations and restrictions imposed on the microgrid are according to the utility regulatory structure and the microgrid must comply with them.
3. VIRTUAL MICROGRIDS:
   Virtual microgrids consist of distributed resources at multiple sites, presented to the utility grid as a single entity, hence forming a virtual network. This would imply that all the DERs included in the virtual microgrid are coordinated in the same way as the in a physically integrated microgrid. Like any other microgrid, the system must be able to perform as a controlled island or multiple coordinated islands, in order to be classified as a virtual microgrid.
4. REMOTE POWER SYSTEMS:
   As the name suggests, these microgrid systems are established in the places which are off the grid. The system has similar components and operation, but unlike the above mentioned microgrids, it works as an isolated system. The system needs to be reliable and resilient, hence the generation and storage should be designed in a way to be able to support the system in case of an event.

2.4 MODES OF OPERATION

A microgrid could have two modes of operation: grid connected and islanded. Point of Common Coupling (PCC), which acts as the link connecting or isolating the microgrid and the utility grid, plays a very significant role in the shift in modes of operation.

GRID CONNECTED MODE

A typical microgrid works in the grid connected mode majority of the time. It stays connected to the utility grid throughout the operational period, exchanging the energy with the grid. The frequency and voltage of the system are determined by the grid. The local sources at the microgrid provide the active and reactive power at fixed set values. The microgrid could export the excess energy produced when the local demand is low and could import energy from the micro grid when the generation in the microgrid does not suffice to meet the local demand. This could lead to intermediate business models which could be mutually beneficial for both the customer and the utility grid.

The connection to the utility grid ensures that the demand in the microgrid satisfied at all the times. Hence, the main aim of the microgrid operation in the grid connected mode is to maximize the revenue.

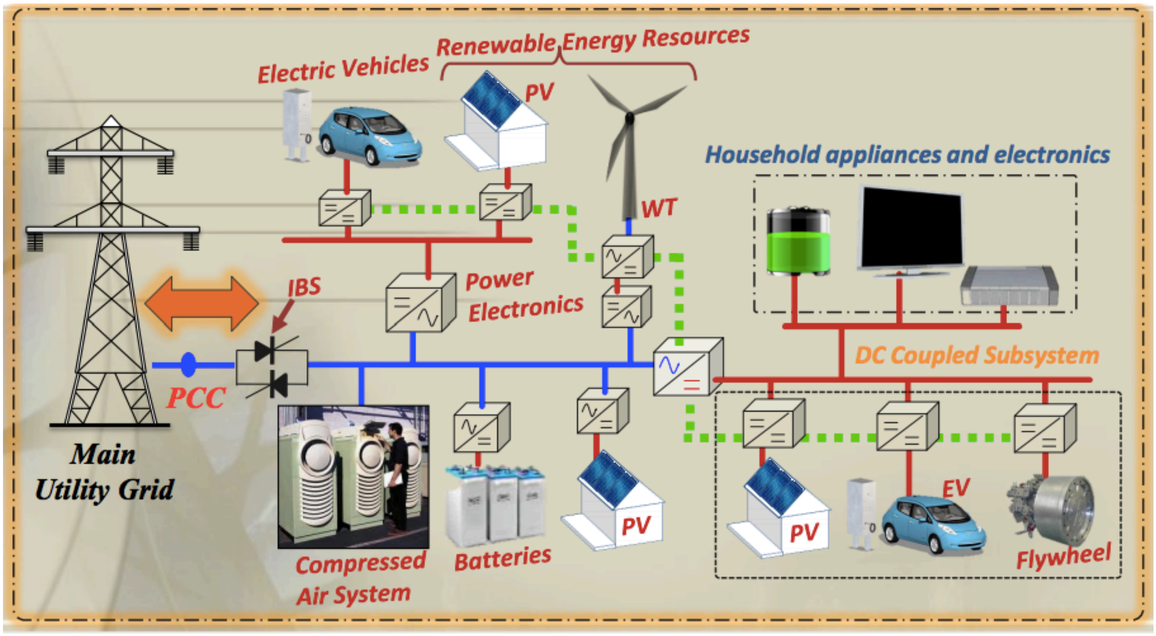

Figure 8 Microgrid operation in grid connected mode [9]

ISLANDED MODE

The microgrid is isolated from the utility grid in islanded mode of operation. There could be different reasons behind transition of a microgrid from grid connected to islanded operation. The most frequent reason for this shift is an outage at the main grid due to a predictable event like a storm or other such calamities. Since the utility grid is absent, it is very important for the system to be able to be support the loads until the grid connection could be restored again. The microgrid generation and energy storage system should have enough capability to keep supplying the customer loads for a short period of time.

In the islanded mode of operation, meeting the customer demand and ensuring them reliable power supply is the highest priority instead of economic gains. Since the microgrid has to support the whole system through its internal generation and storage, it might have to cut unnecessary loads at times in order to supply the more important ones.

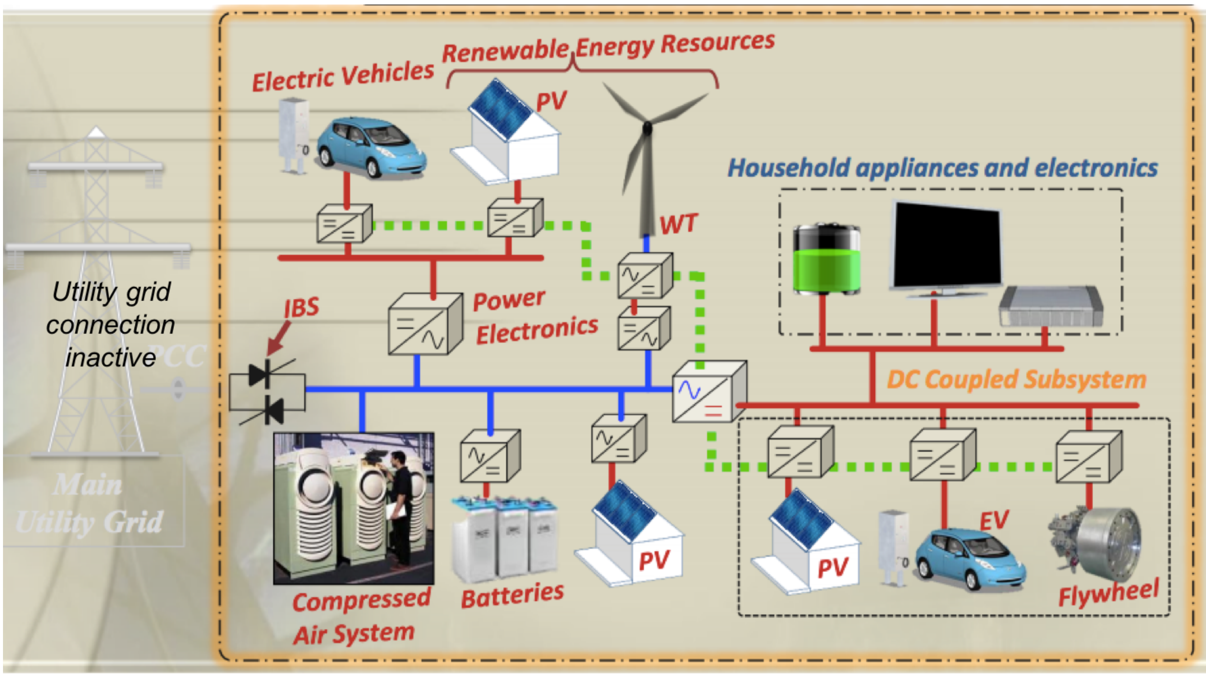

Figure 9 Microgrid operation in islanded mode [9]

2.5 MICROGRID COMPONENTS

A typical microgrid is a network made up of different components, all working together in synchronization, balancing the generation and consumption at any particular point of time. The quality of the microgrid to have the capability of working in the islanded mode in case of an event or other occurrences makes it more important to maintain the balance, with importing only an optimal amount of energy.

DISTRIBUTED ENERGY RESOURCES

According to Consortium for Electric Reliability Technology Solutions (CERTS) [10]:

"Distributed Energy Resources (DERs) are autonomous generating, storage and load control technologies that are located at customer premises and operated for customer's benefit."

A microgrid should have both renewable and non-renewable sources of energy in order to have a more reliable operation. In the case of a microgrid, the most common renewable energy resources are PV and wind, which are connected to the microgrid through a current source inverter in order to operate a maximum power point. Apart from the renewables, CHP (Combined Heat and Power) units could also be very frequent sources, providing electricity as well as heat, which makes them more interesting options for remote microgrids. There could be synchronous generators connected to the microgrid which are commonly driven by natural gas or diesel engine, which act as a perfect backup in case of emergencies. Renewable sources are a desirable part of the microgrids as they have negligible operating costs and CO_2 emissions, hence contributing to the sustainability and improving the carbon footprint. But they have a disadvantage of being unpredictable and uncontrollable, hence could not be the only sources of generation especially in microgrids which is supposed to operate in islanded mode.

Distributed Energy Resources could be classified broadly as dispatchable and non-dispatchable types. Dispatchable resources consist of the DERs which are controllable and could increase or decrease their production according to the requirement. Coal, natural gas and diesel generators are good examples of dispatchable generation, while the only renewable sources which could be classifies under this category are biomass, geothermal and ocean thermal energy conversion sources. Non-dispatchable generators, on the other hand are not flexible and cannot be controlled. These generators are more unpredictable and depend on more altering factors like weather. Solar and wind power are most extended non-dispatchable generation system in the grid at present.

LOADS

Different types of loads could be present in a microgrid and hence management of these loads is a very important aspect of microgrid control. It becomes more so necessary during the islanded operation of the microgrid as the system might not be able to supply all the loads at all times. Hence, load prioritizing and control is required. The different loads could be categorized as fixed or flexible depending on their significance. Fixed loads cannot be disconnected under any scenario and hence its essential to supply them at all the times. Flexible loads could further be classified as essential, priority and non-priority loads, depending upon the time within which you need to full fill the need in case a load demand comes up. While essential loads need to be connected within seconds of the emergence of demand, priority loads have a buffer time of few minutes. Non-priority loads could stay disconnected for long periods of time in case the available generation or storage in the microgrid is not sufficient.

In the case of a smart distribution system, these controllable loads are capable of communicating with the microgrid control system and hence, exchanging real time information. With the known levels of demand at the micro grid central control, the information could be passed on to the customers and they could participate in Demand Side Management (DSM) by making adjustments in their loads. While common controllable loads like refrigerators, air conditioners, water heaters etc. are controlled by load management programs others like battery storage, vehicle-to-grid, heat storage etc. are more likely to participate actively.

ENERGY STORAGE SYSTEM

Energy Storage System (ESS) provides the microgrid, the back-up and support needed in case of a grid event or under the conditions of isolated operation. The ESS could store the excess energy produced from the intermittent resources during low demand, hence saving the extra energy produced. It helps out in smoothening the uneven generation curve by the intermittent sources, hence stabilizing the supply. As a result, there could be higher percentage of renewable integration into the microgrid since ESS ensures the reliability and resilience of the system.

In the grid connected operations, the ESS could help in peak shaving, hence reducing the economic impact on the consumers. Since utility substations have a limited capacity, an ESS connected to a microgrid could help them by providing for the excess energy at peak demand hours, which otherwise could have been resulted in the requirement of an additional substation or making an upgrade, both causing huge expenses. It also helps in reducing the peak generation capacity of the microgrid, as energy storage could act as a generating unit, supplying the energy at peak hours, leading to a better design and optimal use of energy produced. Presence of an ESS also helps in stabilizing the voltage and frequency, maintaining the quality of power supply and making the system safer.

During the transition from utility connected to island operation, fast response and high levels of coordination are required to control the system, where the ESS with batteries prove to be very crucial. During an outage, proven technologies like Li-ion batteries could guarantee instant power and quick response during the transition conditions supporting the system for a short time period, until the generators could be able to serve the loads. Moreover, in a grid connected system, they could result in additional revenue model by storing the energy during low demand hours and selling them to the utility grid during the peak hours at higher prices. Figure 10 below depicts the classification of different storage systems used in the current times.

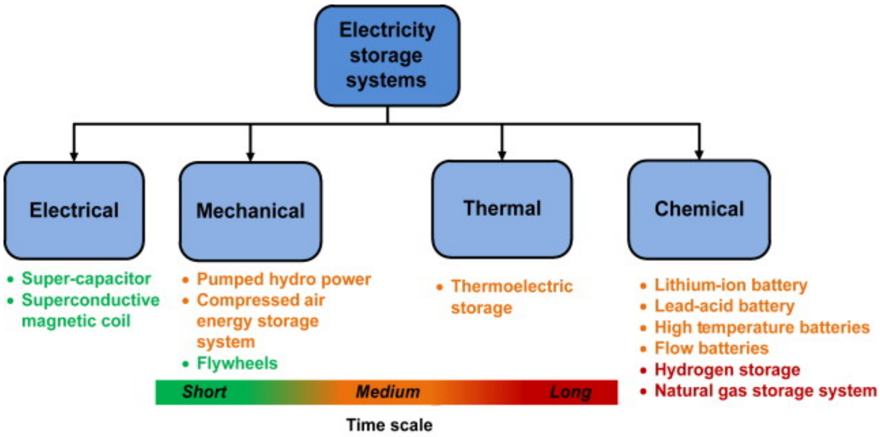

Figure 10 Classification Energy Storage System [11]

COMMUNICATION AND CONTROL

Microgrid control is a challenging work because of the complexity of the system. With predictable or defined loads and unpredictable inputs, different strategies like DSM have been emerging to manage the imbalance especially in case of islanded operation. These factors have been urging the need for better control and information exchange within the microgrid.

Microgrids could have centralized or decentralized control systems. In a centralized control system, all the assets are managed by a central controller, to which all the components of the system communicate. A decentralized system on the other hand uses distributed controller scheme, where each component has its own controller and is self-governed. All the components exchange information continuously with each other through a communication network and hence work in a synchronized way. The benefit of having a decentralized control is the enhanced reliability of system, unlike the centralized control, where failure of the central controller could cause failure of the whole microgrid. It also provides better and easier expandability to the system, making it flexible for future changes. The drawback of a decentralized control could be the conditional operation of different components of the system at a local optimum rather than the global optimum, which would affect the efficiency of the system. Hence, the decision of choice between centralized and decentralized control is a trade-off between the parameters of reliability, flexibility and efficiency; and could largely depend on the requirements of the application area.

POINT OF COMMON COUPLING

Point of Common Coupling (PCC) is the point where the microgrid is electrically connected to the main grid. There are various standards that need to be followed in case of interconnection of the utility grid to a local generation source or a microgrid which impose certain regulations on the local assets. The connection could be done directly through circuit breakers or static switches, which are less complex and less expensive, but the possibility of power flow control is absent in both the ways of connection.

Power electronic interfaces, hence, provide a better way of connection to the main grid. They are capable of providing active and reactive power control, hence making the system more flexible, though at a higher expense. A circuit breaker at the grid side terminal of the power electronic device would still be required, in order to provide a physical way of disconnection in case of any event.

2.6 ADAVNTAGES

There are many demonstrations of microgrids present currently, which have been working successfully and proving the anticipated benefits of the technology to be true. Microgrids have been beneficial not only for the local customer or community which they serve, but also for the utility grid system connected to them, hence being established as a single solution to different affairs. Different benefits of microgrids could be listed as follows:

1. RELIABILITY:
   Reliability is the most important factor when an operational grid is under consideration and hence is given the utmost importance. Power outages could be very dangerous for facilities like hospitals and in case of a grid event caused by a natural calamity, it becomes very important to be able to supply such important loads. There have been examples where microgrids have successfully supplied power while the grid had failed due to the occurrence of storms. The capability of a microgrid to isolate itself from the main grid helps it to avoid any damage being caused to the local supply. After islanding, the microgrid's generators and energy storage systems supply the local loads until the supply is restored in the main grid, hence enhancing the reliability of the system.

2. RESILIENCE:
   Resilience is a factor which could be described as closely related to reliability. Reliability is the quality of the grid to keep the supply on, while resilience is the ability of the grid to avoid power outages and recover quickly in case of the occurrence of an outage. Microgrids could be programmed to have priority in serving the loads, hence only serving the most important loads in case of an outage. Critical loads like hospitals could be provided the highest priority, so that they could keep functioning while avoiding the unnecessary loads, using the minimal required power. The facilities could start their normal operation more quickly once the grid is repaired as they were not completely shut down

3. ENERGY COSTS:
   Microgrids perform the efficient management of energy in the distribution system, hence leading to cost and energy savings. The advanced microgrid controllers could be programmed in to detect the increase in electricity process in the grid and reduce the grid consumption during

those hours averting to the local production and controlling non-priority loads. Moreover, they can also be a source of revenue by selling energy to the grid, hence making the consumers directly involved in the energy markets. Customers can produce, control and sell their energy through the microgrids and hence act not only as consumers but also producers, i.e. prosumers. Microgrids could also participate in demand response programs and similar state run initiatives, leading to a more sustainable use of energy, while providing the customers monetary benefit.

4. STRENGTHENING THE GRID:

   Microgrids could act as an important support to the central distribution system. The grid operators could turn to microgrids during peak demand hours, hence reducing the strain on the system and hence reduce the size of energy storage required. They could also provide ancillary services like frequency regulation to the grid, improving the stability and power quality of the grid. The instantaneous needs could be easily provided by the operating microgrids, by making adjustments in their generation, storage or consumption; eliminating the need for the starting up of extra generators and hence saving the costs while providing grid support.

5. GRID EXTENSION:

   Connecting the off gird areas to the main grid could be easily done through a network of microgrids. This is already being applied in developing countries where there is need of rural electrification. It gives a very practical and easily applicable solution to the inaccessibility to the grid rather than spending huge amounts of money in grid extension. Another disadvantage of the utility grid is that it is not smart and need to be modified to operate efficiently according to the modern day need. But the huge investment required in the area could be avoided by connecting more and more microgrids to the grid, hence making the extended distribution smart, so that the grid could still keep functioning while local decisions of smart operation would be taken by the microgrids.

6. EFFICIENCY:

   Microgrids are built closer to the customer and use the local DERs for the generation, which helps in avoiding line losses caused during the transmission of electricity. Reduction in line losses would hence reduce the total electricity consumption, which would in turn, avert the need to build more generation and distribution capacity. Also, the heat energy produced by CHP plant could be used locally for heating needs in a very effective way, increasing the efficiency of the overall system.

2.7 CONTROL STRUCTURE

The basic function of the microgrid control is monitoring of the system, collecting the required data from the generators and the loads to make decisions during the islanded operation, and to make sure that the system operates according to the grid regulations and requirements in the grid connected mode. Microgrids usually display a hierarchical control structure, which could be divided into four control levels.

INNER CONTROL LOOP

Inner control loop, also called as “0 Level Control”, is concerned with the very first stage of the energy generation. The unpredictability of the DERs make the generation quite intermittent and it becomes very important to have an immediate control within the microsource since it effects the interaction between different microsources present within the microgrid. The installation of intermittent microsources like PV and wind has been increasing with time and so is their inclusion in the microgrids. While PV produces a DC output, wind generation gives output in the form of AC and hence its necessary to have power electronic devices at the microsource level to control different parameters, which otherwise could cause desynchronization. The control at this level should be fast and accurate as the control outputs will be causing a change in the operating points of the microsource, the current being injected into the microgrid, as well as the frequency and voltage at the connection point to the grid.

