Grid connected operations of Demand Responsive Microgrid

PROJECT REPORT

Submitted by

Kumar Pallav Singh Rathore

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Dr. K. Shanti Swarup

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2022

BONAFIDE CERTIFICATE

This is to certify that this thesis (or project report) titled ***"Grid connected operations of Demand Responsive Microgrid"*** submitted by **Kr. Pallav Singh Rathore** to the Indian Institute of Technology Madras, for the award of the degree of **Master of Technology** is a bona fide record of the research work done by him under my supervision. The contents of this thesis (or project report), in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

Dr. K Shanti Swarup
Project Guide
Professor
Department of Electrical Engineering
Indian Institute of Technology Madras

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Abstract

Self-sufficient microgrids are connecting remote parts of habitation. Self -sufficient microgrids could have an option to connect to the grid in case of an emergency like outage or resource inadequacy. Grid-Synchronization is a tricky process and has to pre-planned. In this paper, we propose a check that allows us to determine if an emergency situation warrants a necessity to synchronize with the grid. The microgrid is assumed to be highly demand responsive and will try to mitigate the emergency through demand response first. The proposed methodology is based on Farka's Lemma and will be able to determine if demand response is sufficient or it is necessary to connect to the grid. The proposed methodology was tested on a microgrid setting with 1100 devices and 200 emergency conditions. The paper shows that the reformulation with Farka's Lemma can speed up the emergency check and initiate demand response or grid-synchronization which ever necessary.

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ABBREVIATION

DR Demand Response

IDR Industrial Demand Response

CDR Commercial Demand Response

RDR Residential Demand Response

Chapter 1

Introduction

Renewable energy sources are becoming increasingly popular as a source of power in areas where connecting to the utility grid is either impossible or unreasonably expensive. As electric distribution technology enters the twenty-first century, various trends have emerged that will alter the requirements for energy transmission. The ever-increasing demand for energy, the rising price and limited nature of fossil fuels, as well as the deteriorating global environment, have sparked increased interest in green power generation technologies. Because of the rapid depletion of fossil fuels and rising energy demand, renewable energy sources have attracted worldwide attention. Since the Industrial Revolution, fossil fuels have dominated the electricity generation of most countries on the planet. This has far-reaching repercussions for both the global climate and human health. The burning of fossil fuels for energy accounts for three-quarters of global greenhouse gas emissions. Furthermore, fossil fuels are responsible for a major amount of local air pollution, which causes at least 5 million premature deaths each year. To reduce CO2 emissions and local air pollution, the world must rapidly transition to low-carbon energy sources such as nuclear and renewables. In the coming decades, renewable energy will play a critical role in decarbonizing our energy systems.

1.1 Rural Electrification

Across the globe, billions of people lack access to electricity. The majority are found in developing-country rural areas. Access to electricity provides numerous benefits to developing-world societies, including the replacement of hazardous lighting techniques such as kerosene and the generation of additional cash through enhanced productivity. Traditionally, new electrical connections to villages have been provided through the development of centralised networks. This strategy is economically unsustainable for some isolated populations because it often involves increasing the generation capacity of dispatchable generators, which release pollutants that contribute to the greenhouse effect, and it might take decades to extend infrastructure to rural areas. Decentralized microgrids powered by renewable energy, on the other hand, may be set up reasonably rapidly and cheaply thus It is possible to deliver electricity to remote areas of the world at a low cost.
Microgrids are small electrical grid systems capable of generating and transporting power to points of use in the rural context electrification. Microgrids can function independently as islands or as part of a bigger network. Microgrid development for rural electrification has mostly focused on measures such as net present cost, loss of load likelihood, capital cost, and CO2 emissions. While these indicators are important, demand-side design concerns are often overlooked. Inclusion of design-side factors necessitates a more in-depth understanding of the business framework of rural mini-utilities as well as end-user needs.

1.2 Current State of Global Electrification

The percentage of primary energy consumption that came from renewable technologies — a combination of hydropower, solar, wind, geothermal, wave, tidal, and modern biofuels – is depicted in this graph. The information shown in graph below is based on primary energy determined using the substitution method, which attempts to account for inefficiencies in fossil fuel production. This is achieved by converting non-fossil fuel sources to their 'input equivalents, or the amount of primary energy necessary to produce the same amount of energy using fossil fuels.