PRIMARY CONTROL

The primary control, is the “1st Level Control”, which mainly adjusts the frequency and amplitude of the voltage reference which gives an input to the inner control loops. The voltage and frequency in a microgrid could get destabilized in case of an islanding event due to mismatch in generation and consumption of the system. The primary control is responsible for stabilizing this mismatch by causing adjustments in the reference input. This level of control also requires a very fast response time, usually in the range of milliseconds, in order to be able attend to any changes in the generation or demand. It also plays an important part of reducing circulating currents, which otherwise could cause an over-current situation in the power electronic devices in the system. Moreover, the primary control takes care of the distribution of active and reactive power among the DERs. The power converters for distributed generation could be of two types- grid forming and grid following; and based on these, there could be two different strategies for the primary control. While grid forming strategy operates on voltage control, grid following strategy is based on the concept of current control.

SECONDARY CONTROL

The primary control, though makes adjustments in the frequency through changing the reference to distributed generation units, is unable to provide the power for load-frequency control for long durations. Though the energy storage could compensate for these, their short energy capacity refrains them from stabilizing the deviations which remain for longer periods. Thus the primary control could still cause frequency and voltage deviations in the steady conditions and the responsibility of secondary control is to compensate for these deviations. The secondary control or "2nd Level Control" is responsible to restore the voltage and frequency fluctuations caused due to the primary control. The response time, in the case of secondary control is slower than the primary control. The secondary control makes sure that the deviations are regulated after every change in load or generation in the microgrid, keeping them within allowable limits. The control at this level could be classified into two categories: centralized and decentralized. In the centralized control, the Micro Grid Central Controller acts as a central controller and acts as an interface between each microgrid and the Distribution Management System (DMS). On the other hand, the decentralized control is responsible for making sure that the maximum power is being generated by the microcontrollers while at the same taking care of microgrid's cumulative capabilities to support the loads and participate in the energy market.

TERTIARY CONTROL

Tertiary control or the "3rd Level Control", is the last level of control and is the slowest among all. It operates during the grid connected operation of the microgrid, managing power flow by voltage and frequency control. It includes the economic aspects of the operation of the microgrid while optimizing the system. Apart from managing the power flows, the tertiary control also maintains the power quality at the PCC. The actual value and the required values of the active and reactive power could be compared at the PCC and hence, the tertiary control acts as an information exchange interface to the Distribution System Operator (DSO) to obtain the optimal operation of the microgrid in the grid connected mode. During the islanded operation of the microgrid, tertiary control operation is blocked.

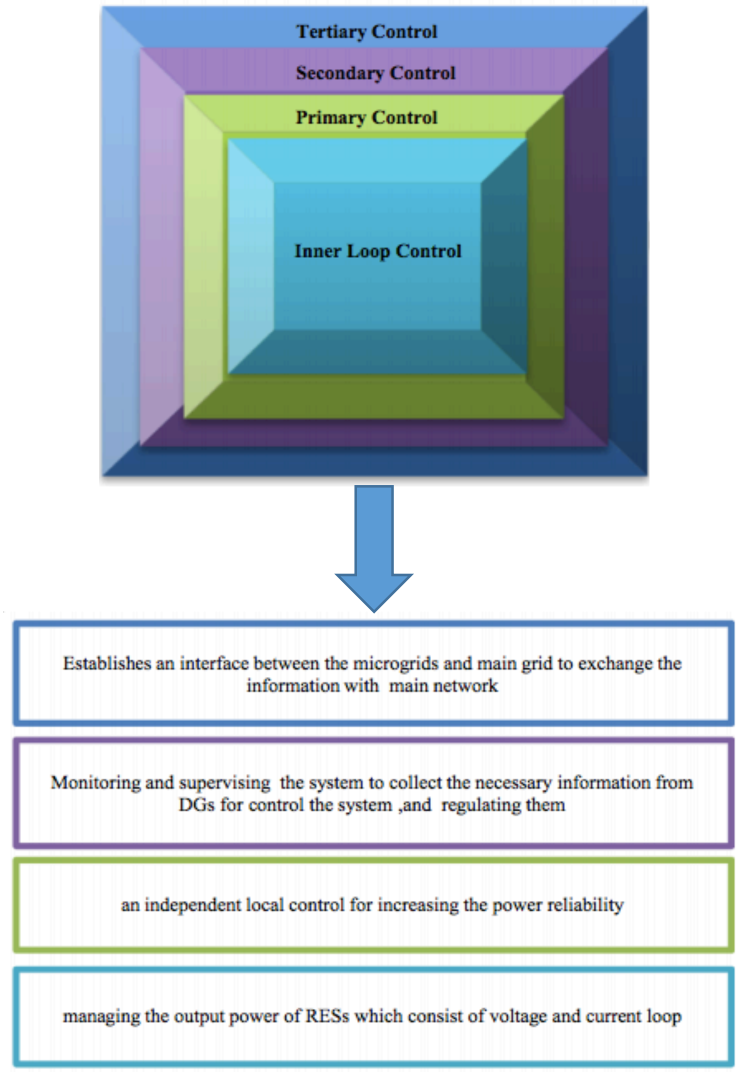

Figure 11 Hierarchial structure of microgrid control [12]

As Figure 11 depicts, the inner control loop forms the very innermost layer with the control of the microsource, the primary control manages the power reliability at the local level, the secondary control monitors the system and ensures the exchange of necessary information between the microsources and the microgrid control system, whereas the tertiary control at the outermost level acts as an interface between the microgrid control and the main grid. The level of hierarchy hence also establishes the response time of each of the control, the minimum at the innermost level to the maximum at the outermost. Figure 12 shows a schematic of the three levels of control in an operational microgrid network having AC and DC microgrids, performing the control and monitoring at local level and exchanging information with the DSO.

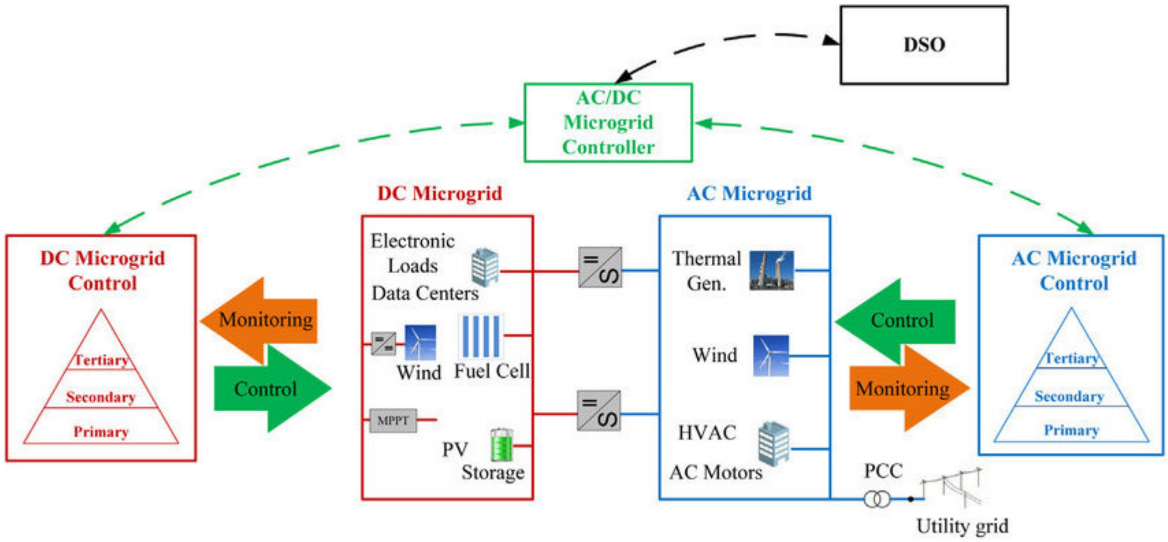

Figure 12 Control structure of a microgrid [13]

2.8 CHALLENGES

Microgrids, being a technologically new concept, have challenges in their successful implementation, which is still being researched upon. Islanded mode operation, which is the very advantage of a microgrid, provides the challenge of the stability of the system. With the smaller, size of the system, the elements present in the system are limited, providing restricted resources to be used in case of an instability event. The operation in grid connected mode is less complex, as the grid is capable of supplying the disturbances. Some of the challenges faced by a current microgrid system could be listed as follows:

1. VOLTAGE CONTROL:
   With the diversity of the DERs and loads present in a microgrid system, it becomes very difficult to maintain the value of the voltage in the network at a particular set point and the fact that these sources of generation display intermittent characteristics make the problem more complicated. Since the microgrids can transition from grid connected to islanded mode, the ability to "plug and play" could be a big challenge given the large number of DERs operating at once. The control of ESS is not sufficient to manage the deviation in voltage.

2. FREQUENCY CONTROL:
   The utility grid is connected to large generators and their inertia plays an important role in the frequency stabilization in the grid. On the other hand, the generators present in a microgrid are small in size having low inertia and systems like PV with no inertia to contribute to the network. In this situation, even small changes in load could lead to deviations in frequency. In the grid

connected operation, the restoration is easily provided by the grid but this becomes a challenge in case of islanded operation, where ESS capacity is not enough to restore the instabilities.

3. COMPATIBILITY OF COMPONENTS:

   A microgrid could have different components with different characteristic properties. There could be a variety of generators present in a micro grid like PV systems, small wind turbines, CHP, fuel cells, micro-turbines etc., every one of them having their own generation capacity, start up and shut down times, efficiency, operation costs. Apart from the generators, the system also includes inverters and ESS. Each of them have their own limitations in control and communication. Hence compatibility and integration of all the different components in a small microgrid system become a challenging task.

4. INTEGRATION OF RENEWABLES:

   Renewable sources of energy are highly intermittent in nature and depend hugely on conditions uncertain like weather changes. Hence, the power output of these resources vary constantly. Accurate forecasting and scheduling hence plays an important role in the better integration and efficient control management of the system. Moreover, renewable energy resources are non-dispatchable in nature. It has been observed that increased integration of renewable share may cause congestion in the microgrid.

5. PROTECTION:

   The fact that protection devices work on the detection of fault current makes it a difficult task to implement them to a microgrid system with the possibility of grid connection. The magnitude of the fault current may differ significantly between the islanded and grid connected modes of operation of the system. Microgrids are designed to have bidirectional flow of currents, whereas the current flow in the traditional grid facilities is unidirectional, which puts up a challenge in the design of a protection device.

6. HARMONICS:

   The presence of power electronic devices and non-linear loads in the network leads to injection of harmonics in the grid which could create distortion in voltage. Hence it becomes very important to keep the total harmonic distortion within the allowable limits, for which different types of filters are used. Increased harmonics could also cause loss of synchronization in the network [14].

7. REGULATORY CHALLENGES:

Regulation play an important part in the operation of a microgrid in the grid connected mode, However, the current regulations imposed on the microgrids are hardly microgrid friendly and hence prevent the best possible utilization of microgrids. These regulations are made based on the main utility grid, ensuring its safety and operation. There are high connectivity costs associated to the microgrid because of the connection policies in implementation at the present moment, which hinders the development and expansion of microgrids. [15]

2.9 COMMUNICATION

The communication system forms a very integral and important part of the microgrid system. The efficient operation of a microgrid system is completely dependent on the exchange of parameter information like voltage, frequency, current etc. This data has to be gathered from different sensors and Intelligent Electronic Devices (IEDs), which must then be processed, transmitted and stored in a safe and reliable way. The green dotted lines in Figure 13 below shows the flow of information within the microgrid. It transmits information from the Micro Grid Central Control (MGCC) to different circuit breakers at generators and loads, and vice versa.

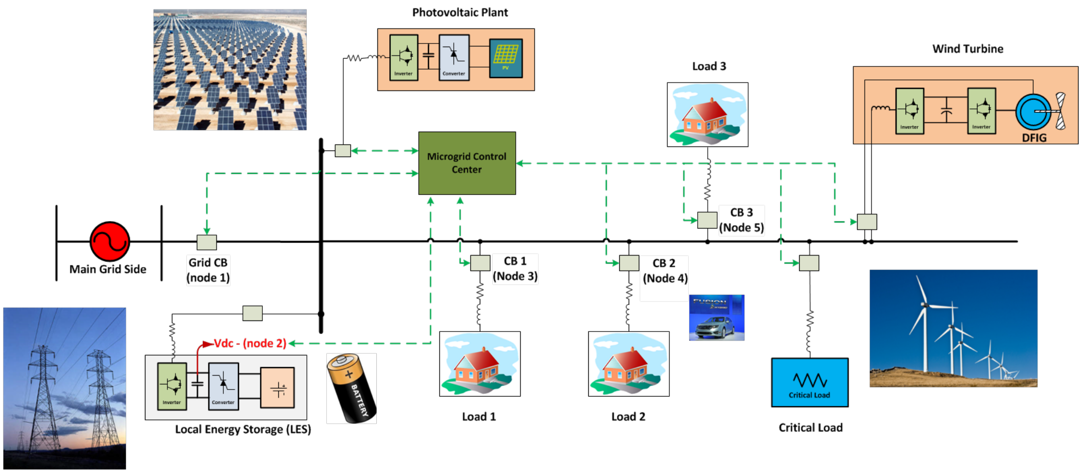

Figure 13 Microgrid communication network [16]

Communication configuration in a microgrid could be classified into three categories: tightly coupled, loosely coupled and broadcast/multicast communication [17]. Tightly coupled systems need the highest availability for the network whereas the loosely coupled and broadcast systems are capable of managing their operations in an independent manner. The Microgrid Control System uses many protocols to maintain the communication between different power system components and IEDs. The reliability and security in the communication between components is ensured by employing an internet communication protocol suite. The presence of a Human Machine Interface (HMI) for monitoring purposes, a data logger to record the system data regularly and an event recorder to record predefined events, are suggested in the communication architecture of the system. The examples of different protocols and standards used in the microgrid communication system are -Internet Protocol suite, Modbus, DNP3 and IEC61850. The benchmark used for the communication architecture of the system is called the Open System Interconnection (OSI) model, which contains seven layers, namely Application, Presentation, Session, Transport, Network, Datalink and Physical. The most widely used protocol had just four of these layers- Application, Transport, Network and Link; called as Transmission Control Protocall/ Internet Protocol (TCP/IP). On the other hand, in SCADA (Supervisory Control and Data Acquisition) systems, Enhanced Performance Architecture (EPA) is used, which uses only three of the seven layers mentioned. The application of these different suits depend on the requirement which a specific system has and hence the compromises that can be made in any specific aspect of communication.

The physical communication links used in a microgrid could be either wired or wireless. But to improve the communication and availability, the wired physical links could be integrated with the wireless links, which would help managing the data traffic in a better way. The traffic congestion speed on the physical wires could be removed by using the wireless system with higher data transfer speed.

2.10 RELIABILITY AND RESILIENCE

Since as a part of the goal, we are addressing the reliability component in the microgrid, it's very important to understand the concept of reliability and resilience. Grid reliability and resilience are two terms are used very often and sometimes interchangeably when grid qualities are discussed. Microgrids performing the same function as the utility grid with limited resources more efficiently makes it more susceptible to face certain events without sufficient back up. In grid connected conditions, there is infinite support available from the utility grid, but in the conditions of islanded operation, it becomes very important that these two factors are taken care of.

Reliability could be defined as the ability of the power system to deliver electricity in quantity and quality as demanded by the user [18]. This means that in a network with multiple user, having a consistent demand for lighting at a particular duration, the lights should be always on during the time period. Integration of renewables into the electric grid has resulted in improvement of the total system reliability and this has been observed in different countries all over the world. The graph below shows the reduction in power outage durations in different countries as more and more renewables were accommodated into the network with time and it is based on the reliability index SAIDI (System Average Interruption Duration Index). With the uncertain nature of renewable energy sources and their distributed location, connection to the grid through a network of various distributed microgrids is the best way to integrate them into the system.

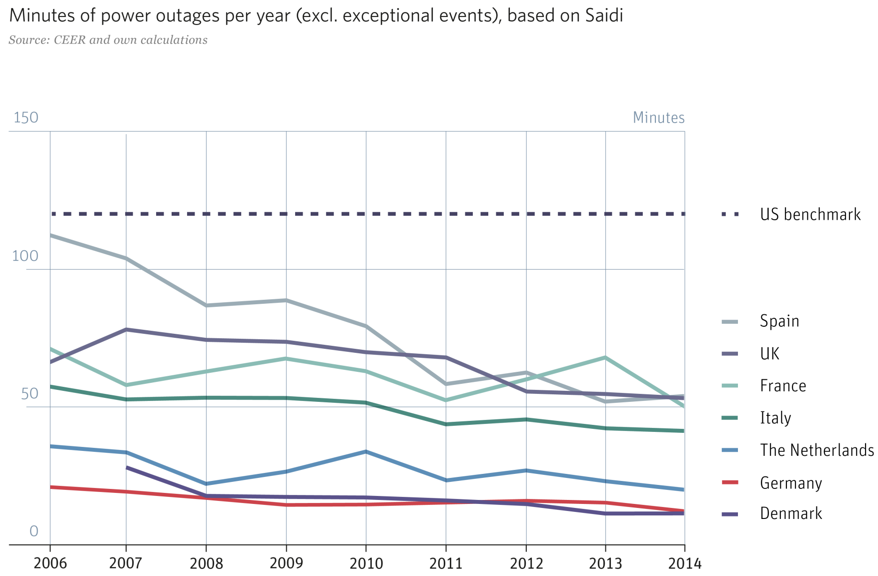

Figure 14 Reliability improvement with increased share of renewables [19]

Reliability is hence measured by the power outages that a system has faced or the loads in the system which have not been supplied. There are various reliability indices which are used in order to quantify this value. The IEEE Guide for Electric Power Distribution Reliability Indices [20] divides these indices into two categories:

1. Sustained Interruption Indices: These indices are basically based on the customer interruption duration, hence useful in the situations where data at the customers' end is available as the interruption duration and the number of customers affected. IEEE Guide for Electric Power Distribution Reliability Indices lists seven indices in this category namely SAIFI, SAIDI, CAIDI, CTAIDI, CAIFI, ASAI and $CEMI_n$.
2. Load Based Indices: These indices use the value of interrupted load in order to make the calculations, hence useful for the grid end calculations, where an aggregated value of load interrupted is available along with the total KVA served in the system. Two indices are listed in this category namely ASIFI and ASIDI.
3. Momentary Indices: These are used for the calculation of momentary interruptions and lists three indices namely MAIFI, $MAIFI_E$ and $CEMSMI_n$.

The concept of resilience, on the other hand deals with the ability of a power system to revert back and recover after the occurrence of an event. Resilience is based on the approach that disruptive events are a regular part of the power system and they should be designed to leap back to their normal operation strong and quick.

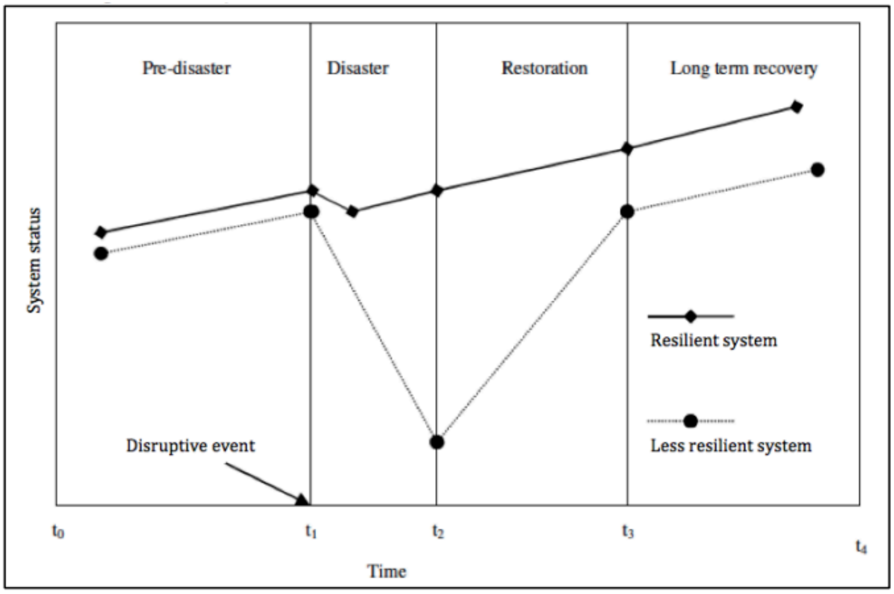

Figure 15 Comparison between a resilient and a less resilient system [18]

Figure 15 compares a resilient and a less resilient system. It can be observed that a resilient system is less effected by the event and is able to withstand its consequences, whereas the less resilient system status drops in case of a disaster and takes some time to revert back to its normal operation.

Hence, reliability and resilience, though related to each other; are two different concepts. A reliable grid need not necessarily be resilient and a resilient grid would not always be reliable. As long as the grid is able to satisfy its demands without interruptions, its reliable whereas, if the grid is able to come back quickly after an event, it is considered resilient.

3. LITERATURE REVIEW

As a part of the literature review, several research papers were studied and analyzed. The following paragraph provides a short summary on the relevant papers that were studied in order to progress ahead with the research on the topic.

The paper [21] by *Shashi B. Patra, Joydeep Mitra and Satish J. Ranade* presents the micro grid architecture with an imposed reliability constraint. A mathematical algorithm for cost optimized building of micro grids has been developed with reliability parameter as a constraint, using dynamic programming formulation. This algorithm is applied to a 22-bus system in which the load is assumed to be the peak load for all the buses. The paper provides an interesting approach on optimization but is directed towards building of a micro grid, unlike an already established micro grid in the case under consideration for this thesis. In the paper [22] by *Faisal A. Mohamed and Heikki N. Koivo*, a Multiobjective Optimization approach has been adopted, aimed at minimizing the cost while imposing system safety and customer demand as constraints. The objective function is developed with three objectives: minimzing the operating cost, reducing the emissions to the lowest and ensuring the fulfillment of load under specific constraints. The objectives are partially conflicting and possibly incommensurable, hence Multiobjective Optimization is adopted in order to produce efficient results which can compromise between different objectives.

The paper [23] by *Il-Yop Chung, Wenxin Liu, David A. Cartes and Karl Schoder* discusses the optimization of control parameters in a micro grid using Particle Swarm Optimization (PSO). The ability of PSO to escape the local minima makes it a good approach while working with complex systems. Three objectives of microgrid control are considered in the paper: control performance, power quality and steady state performance of the system. The optimization process adopted by *Shervin Mizani and Amirnaser Yazdani* in [24] is directed towards the design and operation of a grid connected microgrid. A system with dispatchable and non-dispatchable generators is defined and the optimization is carried out minimizing the life time cost or life time emission or both. In all the cost and emission equations, the grid element is included, establishing a grid connected system and system safety and demand constraints are imposed. The heating load is also included in the system satisfied by generation through a boiler or heat recovery system of the microturbine in the microgrid.

The secondary control of microgrids using a Potential Function based approach is discussed by *Ali Mehrizi-Sani and Reza Iravani* in [25]. The paper discusses the control of two microgrids configurations, cascaded and radial, on both grid connected and islanded modes of operation. It demonstrates the technical feasibility of the secondary control based on potential function. The paper [26] by *Dezheng Deng and Gengyin Li* discussed the optimized economic operation of a DC microgrid in the grid connected mode. It defines the steady state models for each of the distributed generation

(DG) units and determines the cost function of the whole system, including the environmental costs, transmission losses and the exchange costs with the grid. The constraints applied to the system are power balance, generation power limit, interactive power limit between the microgrid and the utility grid, battery operation and spinning reserve constraints. An optimal scheduling strategy has been defined for the microgrid considering the economic factors and Swarm Optimization algorithm has been used to find the optimal results for the system.

M. A. Hassan and M. A. Abido in the paper [27] discuss the modelling of a microgrid in grid connected and autonomous modes. The model includes the components (eg. controller, filter, inverter etc.) playing an active role in each of the modes, in a more detailed manner in the final mathematical representation. Different constraints are applied in each of the modes and then each system is optimized through Particle Swarm Optimization. The effect of different market policies and Demand Side Bidding (DSB) is included in the paper [28] by *Antonis G. Tsikalakis and Nikos D. Hatziargyriou* . The microgrid optimization is done according to the open market prices, the bids received by DG sources and forecasted loads by the MicroGird Cental Controller so as to minimize the operational cost or maximize the profit for the aggregator, depending on the market policy adopted by the microgrid.

The paper [29] by *Amin Khodaei and Mohammad Shahidehpour* presents an optimization of microgrid based power systems in the stages of generation and planning. The optimization includes the impact of annual reliability in the system and the constraints are accordingly added in the planning problem to update the situation. The paper [30] by *Quanyuan Jiang, Meidong Xue and Guangchao Geng* presents a double layer coordinated energy management control model for the microgrid, for both islanded and grid connected modes. In [31] the concept of nested microgrids is explained in detail along with different types, configurations and control requirements. It uses the decentralized microgrid with decentralized Nested Microgrid Network control structure to govern the microgrid, further moving on to different control functions being implemented at different levels. The different types of micorgrids classified under the category are Autonomous, Dependent and Seperable microgrids.

In [32] by *Mohammad Shahidehpour, Zhiyi Li, Shay Bahramirad, Zuyi Li, and Wei Tian*, the paper discusses the heirarchial control of networked microgrids. The paper is written based on the operation of an existing microgrid in the Bronzeville community of Chicago. The operation of the microgrid network is managed in a leader-follower mode. Primary, secondary and tertiary control of the nested network has been discussed briefly. While the paper is based on a microgrid network with two microgrids in connection, it concludes a similar strategy for multiple microgrid connected networks. The paper [33] by *Zhiyi Li, Mohammad Shahidehpour, Farrokh Aminifar, Ahmed Alabdulwahab and Yusuf Al-Turki*, discusses the improvement of power system resilience by forming networked microgrid cluster. The extreme event scenario ride through is explained through the droop characteristics and load sharing. The paper also presents a detailed illustration of hierarchical control of the system. The paper

[34] examines decentralized and hierarchical control methods for intelligent microgrids in parallel. It also includes a stability analysis on the decentralized control methods and mathematically discusses the primary, secondary and tertiary control methods for the hierarchical control.

In the paper [35], by *Marinko Stojkov, Srete Nikolovski and Vladimir Mikuličić*, there is a description of the reliability of the distribution networks in the terms of energy not supplied (ENS). It proposes a new approach for the calculation of ENS and displays the ENS values for two different powerline faults. It proposes a comparison between the proposed ENS calculation and the conventional approach. The paper [36] by *Tomonobu Senjyu, Tsukasa Miyagi, Saber Ahmed Yousuf, Naomitsu Urasaki and Toshihisa Funabashi* explains the details of scheduling of a distribution system inclusive of energy storage through unit commitment.

4. METHDOLOGY

This section describes the methodology adopted in order to solve the optimization problem. The software which has been used for the optimization is GAMS. The approach to the problem has been made by going through the different equations proposed in different papers encountered during the literature survey and, including and modifying the equations that are required for the system similar to what is being considered. The problem developed is based on Unit Commitment and the code has been optimized to determine the operational scheduling of the generators involved in the microgrid system. Unit commitment problem consists of operational planning of the system and the optimized output consists of the scheduling of the different generators involved and performing in the system, in such a way that the operational cost of the system is minimum. The system performs the optimization under various constraints which are found in a real microgrid system.

4.1 GAMS

GAMS (General Algebraic Modelling System) is a high level modelling system which facilitates mathematical programming and optimization exclusively. This software is capable of modelling linear, non-linear and mixed integer problems (MIPs). The problem under consideration is mathematically, a MIP as it contains binary as well as integer variables.

The basic structure of GAMS could be described in the following points:

1. Sets: These are the basic element building up the system. Sets are used for declaration and assignment of members.
2. Data: These include Parameters, Tables and Scalars. This section is responsible for declaration and assignment of values. This section contains the information which has pre-assigned values and need to be declared.
3. Variables: These are the unknowns in the system. The values of these variables is to be calculated while the code is compiled.
4. Equations: These are the mathematical formulations which form the relation between other components present in the system. This section consists of the objective function and the constraints involved in the system.
5. Model and Solve Statement: This consists of the section where the solve statements for compilation are written for the final optimization mentioning the type of optimization model that would be used (linear, non-linear or MIP)
6. Display Statements: These statements are written to include all the values of variables which the user needs to see as an output after the compilation of code.

The software has been chosen because of its advantages with the mathematical optimization, which could be listed as follows:

1. The code could be written in the same manner as its mathematical formulation. It doesn't require complex formulations to write the equations, which simplifies the writing of the code in case of a problem with multiple equations. It consists of specific programming key words and a very clear interface, adding to the advantage.
2. The compilation and debugging of the code becomes easier as GAMS check the errors and displays clear messages in the output window pointing to the error in the specific line of the code and describing the reason behind it.
3. GAMS also helps in the selection of the solver which would be most suitable for the problem under consideration. Though it provides the guidance, it is still possible to change the type of the solver according to the user preferences.

4.2 MODEL

The goal of the project is to optimize the operation of an existing microgrid in islanded mode of operation, in order to obtain the optimal performance of all the individual parts of the micro grid mentioned above and the system as a whole. It deals with the scheduling and operational parameters of a functioning system rather than the planning and sizing of the system. The outcome would be a step towards the scheduling of the microgrid and to make conclusions regarding the reliability of the whole system. The system is also exposed to 4 different generation event scenarios, where each scenario has a different generator or a set of generators not performing because of an event.

After optimizing the individual microgrid, an approach has been made to apply the optimization to a system of networked microgrids and obtain the result. A networked microgrid system is more interesting to observe as it could be more reliable and resilient due to the distribution of the loads and generators over a larger area of interconnected grid, where each microgrid could be considered as a source itself, with the capability if disconnecting in case of an outage. An easier approach would be to start with a system of two networked microgrids and observe the optimization results. Reliability of the system plays an important role and hence an effort has been made to include the parameter Energy Not Supplied (ENS) in the minimization equation and to calculate its value. The code has been written in order to be able to process different kinds of inputs for the system. Hence, the system parameters could be varied according to the system under consideration and values be evaluated for different microgrid systems. This makes the code flexible to be used under different scenarios and input values, providing it flexibility to be used for multiple evaluations.

The system considered has all the basic components of a microgrid system, conventional and non-conventional generation, an energy storage system, loads and the interconnecting distribution system. Figure 16 below represents a schematic of the system under consideration.

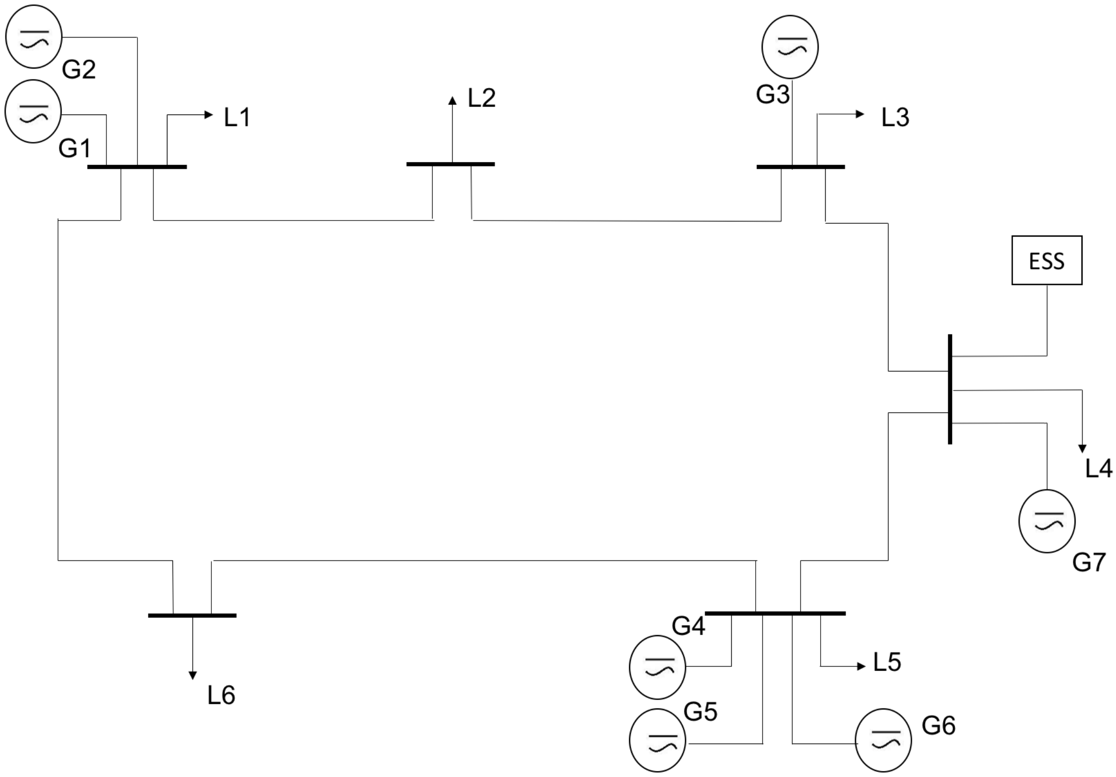

Figure 16 Schematic of the system under consideration for optimization

The assumed microgrid is a small system with a total installed capacity of a little more than 0.5 MW. The system is assumed to have a Li-ion ESS of 4000 KWh, with an efficiency of 90%. The system is a simple microgrid with seven generators G1 to G7 as can be seen in the figure. These generators are distributed at different nodes of the system. Each of the nodes of the system had a load connected to it. The generators G1, G2 are present at the same node with load L1. Two nodes in the system, with loads L2 and L6 have no generators connected to them, hence acting purely as consumers. Generators G4, G5, G6 could be a small generation unit installed by a community along with the load L5. The node with the generator G3 has only one generator along with the load L3. The ESS is located along with the generator G7 and load L4. The system is kept simple in order to make keep the optimization less complicated and observe the trend of results in the system, which could be extrapolated to a larger system. The unit commitment problem has been run for a time period of 24 hours, i.e., one day so that it could be used for daily scheduling of the generators and could be used for intra-day price comparison and operation of the microgrid in the grid connected mode.

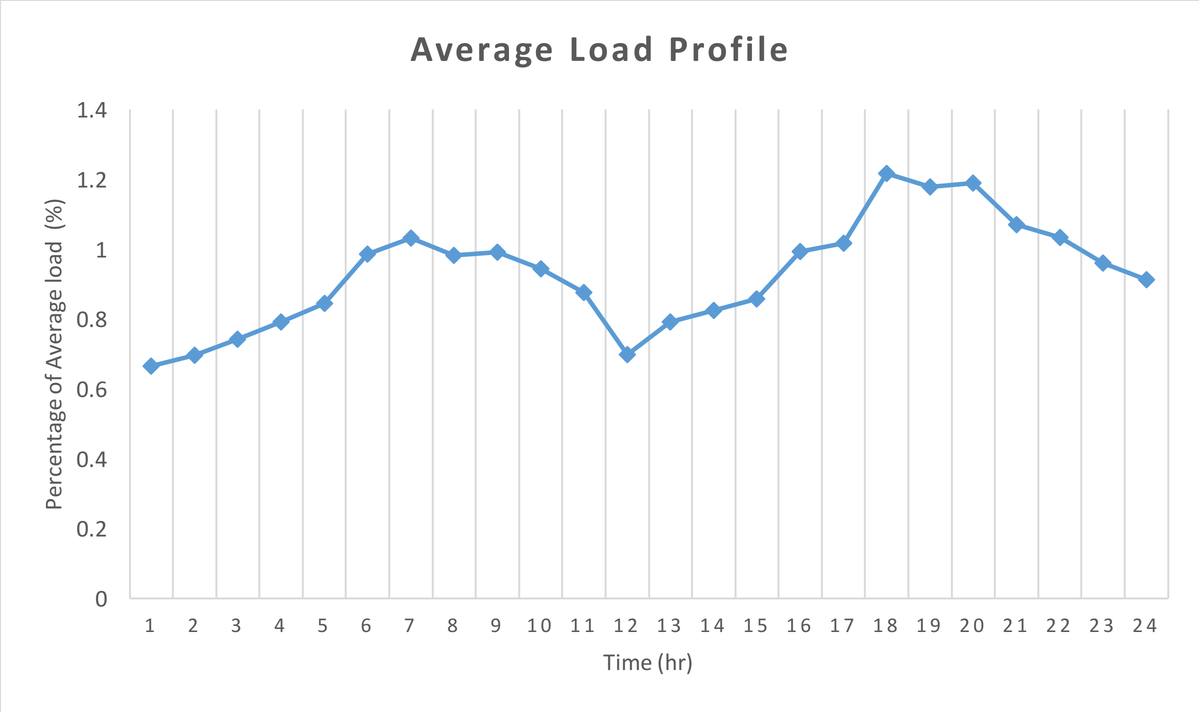

Figure 17 Average Load Profile

Figure 17 is the depiction of the average load profile used as an input for the optimization of the system. The values have been decided based on the reference of an average residential load profile [37]. Since, most of the small microgrids are closely related to a large number of residential customers forming the majority of load, it is better to assume values for the load in resemblance to the regular residential load profile.

The aim of the project only deals with the operational optimization of a microgrid system and hence the initial costs of installation are not considered in the system. The generators in the system could have the operational costs according to the type of the microgrid considered. If it consists of all conventional generation, the operational costs will be inclusive of fuel costs, whereas if the system is considered to be consisting of renewables like PV or wind, the fuel cost should be reduced to zero as the fuel is available for free. Thus the system would have different economic performance under the two configurations and it would be interesting to note the benefit of introducing renewables into the system.

FORMULATION

As a first step towards the optimization, equations have been written for an autonomous microgrid with generators, energy storage system and loads.

The generator fuel cost function $F\left(P_{gen}(g,t)\right)$ is a function of generator power $P_{gen}(g,t)$, which could be defined as [36] :

$$F\left(P_{gen}(g,t)\right) = a * P_{gen}(g,t)^2 + b * P_{gen}(g,t) + c$$

where a, b and c are representing unit cost coefficients. The above equation has been linearized for the optimization in order to reduce the complexity of the optimization. The final fuel cost has again been calculated separately with the obtained values for parameters, using the original function.

The complete objective cost function, which needs to be optimized, consists of the generator cost function $F\left(P_{gen}(g,t)\right)$, warm or cold start-up costs SU_w and SU_c, shut-down costs SD and the penalty charged $Pen(n)$ for the energy not supplied (ENS).

$$Z = \Sigma_g \Sigma_t (F\left(P_{gen}(g,t)\right) + SU_w * ws(g,t) + SU_c * cs(g,t) + SD * sd(g,t)) + \Sigma_n Pen(n)$$

The microgrid system needs to be put under different system constraints, including various parameters acting in the system. The first constraint to be applied is the load balance equation for the different buses included the system.

$$\Sigma_g\left(P_{gen}(g,t) - P_{load}(n,t)\right) + (P_{ch}(t) - P_{dch}(t)) = P_{base} * \Sigma_m(b_{bus}(n,m) * (\Theta(n,t) - \Theta(m,t))$$

where $P_{load}(n,t)$ is the load in the system, $P_{ch}(t)$ and $P_{dch}(t)$ are the charging and discharging power in the energy storage system (ESS) respectively, and the difference between $P_{ch}(t)$ and $P_{dch}(t)$ gives the energy stored in the ESS at any point of time. The terms on the right hand side of the load balance equation estimate the energy consumed by the bus during the transmission as losses.