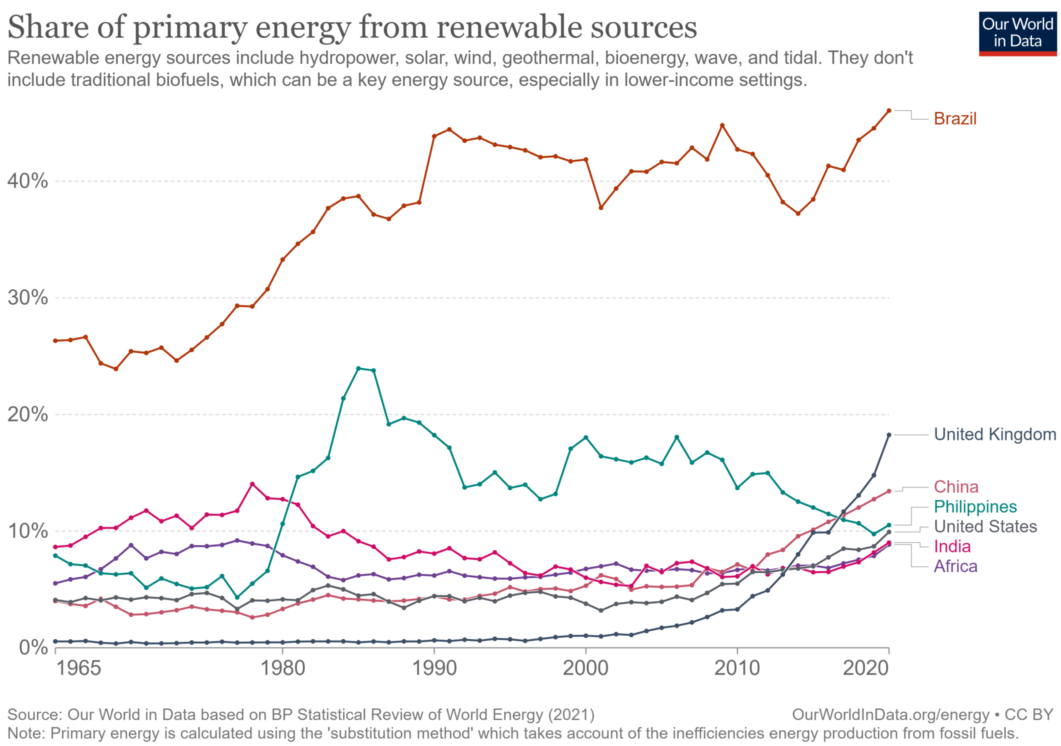


Figure 1.1: Current State of Global Electrification

1.3 Breakdown of Renewables

In the preceding section, we saw how much of the energy mix was accounted for by renewable technologies collectively. The infographics below divide down renewable technologies into their respective components - hydropower, solar, wind, and others. The first chart depicts this as a stacked area chart, allowing us to understand the breakdown of the renewable mix and the relative contribution of each. The second figure is a line chart, which allows us to observe how each source changes over time more clearly.