The variable $cs(g,t)$ and $ws(g,t)$ are binary variables which establish the status of the cold start-up and warm start-up of a particular generator, whereas $u(g,t)$ gives the commitment status of the generator under consideration at the time. The two equations are inter-dependent as a generator would have a cold start up only if it has been shut down and has not been in operation for a particular number of hours. If start-up operation is performed before the specified time, it would only need a warm start up and hence saving the expenses.

$$cs(g,t) \geq u(g,t) - u(g,t-1) - u(g,t-2) - u(g,t-3) - u(g,t-4)$$

$$ws(g,t) \geq u(g,t) - u(g,t-1) - cs(g,t)$$

The equation below puts the condition of shut down status for all the generators in the system.

$$sd(g,t) \geq u(g,t-1) - u(g,t)$$

The above equations controlling the start-up and shut-down status of the generator play an important role in determining the commitment status of the generators and their operational costs and duration.

The ESS is an integrated part of the microgrid system and hence the contribution of the ESS acts as an important constraint.

$$E_{sto}(t) = E_{sto}(t-1) + \eta_{sto} * P_{ch}(t) - P_{dch}(t)$$

The variable $E_{sto}(t)$ depicts the stored energy in the ESS at a specific time t and η_{sto} is the efficiency of the ESS. $P_{ch}(t)$ and $P_{dch}(t)$ represents the charging and discharging power of the ESS.

Line constraints are also included in the system, putting a limit over the transmission capacities of each bus in the system. $w(l,n,m)$ is the matrix giving the information about the location of each bus and Θ is the respective voltage angle of the bus and P_{base} is the base power assumed for the system, while P_{Lmax} is the maximum power capacity of the transmission line or bus.

$$w(l,n,m) * P_{base} * b_{bus} * \left(\Theta(n,t) - \Theta(m,t)\right) \geq -P_{Lmax}$$

$$w(l,n,m) * P_{base} * b_{bus} * \left(\Theta(n,t) - \Theta(m,t)\right) \leq P_{Lmax}$$

Each of the generators involved in the system are limited by their maximum $P_{gmax}(g)$ and minimum $P_{gmin}(g)$ generating limits and these are listed under the generator constraints of the system.

$$P_{gen}(g,t) \leq P_{gmax}(g) * u(g,t)$$

$$P_{gen}(g,t) \geq P_{gmin}(g) * u(g,t)$$

The spinning reserve constraint is included in the system in order to maintain the reliability of the supply in case of an event. $SR(t)$ is the spinning reserve required and $P_{load}(n,t)$ signifies the load in the system at the time t.

$$\Sigma_{\mathrm{g}} P_{gmax}(g) * u(g,t) \geq \ \Sigma_n P_{load}(n,t) + \ \Sigma_n P_{load}(n,t) * SR(t))$$

or

$$\Sigma_{\mathrm{g}} P_{gmax}(g) * u(g,t) \geq \ \Sigma_n P_{load}(n,t) * (1 + SR(t))$$

The generator ramping limits are defined by the ramp up and ramp down constraints respectively. In the following equations, P_{ramp} depicts the maximum amount of ramp in terms of power that could be applied to the generator.

$$P_{gen}(g,t) - P_{gen}(g,t-1) \leq P_{ramp}$$

$$P_{gen}(g,t) - P_{gen}(g,t-1) \geq -P_{ramp}$$

The minimum up-time constraint makes sure that the generator under consideration maintains its ON state of commitment for a particular time period. The reason behind application of this constraint is to make sure that the generator status doesn't go from ON to OFF within a very short time period like an hour or two. This could be very expensive as well as a not a good practice for the durability of the generators.

$$\big(cs(g,t) + ws(g,t)\big) + \big(cs(g,t-1) + ws(g,t-1)\big) + \big(cs(g,t-2) + ws(g,t-2)\big) \leq \ u(g,t)$$

Similarly, minimum downtime constraint is required to make sure that the shut downtime is restricted by a minimum value once the system is switched off. This would again ensure the cost effective operation of the system as the generator once shut down, if turned on again immediately could lead to loss in durability of the generators as well as increased operational cost. In cases where generation is not required for a short period of time, the alternative option could be to keep the generator producing and storing the excess energy in the ESS.

$$sd(g,t) + sd(g,t-1) + sd(g,t-2) + sd(g,t-3) \leq 1 - u(g,t)$$

A maximum uptime constraint is required to ensure that it's not the same generator which is producing continuously for the system. The equation ensures that no generator works at a stretch for more than 12 hours.

$$\begin{aligned} u(g,t) + u(g,t-1) + u(g,t-2) + u(g,t-3) + u(g,t-4) + u(g,t-5) + u(g,t-6) \\ + u(g,t-7) + u(g,t-8) + u(g,t-9) + u(g,t-10) + u(g,t-11) \\ + u(g,t-12) \leq 12 \end{aligned}$$

Charging and discharging constraints are applied in order to limit the power flow in the ESS. This is to ensure that the simulated ESS functions close to a practical energy storage in a microgrid, for e.g. batteries. P_{chmax} and P_{dchmax} are the maximum allowable charging and discharging power in the ESS whereas $u_{ch}(t)$ and $u_{dch}(t)$ are the charging and discharging status respectively. The binary variables $u_{ch}(t)$ and $u_{dch}(t)$ should always have values such that the ESS could perform in only one of its functioning modes , either charging or discharging.

$$P_{ch}(t) \leq u_{ch}(t) * P_{chmax}$$

$$P_{dch}(t) \leq u_{dch}(t) * P_{dchmax}$$

$$u_{ch}(t) + \ u_{dch}(t) \leq \ \ 1$$

Storage limits signify the constraint on the size of the ESS. This should also take into consideration the discharge limit of the system. E_{stomax} signifies the maximum energy that could be stored in the ESS, i.e. the size of total storage. E_{stomin} signifies the minimum energy that needs to be maintained in the storage for its better life cycle and durable operation.

$$E_{sto}(t) \leq E_{stomax}$$

$$E_{sto}(t) \geq E_{stomin}$$

The above equations and constraints define the operation of the system and its boundaries. An effort has been made to include all the basic factors effecting a power distribution system.

4.3 RELIABILITY TERM

Reliability is a very important parameter while concerning the operation of any transmission or distribution system. Any system needs to be operated in order to have maximum reliability possible within the given constraints applicable. Hence, an effort has been made to include the reliability as a part of the optimization code

A reliability term has been added in order to observe the operation of the microgrid under reliability constraints. The variable Energy Not Supplied (ENS) has been added as the reliability index in the code in order to include the parameter. The ENS is evaluated by considering one extra generator at each node, with no constraints put on them and having relatively high operational cost. Hence, it is used in the minimization objective function along with the other generators as a generating unit like any other but with a penalty cost added. The system would use this generator only if there is a fault in the system or an excessive load which the system is not able to satisfy using other generators or if cutting the load if more economic. The value of generation of this generator would be the ENS in the system. Since the goal of the optimization is to minimize the cost of the system, it would try to keep the value of ENS as low as possible because it has higher prices associated. The reduction in the value of ENS hence indicates the improvement in the reliability of the system.

The ENS is depicted in the terms of load not supplied in each of the nodes in the system. There are 6 nodes in the system in total with different loads. The ENS for each of the loads is calculated and represented as a separate term.

4.4 ASSUMPTIONS

Several assumptions have been made in for the formulation and successful computation of results in the system.

- The system is considered to be a congested system in order to make the sensitivity analysis of the system. Hence, the system has a higher value of ENS even in the normal faultless operation.

- A cold start-up time of 4 hours is the assumption made for the computation in case of conventional generators. This would mean that if the generator commitment status is off for more than a duration of four hours, it has to undergo a cold start up. If the system shut down time is lesser than that, only a warm start up is required, since the system still persists heat from the previous generation.
- A minimum up-time of 3 hours has been assumed in this case for the generators, which suggests that once a generator is switched on, supplying the grid, it has to be in that state for a minimum of 3 hours.
- The value of minimum downtime is assumed to be 4 hours in the optimization code, which ensures that a system once shut off remains in that state for a minimum of 4 hours.
- A ramp rate (up and down) of 10% has been assumed for all the generators in the system.
- Shut down cost has been assumed for all the conventional generator to be around 12% of the cold start-up.
- The maximum depth of discharge for the ESS is assumed to be 75%.

4.5 SYSTEM BEHAVIOUR

To understand the behavior of the system, at first two scenarios are considered, the first one with only 17% of the total generation as renewables and the rest is consisting of conventional generation; while the second one with approximately 35% of conventional generation in the system and rest of the generators being renewables. The second scenario is a theoretical situation where the renewable percentage is too high in the system. This is an unrealistic scenario because of the many challenges present in the higher integration of renewables but this would give an idea about the comparative costs avoided with higher renewables in the system under the ideal scenario of 65% renewable generation. It shows the behavior of the system when it works with different kind of generators. The system is optimized only for the values of generation and load without a factor ENS being included.

SYSTEM WITH HIGHER PERCENTAGE OF CONVENTIONAL ENERGY SOURCES

The system designed is first formulated for a higher percentage of conventional generators in the system. The system considered has seven generators out of which only two are based on renewable energy resources, a biomass gasification plant and a solar PV system. The conventional generators considered in the system are small scale CHP plants using conventional fuel like heating oil (kerosene) or gas. Table 1 below describes each generator type and their capacity in Kilo Watts (KW).

Table 1 Generators in the system and their sizes

Generator	Type	Rated Power (KW)
G1	Conventional CHP Plant (Heating oil)	90
G2	Conventional CHP Plant(Gas)	90
G3	Biomass Gasification Plant	50
G4	Conventional CHP Plant (Heating oil)	100
G5	Backup Diesel Generator	50
G6	Conventional CHP Plant(Gas)	150
G7	Photovoltaic system	50

Table 2 defines different costs for each of the respective generators. The different costs have been extracted from different references [38] [39].

Table 2 Different costs involved in the operation of each generator

Generator	Fuel Cost (€/KWh)	Start Up Cost (Warm) (€/KW)	Start Up Cost (Cold) (€/KWh)	Shut Down Cost (€/KWh)
G1	0.054	0.005	0.017	0.002
G2	0.047	0.005	0.017	0.002
G3	0.000	0.000	0.000	0.000
G4	0.054	0.005	0.017	0.002
G5	0.120	0.000	0.000	0.000
G6	0.047	0.005	0.017	0.002
G7	0.000	0.000	0.000	0.000

The costs are either in currency per KW or currency per KWh. Since each of the parameters are being calculated on an hourly basis, the equality of the units in all the costs is maintained. Shut down cost has been assumed in this case to a reasonable value. The fuel cost for biomass has been assumed to be zero since it is assumed to be locally generated and in such cases, the cost is very low. Hot start-up cost is calculated to be 30% of the cold start-up cost according to the reference found [40].

The conventional system had a total daily operational cost of 119.75 €, while the linearized cost including the start-up and shut-down costs was calculated to be 127.697€.

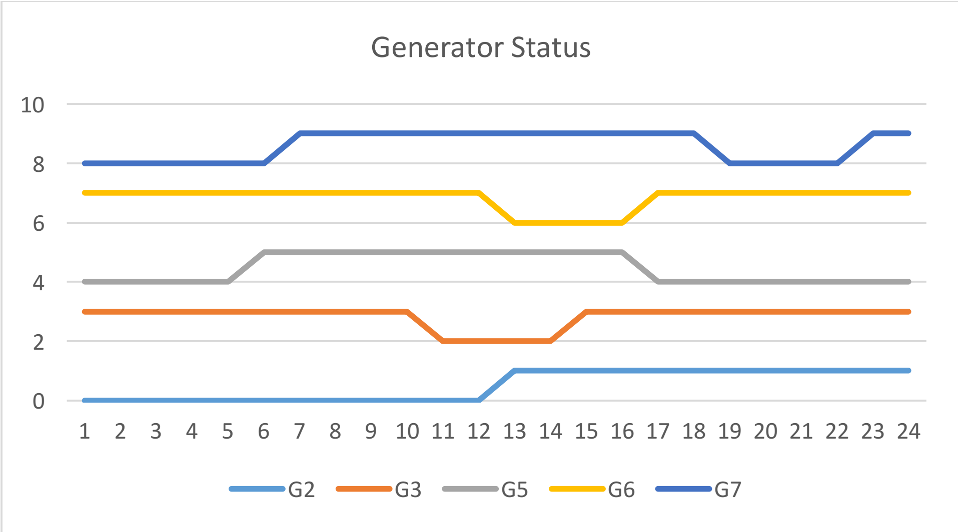

Figure 18 Generator scheduling with 17% renewable generation (ENS not considered)

The power generation looks even and stable in this case with reduced generation during low demand hours from a 11:00 hrs. to 16:00 hrs. The only renewable generated included here is a PV system which produces power during the availability of day light. It should be taken into account that given the complexity of analysis, the intermittency in the generation of renewable sources has not been introduced in the system.

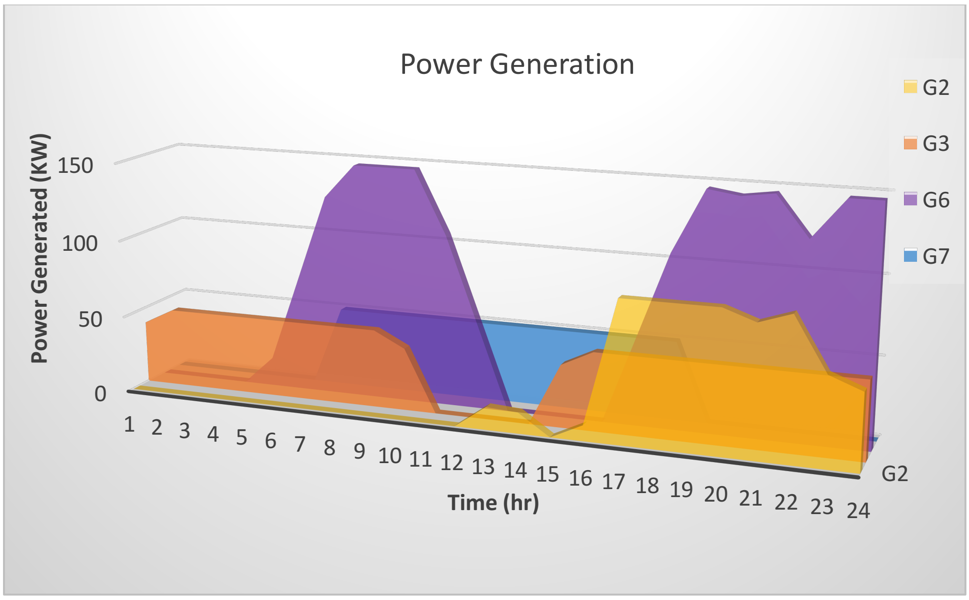

Figure 19 Power generation with 17% renewable generation (ENS not considered)

As Figure 20 depicts, the system uses only four generators out of the available seven in order to keep the costs optimal and the bigger part of the total demand is provided by the generator G6. The ESS behavior doesn't show negative load dependence as it is being charged more on hours of peak load. An explanation for this behavior could be the fact that the conventional generators have start-up and shut down costs, hence its more cost efficient to store the energy required during the peak hours when the system is producing more with larger number of generators working. However, this scenario would change if the microgrid is operating in grid-connected mode and market prices are introduced in the system. The energy storage is charged sufficiently before the peak load at around 18:00 hrs. and hence the drop in the stored energy is linear during the peak load time between 17:00 hrs. to 22:00 hrs.

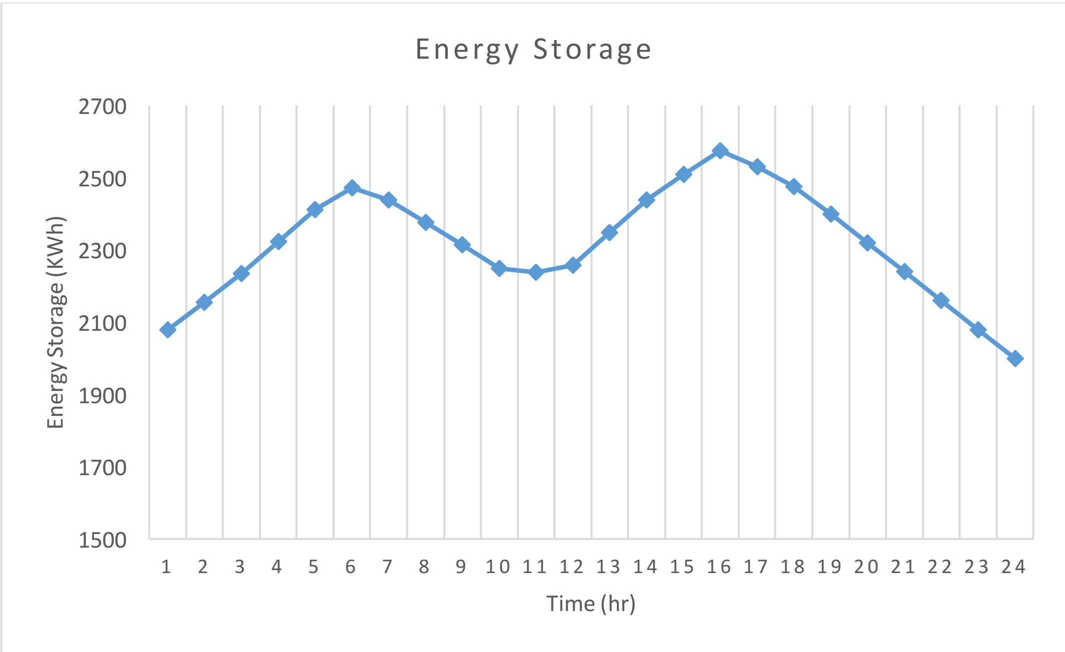

Figure 20 ESS with 17% renewable generation (ENS not considered)

SYSTEM WITH HIGHER PERCENTAGE OF RENEWABLE ENERGY SOURCES

In this case, the system is considered to have only two conventional generation systems, one of which is a back-up diesel generator and the second one is CHP Plant using conventional (gas) fuel. The size of the CHP is kept large considering the practicality of the setting up of a conventional generation plant. Table 3 below describes each generator type and their capacity in Kilo Watts (KW).

Table 3 Generators in the system and their sizes

Generator	Type	Rated Power (KW)
G1	Photovoltaic system	90

G2	Photovoltaic system	90
G3	Biomass Fired Power Plant	50
G4	Wind Power System	100
G5	Backup Diesel Generator	50
G6	Conventional CHP Plant (Gas)	150
G7	Photovoltaic system	50

Table 4 defines different costs for each of the respective generators. The costs for conventional generators have been extracted from different references [38] [39].

Table 4 Different costs involved in the operation of each generator

Generator	**Fuel Cost (€/KWh)**	**Start Up Cost (Warm) (€/KW)**	**Start Up Cost (Cold) (€/KWh)**	**Shut Down Cost (€/KWh)**
G1	0.000	0.000	0.000	0.000
G2	0.000	0.000	0.000	0.000
G3	0.000	0.000	0.000	0.000
G4	0.000	0.000	0.000	0.000
G5	0.120	0.000	0.000	0.000
G6	0.047	0.005	0.017	0.002
G7	0.000	0.000	0.000	0.000

This scenario represents an ideal case with 65% renewable energy penetration, hence the total costs operational costs for the system are zero since the system avoids using the conventional generator. Even though it represents an extreme case scenario, some interesting observations can be made with the help of such a comparison.