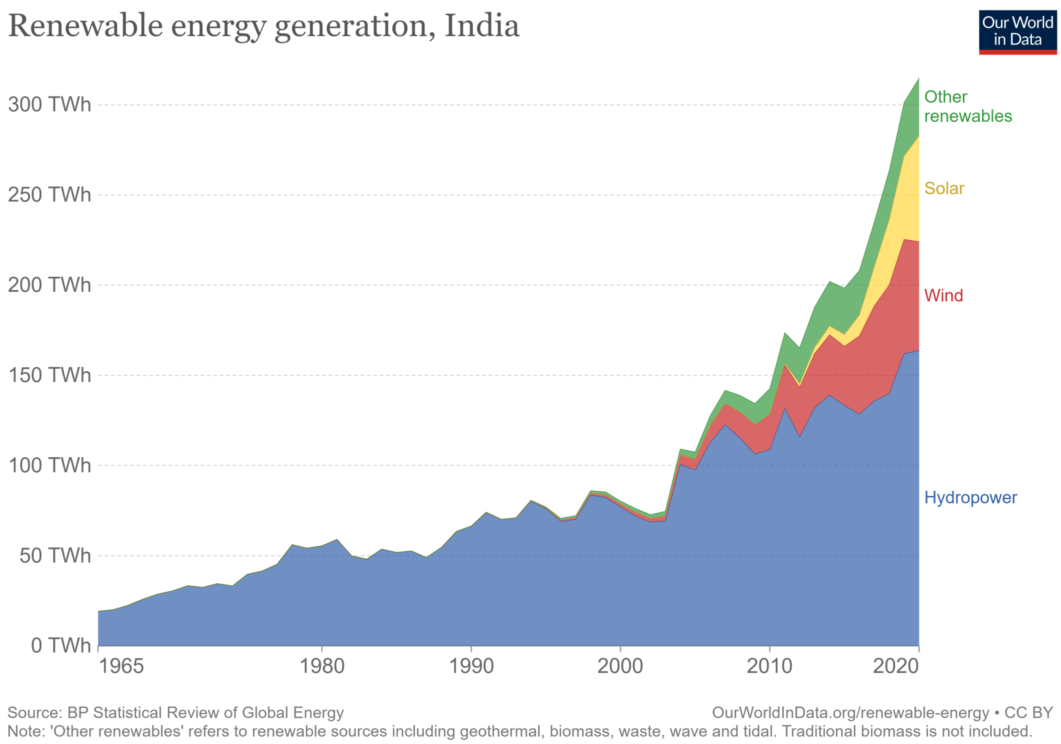


Figure 1.2: Renewable Energy Generation, India

1.4 Share of electricity from renewable technologies

In the previous section, we discussed the role of renewables in the energy portfolio. It would not only include power, but also transportation and heating. Electricity is simply one component of overall energy use. This interactive graph depicts the percentage of electricity generated by renewable technology. Around one-quarter of our global electricity originates from renewable sources.

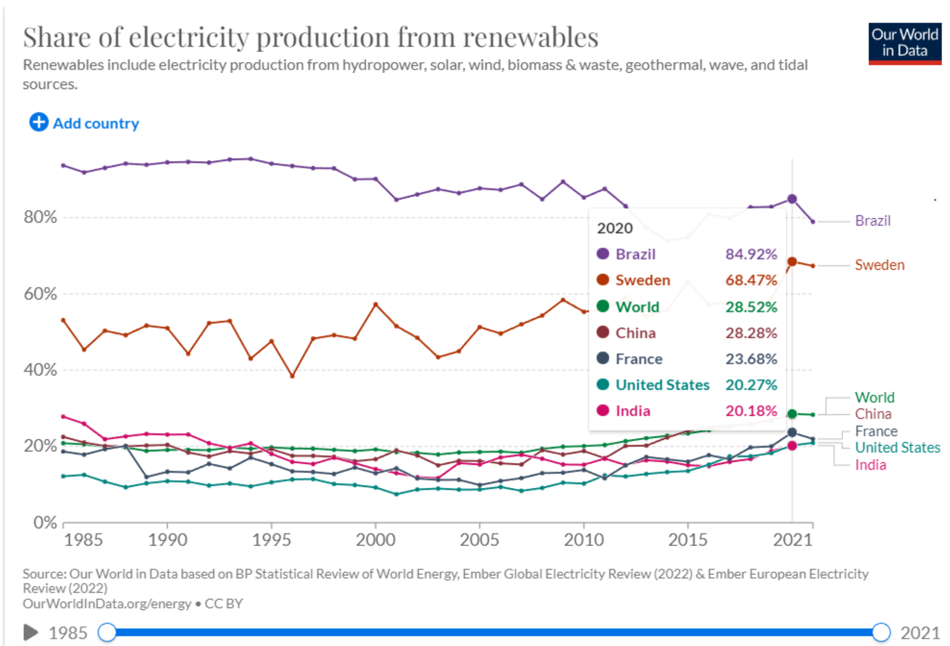


Figure 1.3: Share of electricity production from renewables

1.5 Hydropower, Solar and Wind Energy Generation

- Hydroelectric power is one of oldest and largest low-carbon energy sources. Hydroelectric generating on a significant scale stretches back more than a century and is our most important renewable source - excluding conventional biomass, it accounts for more than 60% of renewable generation. In 2019, around 7% of global energy came from hydropower.
- Wind power generation at scale, in comparison to hydropower, is a relatively new renewable energy source that is rapidly expanding in many nations throughout the world. In 2019, around 2% of global energy came from wind.
- Similar like wind power generation solar generation at scale, in comparison to hydropower, is a relatively new renewable energy source that is rapidly expanding in many nations throughout the world. In 2019, around 1% of global energy came from wind.