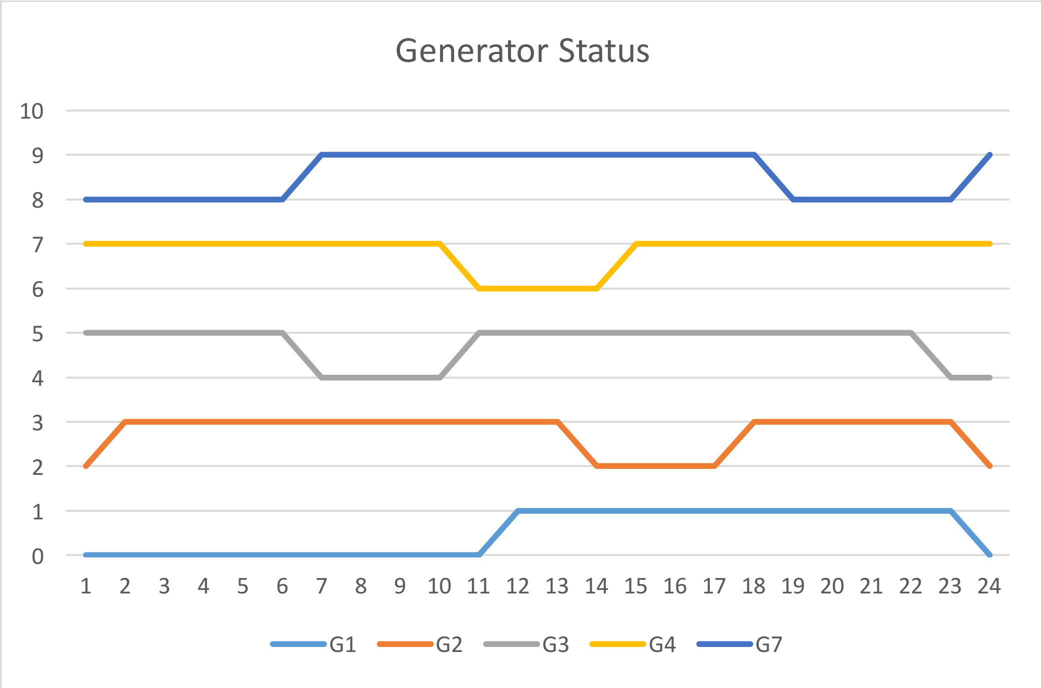

Figure 21 Generator scheduling with 65% renewable generation (ENS not considered)

The power generation in the system with 65% renewables is much more distributed as compared to the case former case. The system is using more generators and the generation seems to be well distributed among the generators. G1, G2 and G7 being PV systems have generation capacity limited during the day light hours and the system utilizes all three in an optimal way. Hence the generators continue to generate even in low demand hours, unlike in the former case.

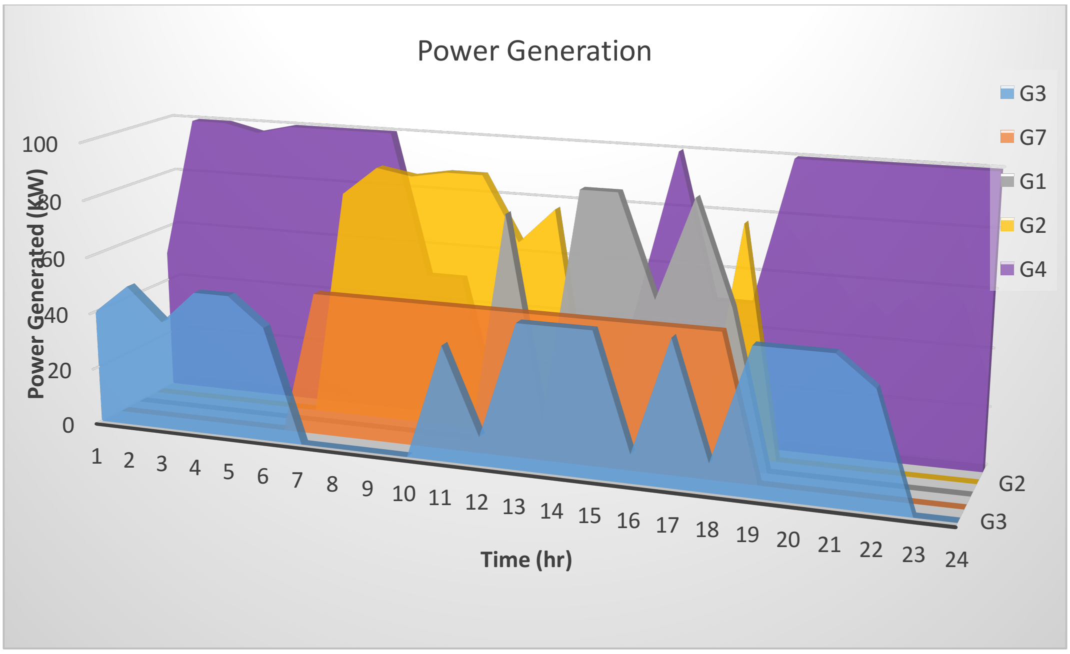

Figure 22 Power generation with 65% renewable generation (ENS not considered)

The energy storage in the ESS seems to be showing a high discharge during the high demand during the evening hours. This behavior could be because of the fact that the system uses three PV generators during the day for the production and avoids conventional generation. This restricts the system's capacity to generate during the evening high demand hours, and hence it makes the best use of the available energy in ESS. As the load reduced, the system starts to charge again slowly.

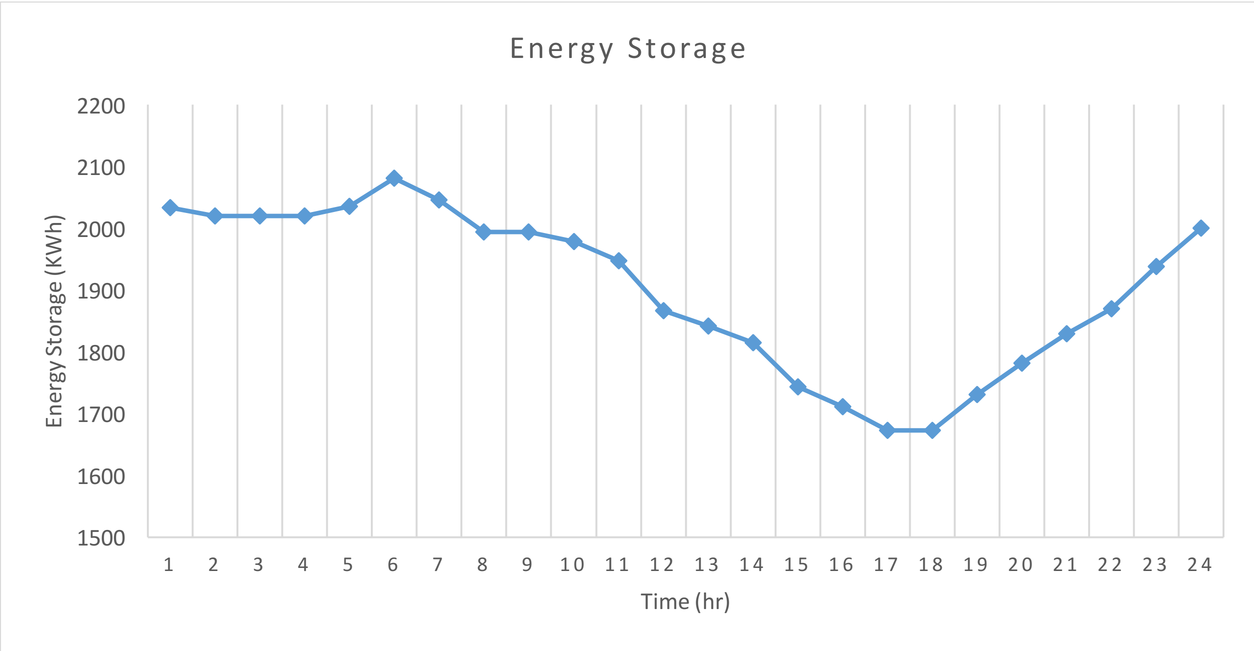

Figure 23 ESS with 65% renewable generation (ENS not considered)

5. RESULTS

Results have been simulated and optimized for different conditions and scenarios in order to gain an insight in to the system behavior depending on different parameters. Firstly, the results have been optimized for two base case scenarios, the first being a system with total conventional generation and the second with 17% integration of renewables in the system. After comparisons being made for the two base cases, the system is further analyzed by introducing fault case scenarios. Four different fault case scenarios have been simulated and optimized. Further, sensitivity analysis for the cost of the system has been done further in order to study the change in the behavior of the system as the percentage of renewable penetration increases. A trend in the ENS has also been studied for the same conditions.

5.1 BASE CASE SCENARIOS

The optimization has been performed keeping two realistic base scenarios in focus. The microgrid under consideration is assumed to be a congested system and hence the value of the generators have been chosen so as to give a higher value of ENS even in the no fault scenario with normal generation. Since the system is a congested one, it has to keep all its generators under operation for some periods throughout the duration of 24 hours.

BASE CASE 1: 100% CONVENTIONAL GENERATION

The first case is a microgrid with 100% conventional generation, which means that there is a fuel cost associated with each of the generators in the system. The total generation capacity of all the generators in the system is 580 KW. The generators G3 and G5 are considered to be back-up generators with (kerosene/diesel) and hence there are no extra start up or shut down costs associated to them. The status of different generators is shown in the Figure 24:

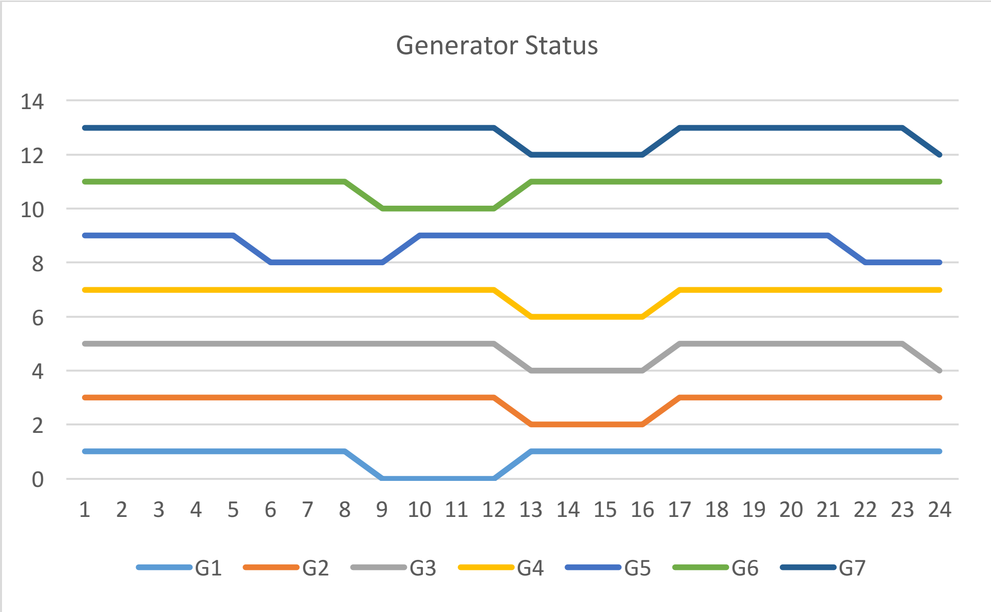

Figure 24 Base Case1: Generator Status

The power generation for different generators in this case has been plotted in Figure 25.The total fuel cost for all the generators in this case was calculated to be 211.8 €/day. Since G3, G4 and G5 have same generation status with respect to time throughout the duration of operation, their generation is depicted by the line describing G5.

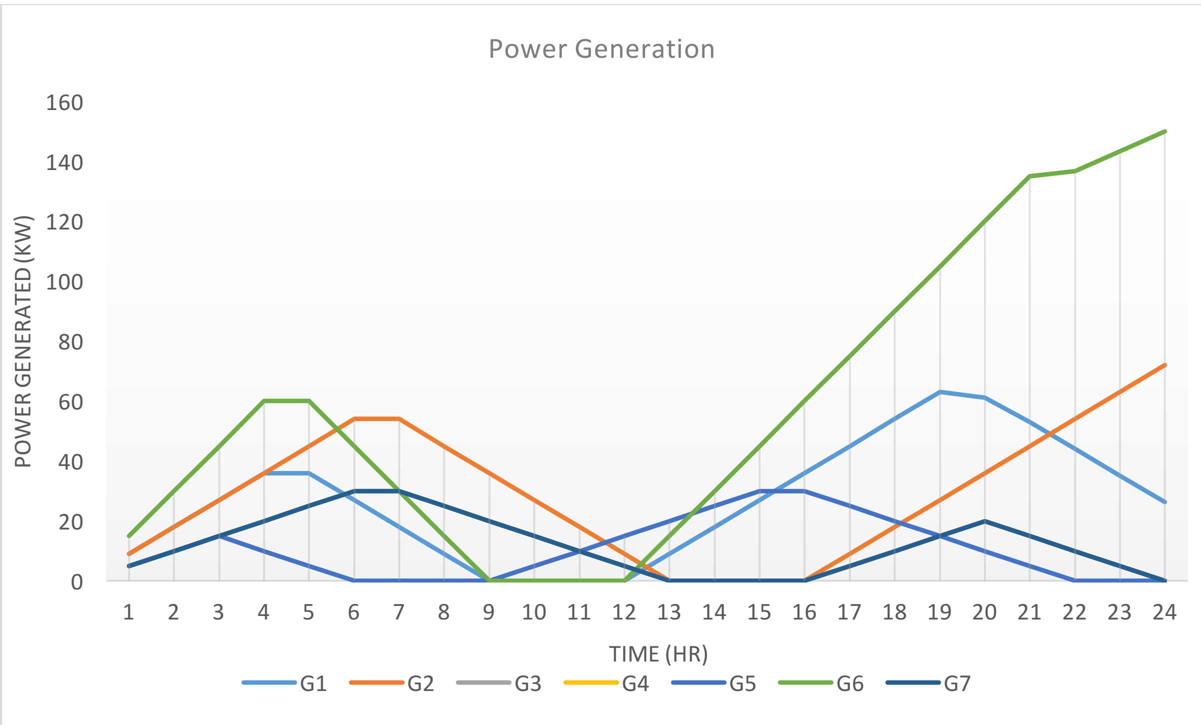

Figure 25 Base Case1: Power Generation

The total value of ENS in the system was calculated to be 237.02 KW for a day. This would represent the load cutting which was required in the system for economic operation. Since the system is assumed to be congested, the value of ENS is high. Figure 26 shows the variation of ENS in the system during different hours of the day. The ENS is calculated for each load point in the system which makes it a total of 6 load points.

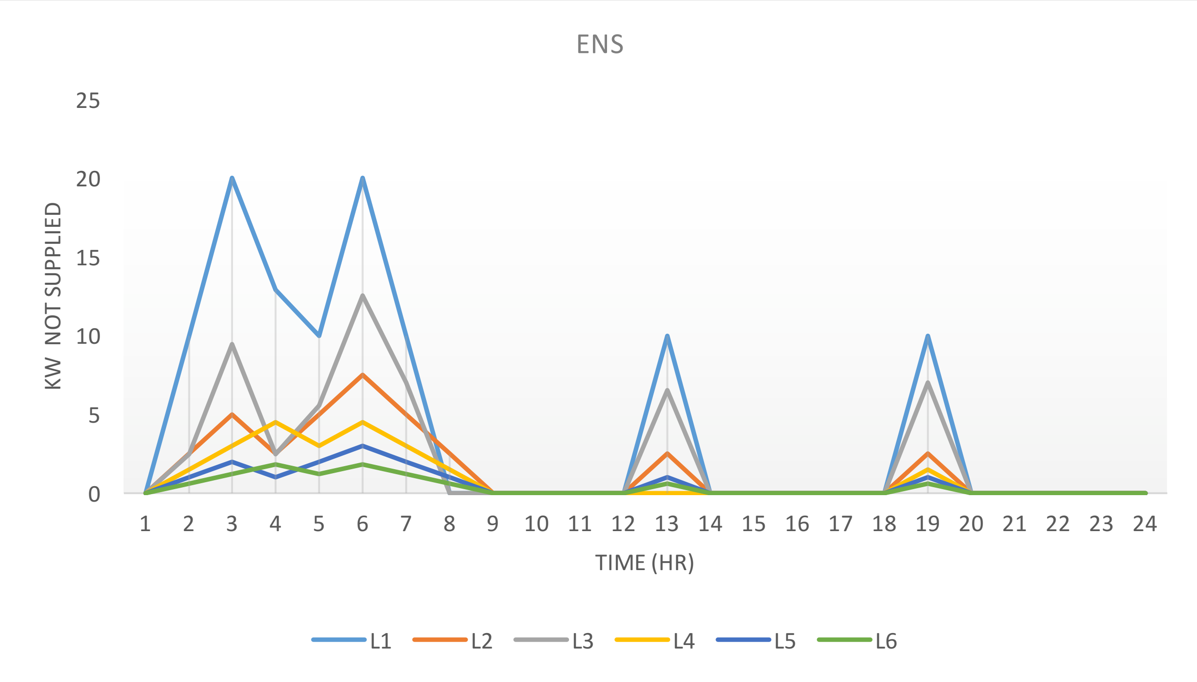

Figure 26 Base Case1: ENS

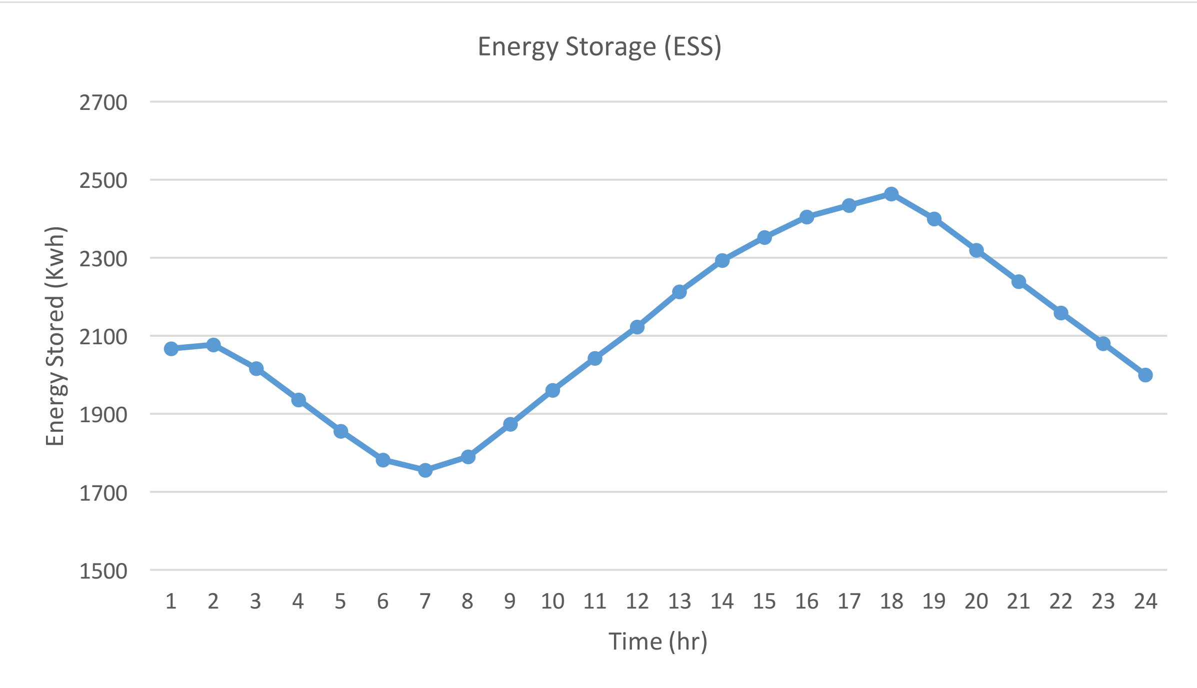

Figure 27 Base Case1: Energy Storage

Figure 27 .shows the energy stored in the ESS throughout the day. The total operational cost of the system, including the start-up and shut-down costs was optimized to 470.4 €/day.

BASE CASE 2: 17% RENEWABLE GENERATION

The second base case introduces a renewable generation of a little more than 17% (17.24% to be exact). 100 KW of generation out of the total generation of 580 KW is considered to be renewables and hence having zero fuel costs. The generators G3 and G7 are considered to be two generation sources based on renewable (not PV).

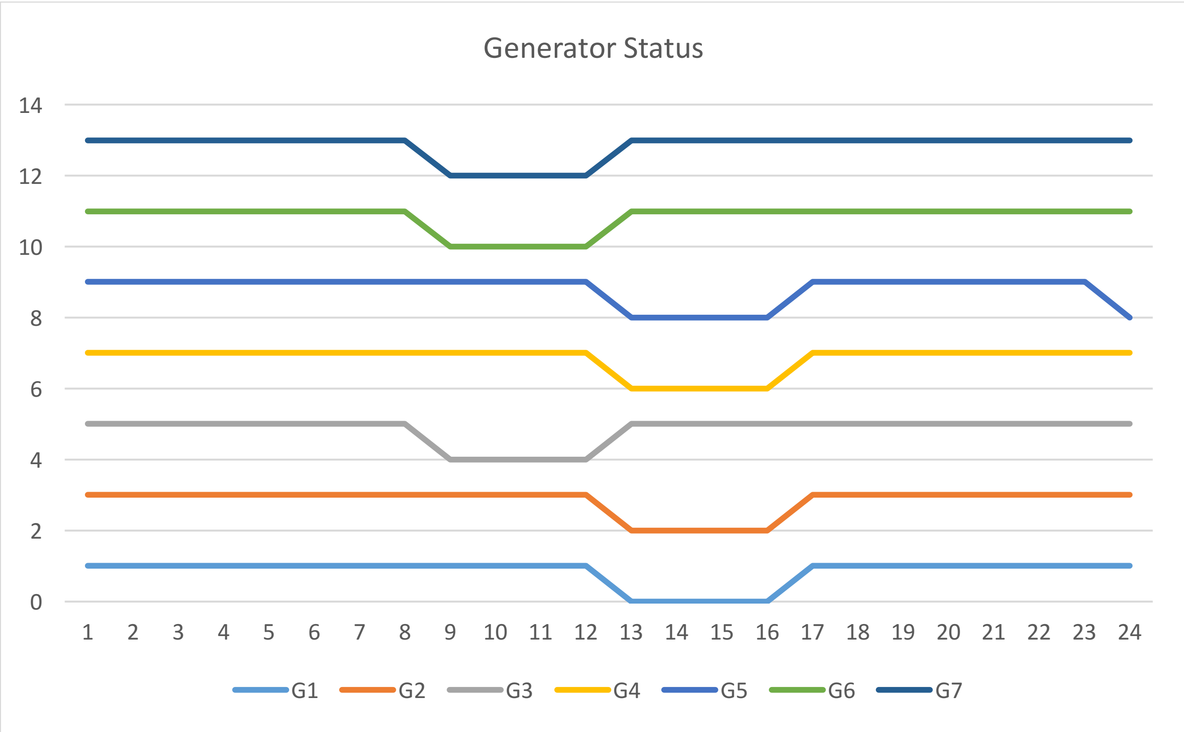

Figure 28 Base Case2: Generator Status

Figure 28 depicts the power generation for different generators. Since G3, G4 and G5 have same generation status with respect to time throughout the duration of operation, their generation is depicted by the line describing G5.

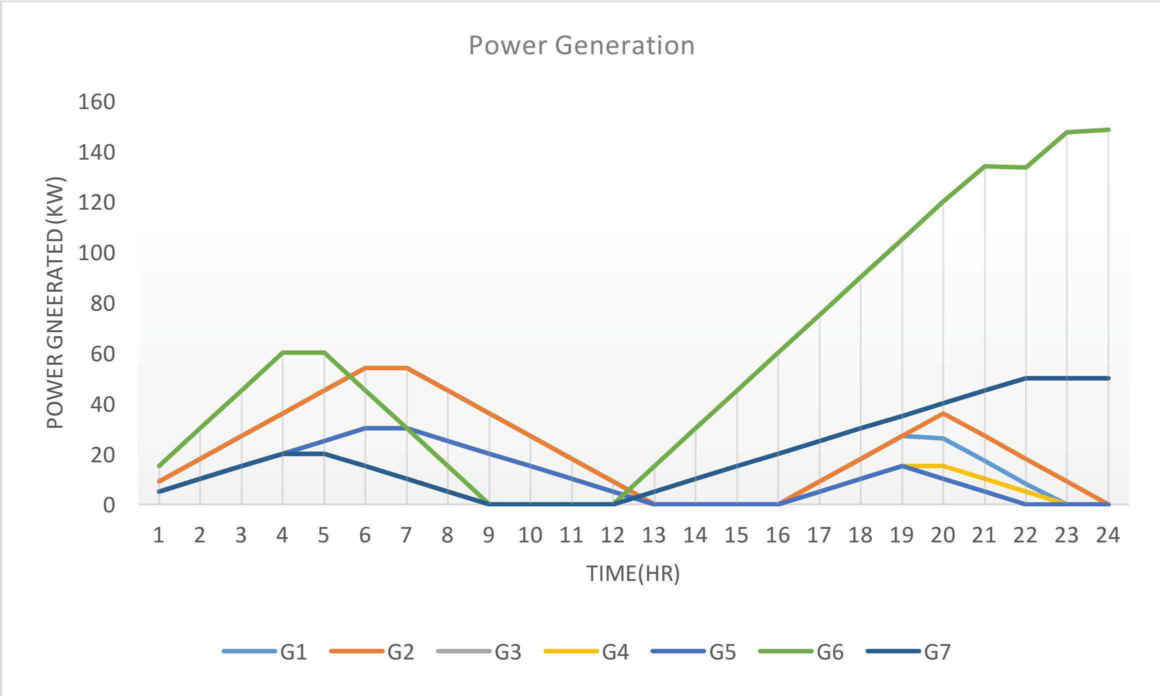

Figure 29 Base Case2: Power Generation

It can be observed that there has been reduction in the generation of conventional generators, while the same power is being compensated by the renewable generators. The total fuel cost for the all the generators was calculated to be 161.8 €/day, which is a 23.6% reduction in the initial cost with all conventional generation.

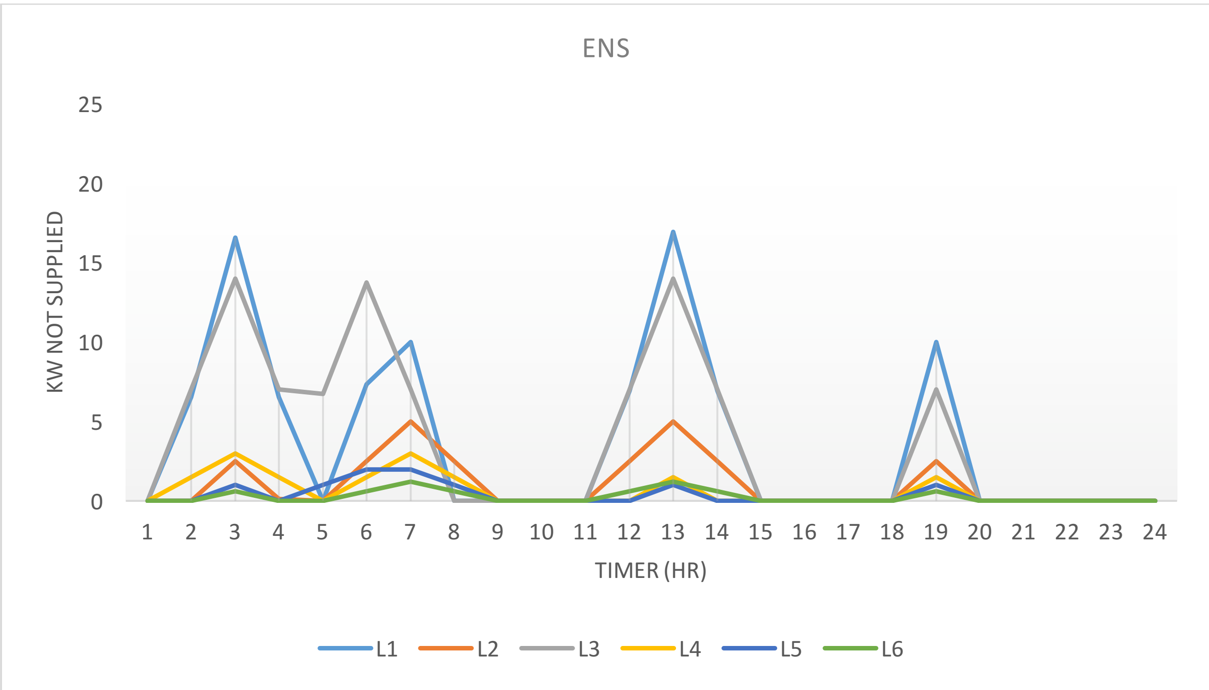

Figure 30 Base Case2: ENS

Figure 30 describes the ENS for Case 2. The total ENS for the duration of 24 hours was calculated to be 233.5 KW, hence, a 1.5 % reduction in the initial ENS from Case 1. The energy storage trend in both the cases is almost the same.

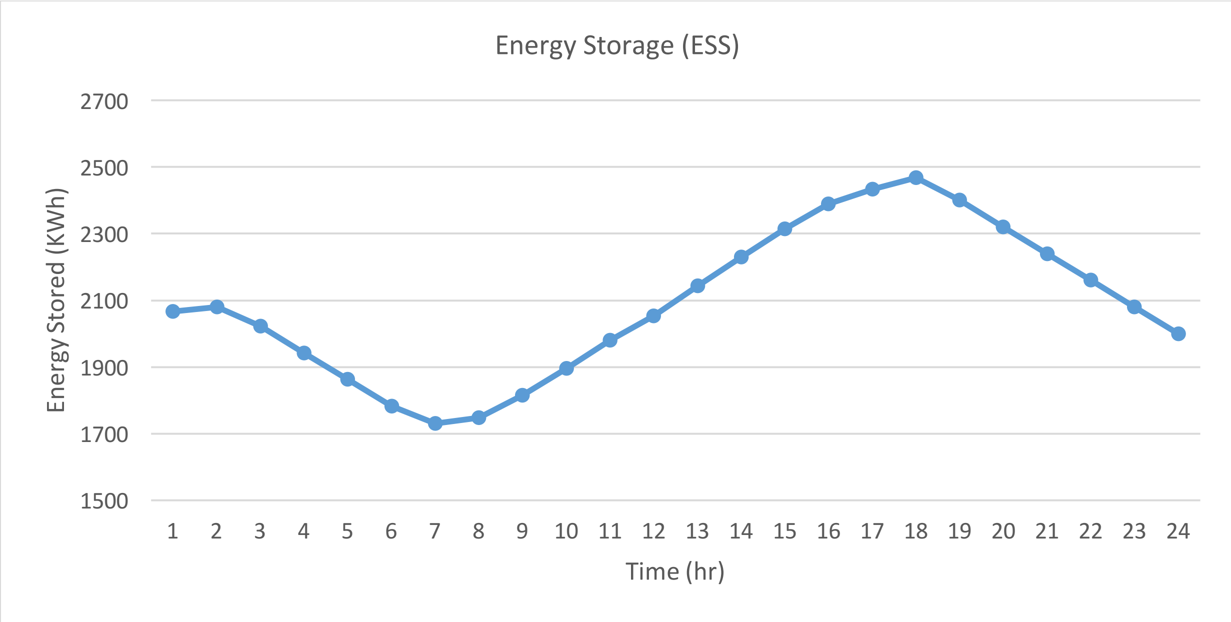

Figure 31 Base Case2:Energy Storage

The total operational cost of the system also shows a reduction in value by 11.4%. The value for the operation cost in Case 2 was calculated to be 416.8 €/day.

5.2 FAULT CASE SCENARIOS

The optimization code was run for four different fault scenarios for the system with 100% conventional generation, as explained further. Including the fault case scenarios evaluates the system vulnerability, the scheduling of generators in case of an event and the cost estimation of the system in case of a fault. The first scenario is no fault case, when probability of all the generators up and running is 100%. The second scenario adds a 20% possibility of fault in generator G1 and its non-availability. The third scenario has a 70% possibility of no fault, 25% of a fault in generator G1 and 5% of a fault in generator G2. Finally, the fourth scenario acts on the probability of 70% no fault operation, 15% probability of a fault in G1, 10% of a fault in G2 and 5% of a fault in G5.

The values for ENS increases from scenario 1 to scenario 4. This is because of the increasing probability of faults from scenario 1 to scenario 4. As the probability of fault increases, there is a higher chance of more load not being satisfied because of one of the generators being down. Hence, the cost effective way for the system in that situation is to cut down the load.

Table 5 Four fault probability scenarios

Scenario	Fault	Probability	ENS (KW)	Fuel cost
1	None	100%	237.028	211.789
2	None,G1	80%,20%	908.790	400.385
3	None, G1, G2	70%,25%,5%	1609.204	612.826
4	None, G1, G2, G5	70%,15%,10%,5%	2121.133	790.139

The values for ENS and fuel cost were plotted against each scenario in order to observe the increase in both the parameters.

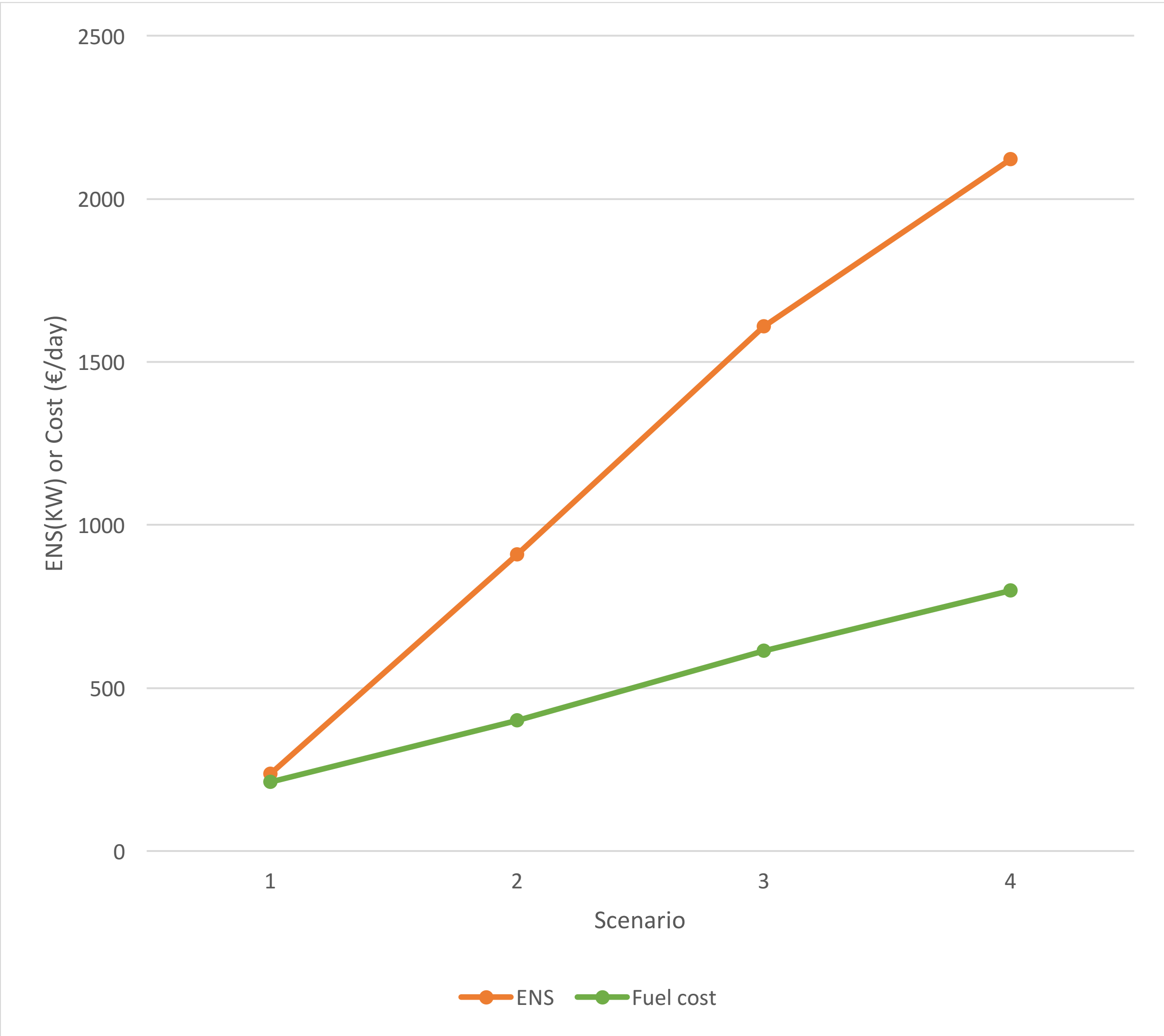

Figure 32 Variation in ENS and Fuel cost in different fault scenarios

The higher slope for ENS in the Figure 32 shows that the system prefers to cut down the loads in case of a sudden fault, rather than increasing the generation in the system. This behavior of the system could be justified by the fact that it tries to minimalize the cost. Moreover, different limits placed on each transmission line makes it more difficult to satisfy the power demand in fault situations as it creates a sudden power drop in the line.

5.3 COST SENSITIVITY ANALYSIS

A cost sensitivity analysis was performed on the microgrid network under consideration for the basic case scenarios by simulating the system for different percentages of renewable integration. The generation capacity of the system with total conventional generation was slowly shifted towards renewables, increasing the renewable share in the system up to approximate 22%. The trends in the actual fuel cost of the system and the linearized operational cost of the system were observed with the increasing integration.