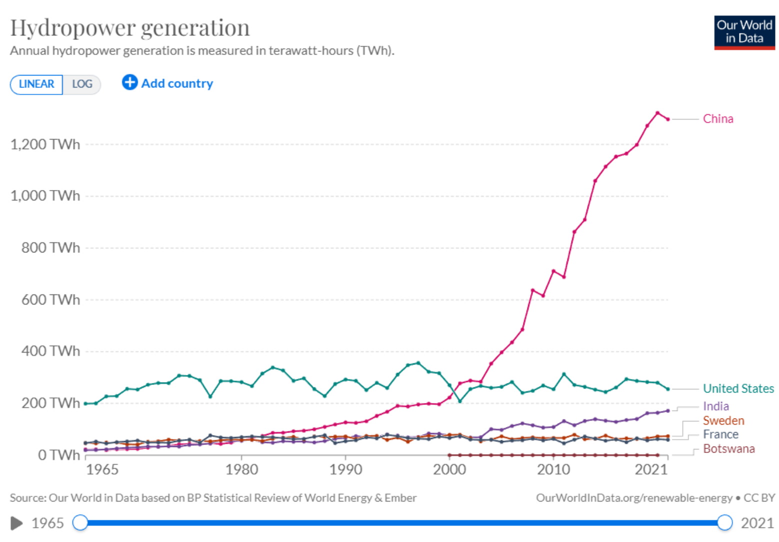


Figure 1.4: Hydropower Generation

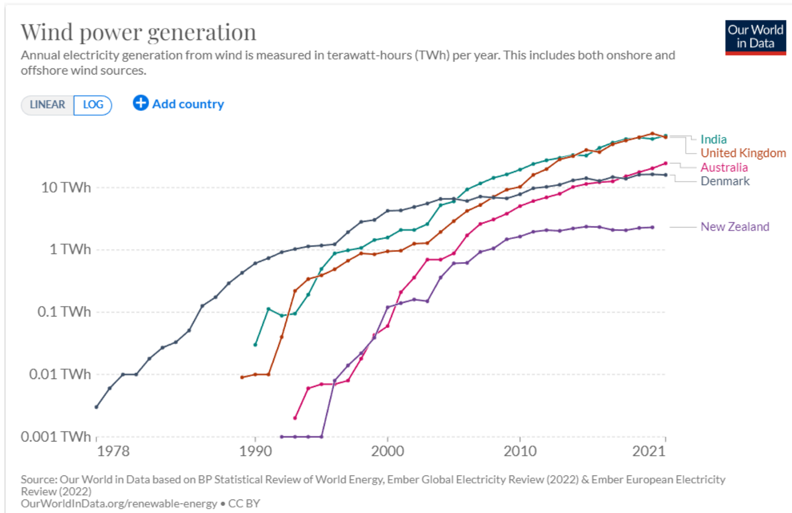


Figure 1.5: Wind Power Generation

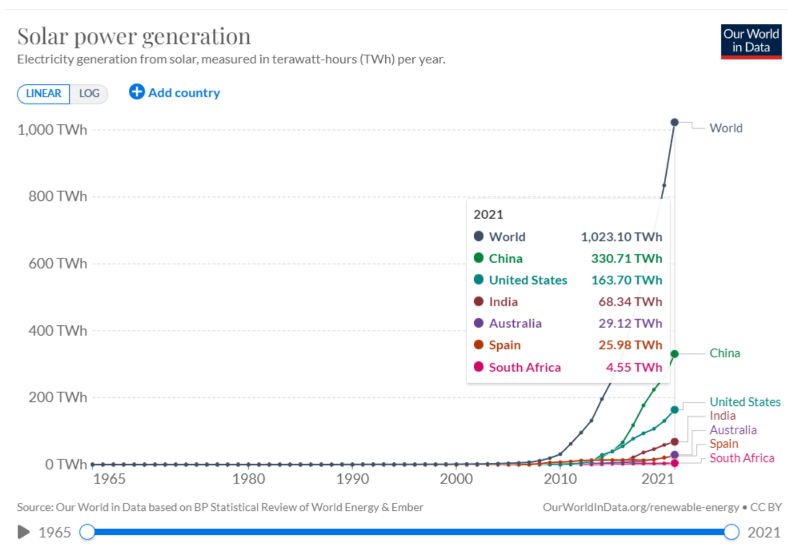


Figure 1.6: Solar Power Generation

1.6 Organization of Thesis

Chapter 1 of this thesis contains a basic introduction of the various topics related to the work. It contains some graphical overview of the current state of electrification and various sources of renewable energy along with their share in the total power sector. Chapter 2 introduces the concept of Demand Response along with its types and different strategies to achieve it. Chapter 3 presents an introduction to micro grids, various components, types of microgrids and several possible problems in it.

Chapter 4 defines the problem to be solved in this work, its mathematical formulation and the approach followed to solve it. We will use the concept of Linear Programming to get over this problem. Different proprietary solvers available for the purpose are briefly introduced. Chapter 5 presents a case study on IEEE 33 bus system microgrid taking into account a standard literature. Chapter 6 presents an optimized view of the problem discussed above with the help of a novel technique called Farkas' Lemma. It also introduces a test system of 1100 devices and 200 generators.

Chapter 7 presents simulation results and some discussions on them, the source code of which is presented in the appendices. The work cuminates with Chapter 8 where the discussions above have been merged to a meaningful conclusion and some related future prospects of the project are also discussed.