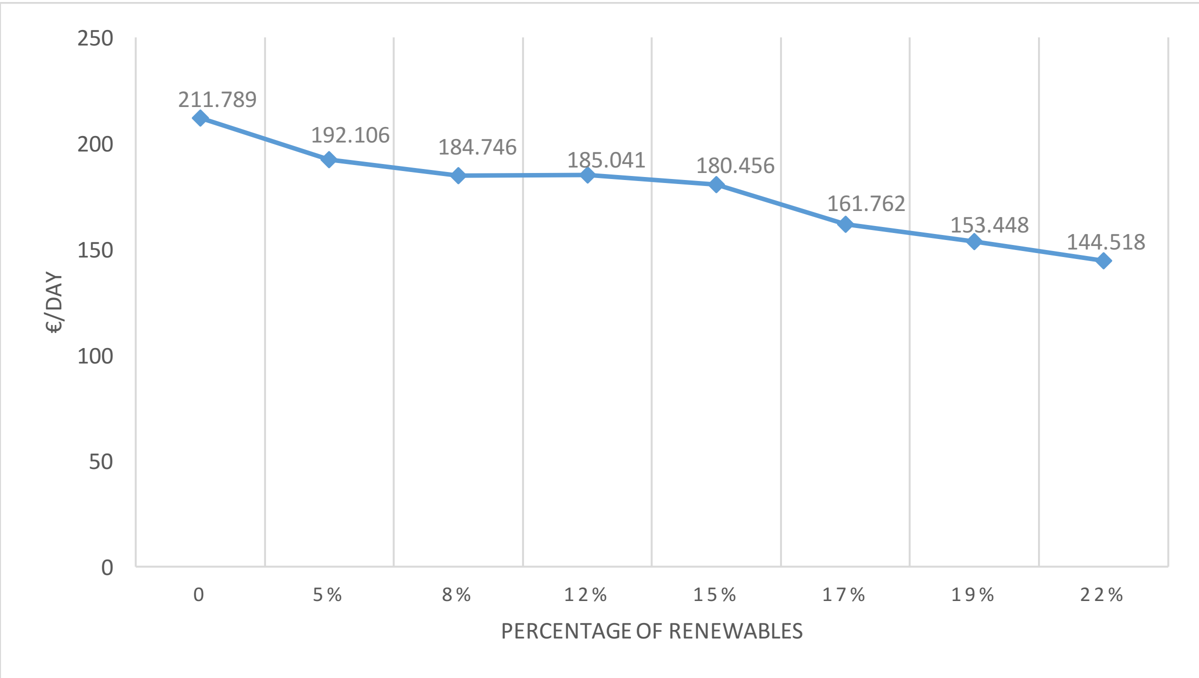

Figure 33 Fuel cost variation with percentage increase in renewables

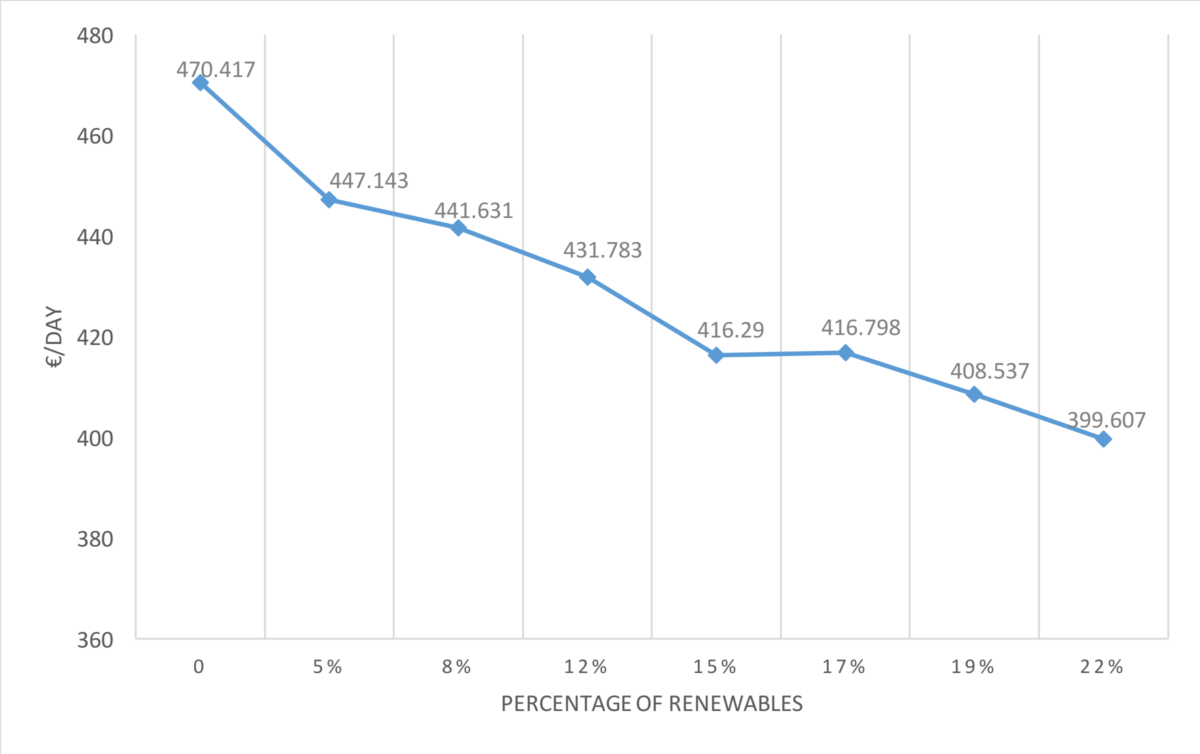

Figure 34 Operational cost variation with percentage increase in renewables

As is clear from the Figure 33, the fuel cost shows a decreasing trend with the increasing share of renewable. This would be the expected result as the fuel cost for the renewable energy sources is zero. The average drop in the fuel cost from a renewable share of 0 to 22% is the around 5.25%. The same trend applies to the operational cost as well because the start-up and shut-down costs for the non-conventional generators is zero, but the percentage drop observed in the operational cost is comparatively lower, with an average value of 2.29% over the integration range depicted in the Figure 34.

The reduction in operational and fuel costs are predictable, but it would be really interesting to note the change in ENS values for the same amount of integration of renewable energy in the system. The system showing a decreasing value over the range gives a positive indication towards the improvement in the reliability of the system as depicted in Figure 35. Though this drop in ENS value is not as consistent as observed in case of the two costs, but the total behavior of the ENS follows a negative gradient with increase in renewable energy share in the system. The sensitivity analysis has been done assuming only up to around 22% of renewable energy source integration in the system, in order to keep the system and the analysis more practical.

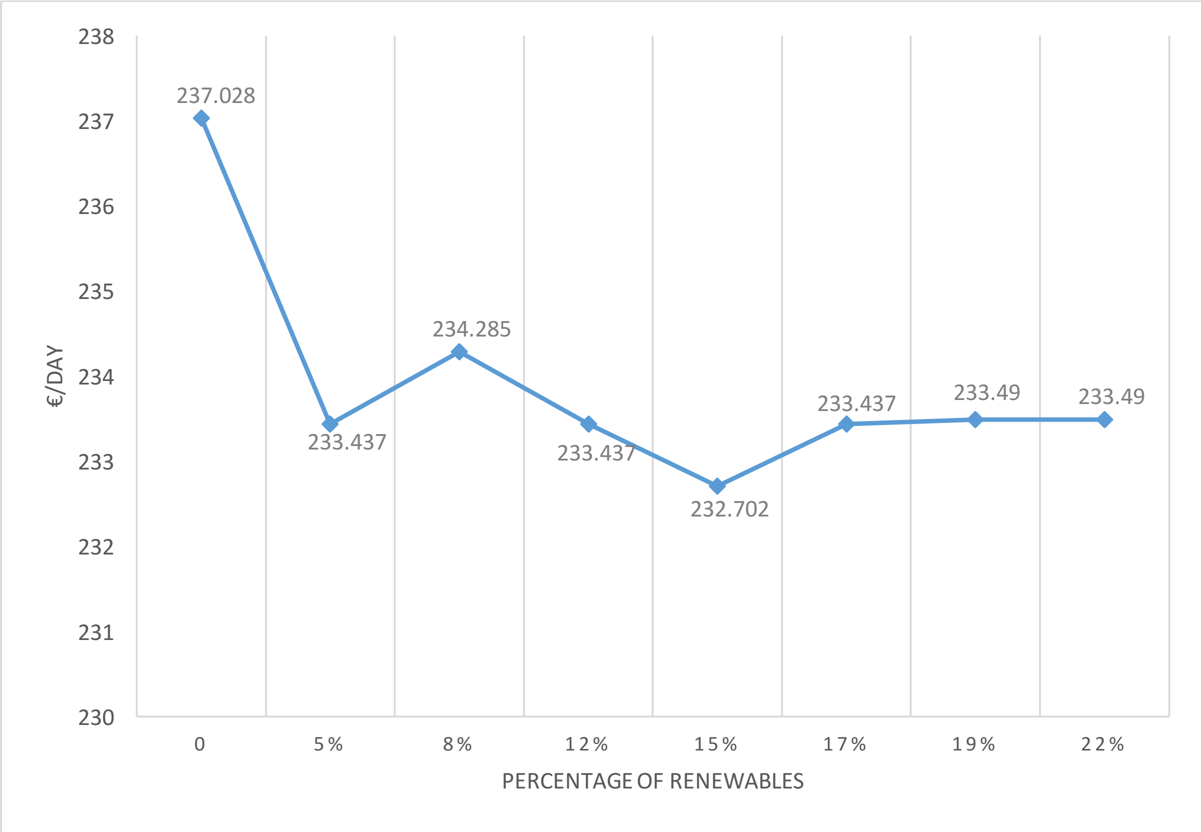

Figure 35 ENS variation with percentage increase in renewables

Hence, the microgrid system is more cost effective with increased renewable share in the system and also shows improvement in the reliability.

6. CONCLUSION

A small autonomous microgrid system with seven generators and a residential load profile was optimized for the cost function, including the fuel cost, start-up and shut-down costs. The system was found to be optimized at a value of 470.4 €/day when the system was supplied using 100% conventional generation at an ENS value of 237.02 KW, since the system assume initially was a congested system. The system was integrated with 17% of renewable energy sources, which showed a decrease in the value of both, operational cost of the system as well as the ENS. The total operational cost of the system was reduced by 11.4 % while the fuel cost only showed a drop of 23.6% with an ENS decrease of 1.5% of the initial. The reduced ENS value shows the improvement in the reliability of the system hence making it more desirable to introduce renewables.

The faults introduced in the conventional system reduced the system reliability increasing the value of ENS. The instant. As the number of generators with fault probability was increased in the system, the value of ENS increased as well as the costs of the system. The relative increase in ENS was much higher as compared to the relative increase in fuel cost, indicating that the system prefers to shut more loads down in case of a fault rather than increasing the generation of the system, finding the solution to be an optimal one. A solution to this would be integrating higher percentage of renewable energy resources in the system, so that the system doesn't have to make huge compromises by cutting down loads to a greater extent to avoid the cost in case of a fault.

The sensitivity analysis confirmed that the integration of renewables in the system reduced the fuel cost as well as the operational cost of the system, while causing a reduction in ENS. Hence, the system with higher percentage of renewables was cheaper with a better reliability.

7. FUTURE WORK

The current autonomous microgrid system was optimized with limited constraints under consideration due to the time limitations, hence only grid related electrical constraints have been included. Other constraint introducing factors like the uncertainty in power generation by renewable energy system could be introduced into the same code algorithm to make the values of power generation more practical. This could have inputs from weather stations for solar PV and wind energy generation forecasts, leading to realistic results. The same algorithm for the system could also be used for optimization in the grid connected operation of the microgrid, which would include parameters like intraday market prices in the grid, sales and purchase, making daily interaction with the grid and earning profit. In this case, depending on the priority of the system, the objective function would be working towards having the maximum profit in the system while ensuring the reliability.

Another possible extension of the work could be to integrate the optimization in a networked microgrid system in order to observe the results produced. A networked microgrid system could again work either in islanded or grid-connected modes, giving rise to different comparison scenarios. It would be interesting to observe the operation of a networked microgrid without grid connection, and to estimate the improvement in the reliability of the microgrid under such conditions.

Technical constraints in the introduction of renewables and their grid integration could also be included as constraints in the system in order to optimize the microgrid for a higher integration of renewables and to know the limit above which this integration would not be theoretically possible for the current day systems.

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9. APPENDIX

CODE FOR BASE CASE SCENARIO

```
GAMS 24.7.3  r58181 Released Jul 11, 2016 WEX-WEI x86 64bit/MS Windows 
09/26/18 16:56:40 Page 1
G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m
C o m p i l a t i o n


      The code is aimed towards basic optimisation of an autonomous
microgrid with various constraints. The objective function is total
cost of the system which includes the fuel cost and startup cost. The
constraints applied areupper and lower line limits, power balance,
generator limits, Spinning reserve, ramp up and down limits.
      Sets
      t                'time'                          /1*24/
      g                'no of generating units'        /1*13/
      n                'buses'                         /1*6/
      l                'lines'                         /1*7/
      bus_data         'bus data'                      /Pd, Voll,
v_int, t_int/
      gen_data         'generator data'                /Pgmax, Pgmin,
a, b, c, w
      arms, colds, ini_p, ini_u, Ramp, shutd/
      line_mat         'line matrix'                   /start, end,
Plmax/
      ;


      alias (n,m);

      Parameters

```

```
Pbase            'Base power'                    /100/
tot_cost         'total cost'                    /0/
ENS              'ENS'                           /0/
P_ch_max(n)      'maximum charging power'        /1      0
                                                  2      0
                                                  3      0
                                                  4      100
                                                  5      0
                                                  6      0/
*KW
P_dch_max(n)     'maximum discharging power'     /1      0
                                                  2      0
                                                  3      0
                                                  4      80
                                                  5      0
                                                  6      0/
eta_s            'efficiency of storage system'  /.9/
E_sto_max     'max energy storage capacity'   /4000/
*KWh
E_sto_min     'min energy storage capacity'    /1000/
*75% DoD
SR(t)            'spinning reserve'             /1      0.15
                                                 2      0.15
                                                 3      0.19
                                                 4      0.20
                                                 5      0.17
                                                 6      0.20
                                                 7      0.18
                                                 8      0.18
                                                 9      0.16
                                                 10     0.20
                                                 11     0.19
                                                 12     0.20
                                                 13     0.15
                                                 14     0.15
                                                 15     0.17
                                                 16     0.20
                                                 17     0.20
                                                 18     0.18
                                                 19     0.19
                                                 20     0.19
                                                 21     0.16
                                                 22     0.20
                                                 23     0.20
                                                 24     0.20/

;




Table load_level(n,t)
        1       2       3       4       5       6       7
8       9
        10      11      12      13      14      15      16      17
18
      19      20      21      22      23      24
```

```
1         0.69    0.78    0.73    0.82    0.85    1.03    0.98
1       0
      .97    0.92    0.60    0.62    0.78    0.78    0.98    0.92
1.09    1.5
      2    1        1.12    1.13    0.94    0.84    0.80
2         0.65    0.69    0.78    0.94    0.82    0.94    1.04
1.05    1
      .04    1.03    0.83    0.60    0.62    0.78    0.78    0.95
0.99    1.1
      9    1.05    1.34    1        1.22    0.95    0.89
3         0.65    0.65    0.73    0.73    0.97    0.99    1.09
1       1
      .03    0.92    0.99    0.70    0.98    0.98    0.75    1.03
1.05    1
           1.25    1.05    0.99    1.02    1.04    1
4         0.60    0.62    0.78    0.78    0.73    1.09    1.07
1       0
      .98    0.99    0.89    0.69    0.78    0.73    0.82    0.96
0.98    1.3
      9    1.05    1.25    1.09    0.97    0.97    0.80
5         0.70    0.73    0.73    0.73    0.73    0.89    1.01
0.92    0
      .95    0.90    0.99    0.98    0.97    0.89    1.03    1.01    1
1.2
      2    1.50    1.09    1.12    1        0.99    0.99
6         0.70    0.70    0.70    0.75    0.97    0.97    1
0.92    0
      .98    0.90    0.95    0.60    0.62    0.78    0.78    1.09
0.99    0.9
      8    1.22    1.28    1.09    1.05    0.97    0.99    ;


 Table bus_info(n,bus_data)
          Pd      Voll           v_int     t_int
1         97.5    100000          0.993    0
2         0       0               0.988    -0.0463
3         74.7    100000          1.003    -0.062
4         5.8     100000          1.001    -0.0396
5         11.2    100000          0.988    -0.0281
6         0       0               0.977    -0.054  ;


  Table gen_info(g,gen_data)
            Pgmax  Pgmin   a         b      c          warms colds
ini_p
          ini_u    Ramp    shutd
1           90      0       0.0       0.054  0          0.75  2.55
41.54
           1        9      0.30
2           90      0       0.0       0.047  0          0.75  2.55
55.4
           0        9      0.30
3           50      0       0.0       0.054  0          0.00  0.00
16.2
           1        5      0.00
4           100     0       0.0       0.054  0          0.75  2.55
22.74
           1        5      0.30
```

```
5          50      0        0.0        0.120  0          0.00  0.00
16.27
           1        5      0.00
6          150     0        0.0        0.047  0          0.75  2.55
39.91
           1        15     0.30
7          50      0        0.0        0.054  0          0.00  0.00
22.74
           1        5      0.00
8          97.5    0        0          1      0          0     0
2
           0        10     0
9          25.5    0        0          1      0          0     0
2
           0        2.5    0
10         74.7    0        0          1      0          0     0
5
           0        7      0
11         15.8    0        0          1      0          0     0
1
           0        1.5    0
12         11.2    0        0          1      0          0     0
1
           0        1      0
13         6.8     0        0          1      0          0     0
0.5
           0        0.6    0
 ;
*assuming a ramp of 10%

Table gen_bus(g,n) 'generator location information'
           1       2       3       4       5       6
1          1       0       0       0       0       0
2          1       0       0       0       0       0
3          0       0       1       0       0       0
4          0       0       0       0       1       0
5          0       0       0       0       1       0
6          0       0       0       0       1       0
7          0       0       0       1       0       0
8          1       0       0       0       0       0
9          0       1       0       0       0       0
10         0       0       1       0       0       0
11         0       0       0       1       0       0
12         0       0       0       0       1       0
13         0       0       0       0       0       1

 ;

Table    Line(l,line_mat) Lina data ( start. end. Plmax)
       start        end      Plmax
1      1            2        469.71
2      1            5        271.90
3      1            7        452.55
4      2            3        343.68
5      2            4        126.03
6      3            4        134.97
7      3            5        216.91      ;