Chapter 2

Demand Response in Microgrids

2.1 Introduction

With the increasingly demanding challenges of the growing electricity needs, aging infrastructure and the integration of renewable green energy resources, a new way of addressing these demands will need to be developed by electricity distribution networks. As we have already mentioned, new smart electricity distribution networks face these challenges by managing the concept of demand response. Essentially, the demand response management refers to the implementation of techniques to control energy consumption by consumers, improve energy efficiency and reduce the cost of electricity generation from electricity companies. One of the key objectives of demand response management is to reduce the differences between electricity consumption and average consumption in the network so that there is a balance between demand and supply. DR generally refers to the mechanisms created in order to manage (or try and influence) the Consumer Demand in response to the prevalent Supply Conditions. It rides mainly on the existence of Dynamic Energy Management Systems on the grid.

DR is the action taken to change peak load in response to:

- Price Signals

- Shifting load to avoid high priced periods or take benefit of low priced periods
- Reliability signals
- curtailment of load to address demand supply imbalances that threaten system operation
- Contingencies (emergencies congestion) occur to address transmission or distribution congestion and voltage problems

Another way is to implement a proper demand response mechanism which will encourage users to adapt their demands such that the load is shifted from peak hours to offpeak hours. This shifting will enable the grid to manage the electricity demand more aptly because now the peak demand would be within its limits. This kind of a demand response execution requires some sort of incentive for the consumers to not participate in the program and adapt their electricity requirement to make the overall demand as steady as possible.

Usually, dynamic pricing is the best measure to achieve this; the electricity companies would make electricity expensive during the peak load hours and cheaper during hours when the demand is lower. Electricity companies usually have a very good idea of the load pattern that is going to be followed any given day and coordinating this data along with the supply capacity of their generation plants they can devise a more dynamic form of their electricity pricing. The closer the demand pattern to the pricing pattern, the better the load management and a more steady overall demand from the consumers. Some of the classic forms of load pattern management are Peak Clipping, Load Shifting and Valley Filling.

- **Peak Clipping** solely focuses on reducing the peak electricity demand, it doesn't care about the rest of the demand curve but only tries to bring the peak value into its achievable value.
- **Valley Filling** is when the depression in the demand curve are filled so as to reduce the possible demand later, this can be done by lowering the pricing

when the demand is low or by encouraging users to store energy backup so they can be utilised at the peak hours.

- **Load Shifting** is when the loads are shifted from peak to valley times, this includes applications such as space heating, water heating etc. The difference between this and clipping is that here the net demand is not changed whereas in clipping the demand is eliminated.

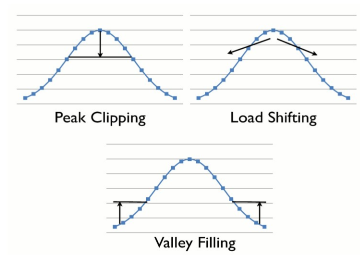
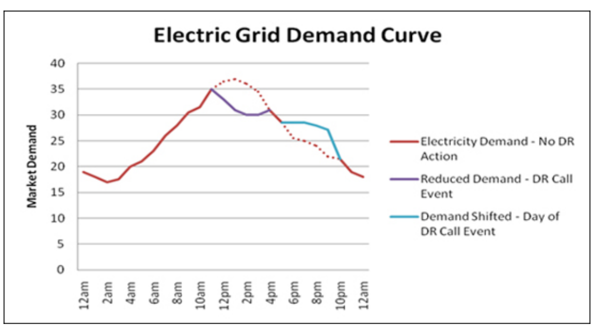
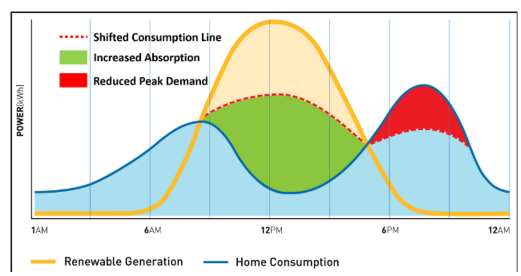


Figure 2.1: Load Pattern Management



(a) Demand Curve (1)



(b) Demand Curve (2)

Figure 2.2: Demand Response Curves

2.2 Types of Demand Response

1. Emergency Demand Response
2. Economic Demand Response
3. Ancillary Service Demand Response

Emergency Demand Response is used to mitigate the potential for blackouts or brownouts during times when demand threatens to exceed supply resources. This typically occurs on days of extreme hot or cold temperatures when heating and cooling systems are causing greater demand on the grid. **Economic Demand Response** is employed by utilities to avoid the significantly higher costs of producing energy during peak demand times of the day that is associated with ramping up ”peaking” power plants to meet higher than expected demand. **Ancillary Service Demand Response** is used to support the transmission of electricity to loads in a manner consistent with reliability requirements that are imposed on utility companies by industry regulators.