```

```
Table    bbus(n,m) the matrix used for calculating of teta for bus n by productions of buses (P=BT))
        1         2           3           4           5         6
1       -87.51    78.018      0           0           3.846     0
2       78.018    -84.545     4.762       1.786       0         0
3       0         4.762       -70.926     41.616      20.435    4.112
4       0         1.786       41.616      -43.402     0         0
5       3.846     0           20.435      0           -24.281   0
6       0         0           4.112       0           0         -7.849
 ;

Table w(l,n,m)
         1.2     1.4     1.6     2.3     3.4     4.5     5.6
1        1       0       0       0       0       0       0
2        0       0       0       1       0       0       0
3        0       0       0       0       1       0       0
4        0       1       0       0       0       0       0
5        0       0       0       0       0       1       0
6        0       0       0       0       0       0       1
7        0       0       1       0       0       0       0
;


Binary variables

u(g,t)    'commitment status of gen g at time t'
ws(g,t)   'warm start up status of gen g at time t'
cs(g,t)   'cold start up status of gen g at time t'
sd(g,t)   'shut down status of gen g at time t'
u_ch(n,t)  'charging status of the storage system'
u_dch(n,t) 'dischrging status of the storage system'
;

Positive variable

P(g,t)    'power of generatin unit g'
P_ch(n,t)  'charging power of the storage for time t'
P_dch(n,t) 'discharging power of the storage fpr time t'
 ;

Variable

theta(n,t)       'voltage angle of bus n at time t'
Z                'total costs'
E_sto(t)         'storage energy at time t'
;

theta.lo(n,t)=-pi;
theta.up(n,t)=pi;

loop((n,t),theta.l(n,t)=bus_info(n,'t_int'));
loop((g,t),P.l(g,t)=gen_info(g,'ini_p'));
loop ((g,t),u.l(g,t)=gen_info(g,'ini_u'));

Equations
```

```
totcost                    'objective function'
slack_theta(t)             'slack angle'
ws_def(g,t)                'define warm start up'
cs_def(g,t)                'define cold start up'
sd_def(g,t)                'define shut down'
E_sto_def(t)               'E_sto definition'
E_sto_def2
line_const1(l,n,m,t)       'line limit upper boud'
line_const2(l,n,m,t)       'line limit lower bound'
pow_bal_const              'power balance constraint'
gen_const1(g,t)             'gen limit upper bound'
gen_const2(g,t)            'gen limit lower bound'
SR_const(t)                'spinning reserve constraint'
ramp_up(g,t)               'ramp up rate constraint'
ramp_down(g,t)             'ramp down rate constraint'
min_uptime(g,t)            'minimum up time constraint'
min_downtime(g,t)          'minimum down time constraint'
max_uptime(g,t)            'maximum up time constraint'
ch_const(n,t)                'charging constraint'
dch_const(n,t)               'discharging constraint'
ch_dch(n,t)                  'charge discharge status constraint'
E_sto_up_lim(t)            'storage capcity upper limit'
E_sto_down_lim(t)          'storage capacity lower limit'
;


totcost..                  Z =e=
sum((g,t),(gen_info(g,'b')*P(g,t)+gen_info(
      g,'c')))+
sum((g,t),ws(g,t)*gen_info(g,'warms'))+sum((g,t),cs(g,t)*gen_inf
      o(g,'colds'))+ sum((g,t),sd(g,t)*gen_info(g,'shutd'));


slack_theta(t)..           theta('1',t)=e=0 ;

cs_def(g,t)..              cs(g,t)=g=u(g,t)-u(g,t-1)-u(g,t-2)-
u(g,t-3)-u(g,t
      -4);
ws_def(g,t)..              ws(g,t)=g=u(g,t)-u(g,t-1)-cs(g,t);
*assuming a cold start up time of 4 hrs
sd_def(g,t)..              sd(g,t)=g=u(g,t-1)-u(g,t);

E_sto_def(t)..             E_sto(t)=e=E_sto(t-
1)+(E_sto_max/2)$(ord(t)=1)+ s
      um(n,eta_s*P_ch(n,t)-P_dch(n,t));
E_sto_def2..               E_sto('24')=e=E_sto_max/2;

line_const1(l,n,m,t)..     w(l,n,m)*Pbase*(bbus(n,m)*(theta(n,t)-
theta(m,t))
      *1.0)=l=line(l,'Plmax');
line_const2(l,n,m,t)..     w(l,n,m)*Pbase*(bbus(n,m)*(theta(n,t)-
theta(m,t))
      *1.0)=g=-line(l,'Plmax');

pow_bal_const(n,t)..       sum(g,gen_bus(g,n)*P(g,t))-
(bus_info(n,'Pd')*load
      _level(n,t))+(P_ch(n,t)-P_dch(n,t))=e=
Pbase*sum(m,bbus(n,m)*(theta(n,t)-t
```

```
heta(m,t)));

gen_const1(g,t)..       P(g,t)=l=gen_info(g,'Pgmax')*u(g,t);
gen_const2(g,t)..        P(g,t)=g=gen_info(g,'Pgmin')*u(g,t);

SR_const(t).. sum(g,gen_info(g,'Pgmax')*u(g,t))=g=sum(n,(bus_info(n,'Pd')*load_level(n,t)*(1+SR(t))));

ramp_up(g,t)..           P(g,t)- P(g,t-1)=l=gen_info(g,'Ramp');
ramp_down(g,t)..         P(g,t)- P(g,t-1)=g=-gen_info(g,'Ramp');



min_uptime(g,t)..        (cs(g,t)+ws(g,t))+(cs(g,t-1)+ws(g,t-1))+(cs(g,t-2)+ws(g,t-2))=l=u(g,t);
*min up time of 3 hrs
min_downtime(g,t)..      sd(g,t)+sd(g,t-1)+sd(g,t-2)+sd(g,t-3)=l=1-u(g,t);
*min downtime of 4 hrs

max_uptime(g,t)..         u(g,t)+u(g,t-1)+u(g,t-2)+u(g,t-3)+u(g,t-4)+u(g,t-5)+u(g,t-6)+u(g,t-7)+u(g,t-8)+u(g,t-9)+u(g,t-10)+u(g,t-11)+u(g,t-12)=l=12;

ch_const(n,t)..          P_ch(n,t)=l=u_ch(n,t)*P_ch_max(n);

dch_const(n,t)..         P_dch(n,t)=l=u_dch(n,t)*P_dch_max(n);

ch_dch(n,t)..            u_ch(n,t)+u_dch(n,t)=l=1;

E_sto_up_lim(t)..        E_sto(t)=l=E_sto_max;

E_sto_down_lim(t)..      E_sto(t)=g=E_sto_min;


Model OAMG /all/;
*options optcr = 0;
*options optca = 0;
*OAMG.nodlim = 10000000;
*OAMG.iterlim = 100000000;
*OAMG.reslim = 10000000 ;
Solve OAMG using MIP minimizing Z;

ENS= sum(t,P.l('8',t)+P.l('9',t)+P.l('10',t)+P.l('11',t)+P.l('12',t)+P.l('13',t) ) ;

tot_cost = sum((g,t),(gen_info(g,'a')*P.l(g,t)*P.l(g,t)+gen_info(g,'b')*P.l(g,t)+gen_info(g,'c')))-ENS*gen_info('8','b');

Display tot_cost, u.l, ws.l, cs.l, P.l, P_ch.l, P_dch.l, theta.l, E_sto.l,
 Z.l, ENS ;
```

CODE FOR FAULT CASE SCENARIOS

```
GAMS 24.7.3  r58181 Released Jul 11, 2016 WEX-WEI x86 64bit/MS Windows
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G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m
C o m p i l a t i o n


      The code is aimed towards basic optimisation of an autonomous
microgrid wi
      th various constraints. The objective
      function is total cost of the system which includes the fuel cost
and star
      t up cost. The constraints applied are
      upper and lower line limits, power balance, generator limits,
Spinning res
      erve, ramp up and down limits.
      Sets
      t                 'time'                          /1*24/
      g                 'no of generating units'        /1*13/
      n                 'buses'                         /1*6/
      l                 'lines'                         /1*7/
      s                 'scenarios'                     /1*4/
      bus_data          'bus data'                      /Pd, Voll,
v_int, t_int/
      gen_data          'generator data'                /Pgmax, Pgmin,
a, b, c, w
      arms, colds, ini_p, ini_u, Ramp, shutd/
      line_mat          'line matrix'                   /start, end,
Plmax/
      ;
      alias (n,m);
      Parameters
      Pbase             'Base power'                    /100/
      tot_cost          'total cost'                    /0/
      ENS               'ENS'                           /0/
      P_ch_max(n)       'maximum charging power'        /1      0
                                                         2      0
                                                         3      0
                                                         4      100
                                                         5      0
                                                         6      0/
      *KW
      P_dch_max(n)      'maximum discharging power'     /1      0
                                                         2      0
                                                         3      0
                                                         4      80
                                                         5      0
                                                         6      0/
      eta_s             'efficiency of storage system'  /.9/
      E_sto_max     'max energy storage capacity'   /4000/
```

```
*KWh
E_sto_min      'min energy storage capacity'    /1000/
*75% DoD
SR(t)            'spinning reserve'             /1      0.15
                                                  2      0.15
                                                  3      0.19
                                                  4      0.20
                                                  5      0.17
                                                  6      0.20
                                                  7      0.18
                                                  8      0.18
                                                  9      0.16
                                                  10     0.20
                                                  11     0.19
                                                  12     0.20
                                                  13     0.15
                                                  14     0.15
                                                  15     0.17
                                                  16     0.20
                                                  17     0.20
                                                  18     0.18
                                                  19     0.19
                                                  20     0.19
                                                  21     0.16
                                                  22     0.20
                                                  23     0.20
                                                  24     0.20/


;


Table load_level(n,t)
        1       2       3       4       5       6       7
8       9
        10      11      12      13      14      15      16      17
18
        19      20      21      22      23      24
1       0.69    0.78    0.73    0.82    0.85    1.03    0.98
1       0
.97     0.92    0.60    0.62    0.78    0.78    0.98    0.92
1.09    1.5
2   1       1.12    1.13    0.94    0.84    0.80
2       0.65    0.69    0.78    0.94    0.82    0.94    1.04
1.05    1
.04     1.03    0.83    0.60    0.62    0.78    0.78    0.95
0.99    1.1
9   1.05    1.34    1       1.22    0.95    0.89
3       0.65    0.65    0.73    0.73    0.97    0.99    1.09
1       1
.03     0.92    0.99    0.70    0.98    0.98    0.75    1.03
1.05    1
    1.25    1.05    0.99    1.02    1.04    1
4       0.60    0.62    0.78    0.78    0.73    1.09    1.07
1       0
.98     0.99    0.89    0.69    0.78    0.73    0.82    0.96
0.98    1.3
9   1.05    1.25    1.09    0.97    0.97    0.80
```

```
5         0.70    0.73    0.73    0.73    0.73    0.89    1.01
0.92    0
     .95    0.90    0.99    0.98    0.97    0.89    1.03    1.01    1
1.2
     2    1.50    1.09    1.12    1       0.99    0.99
6         0.70    0.70    0.70    0.75    0.97    0.97    1
0.92    0
     .98    0.90    0.95    0.60    0.62    0.78    0.78    1.09
0.99    0.9
     8    1.22    1.28    1.09    1.05    0.97    0.99    ;

 Table bus_info(n,bus_data)
          Pd      Voll           v_int     t_int
1         97.5    100000          0.993    0
2         0       0               0.988    -0.0463
3         74.7    100000          1.003    -0.062
4         5.8     100000          1.001    -0.0396
5         11.2    100000          0.988    -0.0281
6         0       0               0.977    -0.054  ;

Table gen_info(g,gen_data)
           Pgmax  Pgmin   a         b      c          warms colds
ini_p
      ini_u    Ramp    shutd
1          90      0       0.0       0.054  0          0.75  2.55
41.54
       1        9      0.30
2          90      0       0.0       0.047  0          0.75  2.55
55.4
       0        9      0.30
3          50      0       0.0       0.054  0          0.00  0.00
16.2
       1        5      0.00
4          100     0       0.0       0.054  0          0.75  2.55
22.74
       1        5      0.30
5          50      0       0.0       0.120  0          0.00  0.00
16.27
       1        5      0.00
6          150     0       0.0       0.047  0          0.75  2.55
39.91
       1        15     0.30
7          50      0       0.0       0.054  0          0.00  0.00
22.74
       1        5      0.00
8          97.5    0       0         1      0          0     0
2
       0        10     0
9          25.5    0       0         1      0          0     0
2
       0        2.5    0
10         74.7    0       0         1      0          0     0
5
       0        7      0
11         15.8    0       0         1      0          0     0
1
```

```
            0        1.5    0
12         11.2   0       0         1      0          0     0
1
            0        1      0
13          6.8    0       0         1      0          0     0
0.5
            0        0.6    0
 ;
*assuming a ramp of 10%

Table gen_bus(g,n) 'generator location information'
          1       2       3       4       5       6
1         1       0       0       0       0       0
2         1       0       0       0       0       0
3         0       0       1       0       0       0
4         0       0       0       0       1       0
5         0       0       0       0       1       0
6         0       0       0       0       1       0
7         0       0       0       1       0       0
8         1       0       0       0       0       0
9         0       1       0       0       0       0
10        0       0       1       0       0       0
11        0       0       0       1       0       0
12        0       0       0       0       1       0
13        0       0       0       0       0       1

 ;

Table    Line(l,line_mat) Lina data ( start. end. Plmax)
      start        end      Plmax
1     1            2        469.71
2     1            5        271.90
3     1            7        452.55
4     2            3        343.68
5     2            4        126.03
6     3            4        134.97
7     3            5        216.91      ;

Table    bbus(n,m) the matrix used for calculating of teta for
bus n by pr
      oductions of buses (P=BT))
        1          2          3          4          5          6
1      -87.51      78.018     0          0          3.846      0
2      78.018      -84.545    4.762      1.786      0          0
3      0           4.762      -70.926    41.616     20.435
4.112
4      0           1.786      41.616     -43.402    0          0
5      3.846       0          20.435     0          -24.281    0
6      0           0          4.112      0          0          -
7.849
 ;

Table w(l,n,m)
          1.2     1.4     1.6     2.3     3.4     4.5     5.6
1         1       0       0       0       0       0       0
2         0       0       0       1       0       0       0
3         0       0       0       0       1       0       0
4         0       1       0       0       0       0       0
```

```
5        0       0       0       0       0       1       0
6        0       0       0       0       0       0       1
7        0       0       1       0       0       0       0
;


Table gen_avail(s,g)
         1       2       3       4       5       6       7
8       9
        10      11      12      13
1        1       1       1       1       1       1       1
1       1
        1       1       1       1
2        0       1       1       1       1       1       1
1       1
        1       1       1       1
3        1       0       1       1       1       1       1
1       1
        1       1       1       1
4        1       1       1       1       0       1       1
1       1
        1       1       1       1
;

Binary variables

u(s,g,t)          'commitment status of gen g at time t'
ws(s,g,t)         'warm start up status of gen g at time t'
cs(s,g,t)         'cold start up status of gen g at time t'
sd(s,g,t)         'shut down status of gen g at time t'
u_ch(s,n,t)       'charging status of the storage system'
u_dch(s,n,t)      'dischrging status of the storage system'
;

Positive variable

P(s,g,t)          'power of generatin unit g'
P_ch(s,n,t)       'charging power of the storage for time t'
P_dch(s,n,t)      'discharging power of the storage fpr time t'
 ;

Variable

theta(s,n,t)      'voltage angle of bus n at time t'
Z(s)              'scenario costs'
E_sto(s,t)          'storage energy at time t'
X                 'total cost'
;

theta.lo(s,n,t)=-pi;
theta.up(s,n,t)=pi;

loop((n,t),theta.l(s,n,t)=bus_info(n,'t_int'));
loop((g,t),P.l(s,g,t)=gen_info(g,'ini_p'));
loop ((g,t),u.l(s,g,t)=gen_info(g,'ini_u'));

Equations
totcost                   'objective function'
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```
scencost(s)              'cost function of each scenario'
slack_theta(s,t)         'slack angle'
ws_def(s,g,t)            'define warm start up'
cs_def(s,g,t)            'define cold start up'
sd_def(s,g,t)            'define shut down'
E_sto_def(s,t)           'E_sto definition'
E_sto_def2
line_const1(s,l,n,m,t)     'line limit upper boud'
line_const2(s,l,n,m,t)     'line limit lower bound'
pow_bal_const(s,n,t)          'power balance constraint'
gen_const1(s,g,t)            'gen limit upper bound'
gen_const2(s,g,t)          'gen limit lower bound'
SR_const(s,t)              'spinning reserve constraint'
ramp_up(s,g,t)             'ramp up rate constraint'
ramp_down(s,g,t)           'ramp down rate constraint'
min_uptime(s,g,t)          'minimum up time constraint'
min_downtime(s,g,t)        'minimum down time constraint'
max_uptime(s,g,t)          'maximum up time constraint'
ch_const(s,n,t)              'charging constraint'
dch_const(s,n,t)             'discharging constraint'
ch_dch(s,n,t)                'charge discharge status constraint'
E_sto_up_lim(s,t)          'storage capcity upper limit'
E_sto_down_lim(s,t)        'storage capacity lower limit'
;

totcost..                X=e= Z('1')*0.7+
Z('2')*0.15+Z('3')*0.10+Z('4')*0
      .05;
scencost(s)..            Z(s)=e=
sum((g,t),(gen_info(g,'b')*P(s,g,t)+gen_i
      nfo(g,'c')))+
sum((g,t),ws(s,g,t)*gen_info(g,'warms'))+sum((g,t),cs(s,g,t)
      *gen_info(g,'colds'))+ sum((g,t),sd(s,g,t)*gen_info(g,'shutd'));


slack_theta(s,t)..         theta(s,'1',t)=e=0 ;

cs_def(s,g,t)..          cs(s,g,t)=g=u(s,g,t)-u(s,g,t-1)-u(s,g,t-
2)-u(s,g,
      t-3)-u(s,g,t-4);
ws_def(s,g,t)..          ws(s,g,t)=g=u(s,g,t)-u(s,g,t-1)-
cs(s,g,t);
*assuming a cold start up time of 4 hrs
sd_def(s,g,t)..          sd(s,g,t)=g=u(s,g,t-1)-u(s,g,t);

E_sto_def(s,t)..         E_sto(s,t)=e=E_sto(s,t-
1)+(E_sto_max/2)$(ord(t)=1
      )+ sum(n,eta_s*P_ch(s,n,t)-P_dch(s,n,t));
E_sto_def2(s)..          E_sto(s,'24')=e=E_sto_max/2;

line_const1(s,l,n,m,t)..
w(l,n,m)*Pbase*(bbus(n,m)*(theta(s,n,t)-theta(s
      ,m,t))*1.0)=l=line(l,'Plmax');
line_const2(s,l,n,m,t)..
w(l,n,m)*Pbase*(bbus(n,m)*(theta(s,n,t)-theta(s
      ,m,t))*1.0)=g=-line(l,'Plmax');

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pow_bal_const(s,n,t)..    sum(g,gen_bus(g,n)*P(s,g,t))-(bus_info(n,'Pd')*load_level(n,t))+(P_ch(s,n,t)-P_dch(s,n,t))=e=Pbase*sum(m,bbus(n,m)*(theta(s,n,t)-theta(s,m,t)));

gen_const1(s,g,t)..       P(s,g,t)=l=gen_info(g,'Pgmax')*u(s,g,t)*gen_avail(s,g);
gen_const2(s,g,t)..       P(s,g,t)=g=gen_info(g,'Pgmin')*u(s,g,t);

SR_const(s,t)..           sum(g,gen_info(g,'Pgmax')*u(s,g,t))=g=sum(n,(bus_info(n,'Pd')*load_level(n,t)*(1+SR(t))));

ramp_up(s,g,t)..          P(s,g,t)- P(s,g,t-1)=l=gen_info(g,'Ramp');
ramp_down(s,g,t)..        P(s,g,t)- P(s,g,t-1)=g=-gen_info(g,'Ramp');

min_uptime(s,g,t)..       (cs(s,g,t)+ws(s,g,t))+(cs(s,g,t-1)+ws(s,g,t-1))+(cs(s,g,t-2)+ws(s,g,t-2))=l=u(s,g,t);
*min up time of 3 hrs
min_downtime(s,g,t)..     sd(s,g,t)+sd(s,g,t-1)+sd(s,g,t-2)+sd(s,g,t-3)=l=1-u(s,g,t);
*min downtime of 4 hrs

max_uptime(s,g,t)..        u(s,g,t)+u(s,g,t-1)+u(s,g,t-2)+u(s,g,t-3)+u(s,g,t-4)+u(s,g,t-5)+u(s,g,t-6)+u(s,g,t-7)+u(s,g,t-8)+u(s,g,t-9)+u(s,g,t-10)+u(s,g,t-11)+u(s,g,t-12)=l=12;

ch_const(s,n,t)..         P_ch(s,n,t)=l=u_ch(s,n,t)*P_ch_max(n);

dch_const(s,n,t)..        P_dch(s,n,t)=l=u_dch(s,n,t)*P_dch_max(n);

ch_dch(s,n,t)..           u_ch(s,n,t)+u_dch(s,n,t)=l=1;

E_sto_up_lim(s,t)..       E_sto(s,t)=l=E_sto_max;

E_sto_down_lim(s,t)..     E_sto(s,t)=g=E_sto_min;

Model OAMG /all/;
*options optcr = 0;
*options optca = 0;
*OAMG.nodlim = 10000000;
*OAMG.iterlim = 100000000;
*OAMG.reslim = 10000000 ;
```

```
Solve OAMG using MIP minimizing X;

ENS= sum((s,t),(P.l(s,'8',t)+P.l(s,'9',t)+P.l(s,'10',t)+P.l(s,'11',t)+P.l(s,'12',t)+P.l(s,'13',t))) ;
tot_cost = sum((s,g,t),(gen_info(g,'a')*P.l(s,g,t)*P.l(s,g,t)+gen_info(g,'b')*P.l(s,g,t)+gen_info(g,'c')))-ENS*gen_info('8','b');

Display  tot_cost, u.l, ws.l, cs.l, P.l, P_ch.l, P_dch.l, theta.l, E_sto.l, Z.l, X.l, ENS;
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