2.3 Demand Response Strategies

There are two common ways in which demand response events are executed by utility companies including:

- **Direct Load Control** demand response events involve the remote interruption of customers' energy usage, in which power distributors cycle loads like heating, cooling, elevators, washing etc. on and off at varying time intervals during peak hours of the day.
- **Dynamic Pricing** uses variable electricity rates to encourage customers' voluntary curtailment during demand response events. Utilities use a variety of pricing schemes including peak time rebates, critical peak pricing, and time of use rates to curtail usage.

2.4 Introduction to Microgrids

Microgrid is a modern distributed power system that is constructed using localized sustainable power supplies as part of several smart-grid efforts. It also provides energy security for a local community because it may function independently of the larger utility grid. In general, microgrid technology represents three essential societal goals: reliability (physical and cyber), sustainability (environmental considerations), and economics (cost optimizing, efficiency). The term ”distributed generation” (DG) refers to power generation that is placed close or at the consumption sites. In compared to ”central generation,” distributed generation can minimise generating, transmission, and distribution costs while enhancing efficiency by reducing factors of complexity and interdependence. Distributed generators can often give reduced generation costs, improved reliability, and increased security.

A microgrid reduces generation costs significantly while providing reliable and sustainable electricity to loads. Because of the system's localised character, cyber security is also addressed. Microgrid technology is appropriate for areas with limited transmission infrastructure, such as rural villages, where an island microgrid would be the most effective type of power network.

2.5 Components of Microgrids

Although there is no uniform definition of what a microgrid is, it can be said that a microgrid is madeup of many important components that are not often seen in traditional power systems. The complexity of the microgrid EMS is increased by the high penetration of these components.

- Distributed Generation (Such as renewable sources and tiny combustion turbines)
- Energy Storage Capacity (Such as batteries and thermal storage)

- Demand Response and Efficiency Measures (Reduce non-critical load when running in isolation Minimizes total energy use)
- Energy Management Systems (Balances and Stabilizes Systems)
- Interconnection of utility grids

Components	Examples	Functionalities
DG	Reciprocating internal combustion engines with generators, fuel cells, microturbines, small-scale wind turbines, and photovoltaic arrays	Utilize a range of energy resources to provide electricity and suitable heat for local customers.
DES	Battery banks, flywheels, super-capacitors, compressed air energy storage	Excess energy is stored during off-peak hours and used as a secondary generator during peak hours.
Controllable load	Heating, ventilation, and air conditioning (HVAC) system, plug-in hybrid electric vehicle (PHEV), plug-in electric vehicle (PEV), and commercial and residential buildings	Dispatch the load to minimise electricity grid disruption and optimise customer preference.
Critical load	School, hospital	Serve as base load. Need power quality support for critical loads.
PCC	Static switch	Switch between islanded and interconnected modes.

Figure 2.3: Components of microgrids

2.6 Types of Microgrids

There are two types of microgrids:

- **Off-grid Microgrids**

  Off-grid microgrids are constructed where there is a significant need for electricity but no access to a wide-area electrical grid. Islands that are too far from the mainland are typically served by their own microgrid. In the past, island microgrids were usually built around diesel or heavy fuel oil generators. While easy to transport and easy to store, these fuels could prove to be expensive. However, in the absence of a suitable alternative, many islands continue to rely heavily on such generators. Why were suitable alternatives absent? Islands have more than enough wind and plenty of sun. Yes, but integrating large quantities of solar arrays and wind turbines on the electrical system of an island can be very difficult. Diesel generators can be switched on and off, on-demand. They have the capability to closely match the electrical demand of the island as it increases and decreases. Wind turbines, in contrast, produce electricity when there is wind. Solar panels work when the sun is shining. If the wind abates or if clouds obscure the sun for moments, another source of electricity needs to be available to pick up the slack and meet the electrical load demand. This type of dynamic management of generation and demand requires sophisticated supervisory controls and advanced power electronics. In the past neither were a practical option for small-scale island systems. A schematic can be seen in figure 2.4

- **Grid Connected Microgrids**
  You don't need to be on an island or in the middle of the desert to benefit from a microgrid. In fact, many microgrid users are located in urban or industrial areas that are fully served by an electric utility. Why do businesses and institutions go through the trouble of investing in a microgrid when they can simply receive electricity from the utility? There are two main reasons. One reason is that they want to avoid power outages. Homeowners invest in a home generator for the same reason. The difference between a home with a generator and, for example, a military base with a microgrid is complexity and scale. A home has one, maybe two electrical panels. All it takes to integrate a home generator to a residential electricity system is a transfer switch. A military base includes dozens of buildings, several generators and a variety of critical electrical equipment such as radars and air traffic control systems, often spread over hundreds of acres. Integrating these components requires a sophisticated electrical infrastructure—in other words, a microgrid. Civilian facilities with complex electrical systems incorporate microgrids to ensure the reliability of their electrical service as well. Hospitals, airports, university campuses and

large industrial plants all utilize microgrid components to effectively integrate backup power generation into their electrical system. Refer figure 2.5 for the schematic.

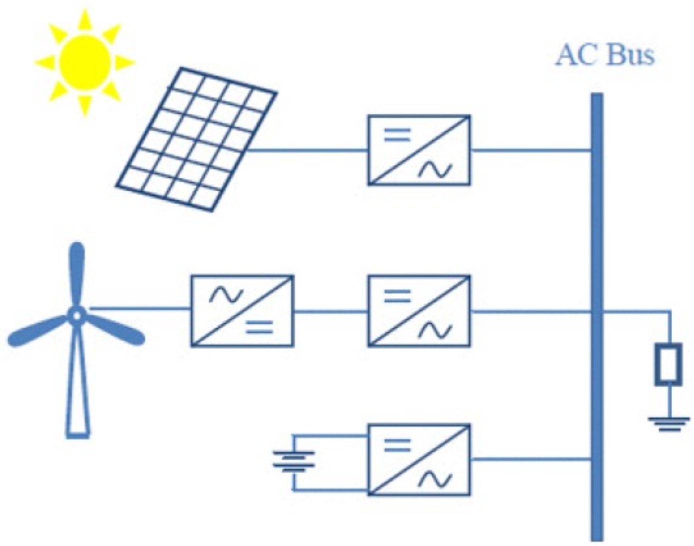


Figure 2.4: Stand Alone Microgrids

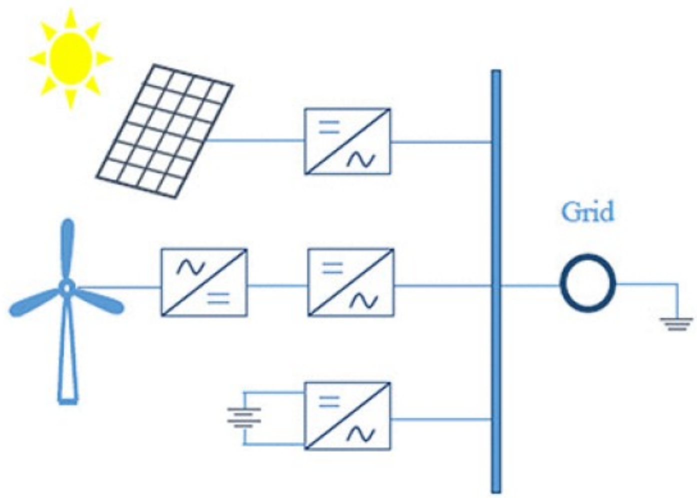


Figure 2.5: Grid Connected Microgrids

2.7 Problems in Microgrids

Reliability is one of the primary requirements necessary for supplying power to local clients such as schools, hospitals, and so on, and has a significant impact on grid economics and security.The modelling and estimation of dependability of forthcoming microgrid distribution systems like as distributed generation are being researched (DG). Microgrids face significant challenges in terms of security. All of the proposed protection mechanisms ensure that both main grid (utility) and microgrid faults are responded to as quickly as possible in order to properly isolate the microgrid from the main grid. The rapid operation of the protection mechanism is critical to the stability of the microgrid after the shift to islanded operation. Overcurrent protection is a critical component of the electrical grid. This is a difficult issue in microgrid since the overall shortcircuit current capacity of a microgrid in islanded and gridtied modes differs. In reality, the potentially significant fault currents simplify protection in gridtied mode of operation, whereas these fault currents may have relatively low values in islanded mode due to integrated power electronics interfaces in microgrid.

Some specific problems pertaining to microgrids are as follows:

- **Outage** The ability to continue supply power to customers in the event of random breakdowns was presented as a measure of power system reliability. The system dependability index is calculated using the forced outage rate of electric components. Its value is often provided by the component manufacturer or calculated using statistical data. Nonrandom uncertainty is another type of failure event. These types of events cannot be repeated, and their statistics cannot be extrapolated from previous data. Unintentional attack is one type of such incident, and it has gotten some consideration in the transmission system 9-11 planning challenge. Although deliberate attacks on microgrids are rare, unintentional attacks should be considered for the following reasons.
  - Strong winds, temperature shock, and blizzard are examples of extreme weather conditions. The vulnerability of many meteorological events in Sweden was assessed.
  - Unexpected disruptions in daily life, such as a fire, a riot, a vehicle accident, or municipal construction.
  - Pilferages and terrorist acts are examples of deliberate attacks. Terrorist attacks on microgrids have less impact on customers and utilities than on transmission systems; nevertheless, less investment, including both human and material resources, is required.
  - The operation mode of DG, which has the property of 'plug in and play,' is governed by the owner's behaviour. The behaviour is not in power utility dispatch scheduling. All of the outages stated above are classified as 'undesired outages.' Although unintended outages are predicted using statistical methods, they are certain to have major consequences for system security. Any major consequences of unanticipated outages are expected to be avoided throughout the planning period.
- **Reliability** One of the primary goals of building a microgrid system is to assure reliable power supply to loads within the microgrid. As a result, it

is critical to assess the reliability of the microgrid's power generation under various uncertainty. This is due to stochastically variable wind speed and changes in microgrid operational modes, which are the key factors influencing the generating capability of the microgrid's individual generating units. A recent review study on reliability and economic evaluation of a power system suggests that the reliability and economic evaluation of power systems with renewable energy sources needs to perform simultaneously. Several researchers have investigated wind turbine generator dependability in power system applications. However, stochastic variation and interactions of wind speed are avoided, as are time-dependent wind power effects.

- **Uncertainity** Renewable energy sources in microgrids are easily affected by external environmental factors such as sun radiation, temperature, wind flow, and so on, making system stability impossible to ensure, especially when running in islanded mode. Many prior studies have explored the impact of uncertainties on Microgrid functioning but have failed to demonstrate the considerable influence of these factors in practise.

Chapter 3

Problem Formulation of DR Microgrid

3.1 Introduction

Self-sufficient Microgrids are increasingly being used to cater the demand in remote and rural regions. One of the reasons of the popularity of self-sufficient microgrids in remote and rural areas is the unreliable power supply from the grid [4]. Self-sufficient microgirds usually have an option to operate in both an islanded and grid-connected mode [7]. However, the state management of a microgrid between islanded and grid connected operation is a complicated process [7]. Recently authors in [8] have proposed a neural network based controller for microgrid synchronization. [7] proposes a dynamic simulation based assessment and approach for seamless mode transfer for microgrids.

Therefore it is important to predict the requirement for such a mode transfer in advance so as to prepare the transition process of a microgrid operation model. In this paper a methodology to assess the requirement of mode transfer of a microgrid to grid-connected one is presented. The proposed technique exploits the fundamental Simplex Algorithm [5] which is based on visiting the extreme points in a polytope iteratively on the boundary of a feasible region.

The key idea is to reduce the number of possible extreme points to evaluate and ease the problem. This change in the number of extreme points is acheived through Farka's Lemma [6]. The key contribution of this report is to propose a variant of the microgrid assessment framework that would execute faster and predict if a mode transfer is required for microgrid operation.

3.2 Nomenclature

Sets : Indices

$I : i \rightarrow$ Devices in System

Variables

$g_i \rightarrow$ Demand response effect of device i

Parameters

$D \rightarrow$ Total generation-demand gap
$\overline{G}_i \rightarrow$ Maximum demand responsiveness of device i
$\underline{G}_i \rightarrow$ Minimum demand responsiveness of device i

Operators

$|.| \rightarrow$ Cardinality of set

Matrices

$\mathbf{0} \rightarrow$ Zero-matrix
$\mathbf{1} \rightarrow$ Ones-matrix
$\mathbf{I} \rightarrow$ Identity-matrix
$\mathbf{g} \rightarrow$ Matrix of variables g_i
$\mathbf{S} \rightarrow$ Matrix of all slack variables

3.3 Problem Definition

The microgrid has multiple devices that are demand responsive and schedulable generation sources. The generation sources are scheduled based on a forecast of the demand requirement. If one of the generation resources:

1. Go into an outage or,
2. Cannot generate at scheduled capacity due to renewable generation unavailability.

it could easily create a generation-demand gap. At this time instant, the microgrid falls on the demand-responsiveness of the devices in micorgrid to fill in this gap. In case, the demand-responsiveness of the devices cannot fill this gap, it will be imperative to grid-connect the microgrid to draw power as the local resources cannot provide for the demand. The problem formulation proposed in next section assess if such a grid-synchronization is needed or not.

3.4 Problem Formulation

The problem formulation here tries to find a feasible solution in order to fulfill the generation-demand gap through the combined effect of all demand responsive devices.

$$\{g_i\} := arg\{$$

$$\sum_{i \in I} g_i = D \tag{3.4.1a}$$

$$\underline{G}_i \leq g_i \leq \overline{G}_i,\ \forall i \in I\} \tag{3.4.1b}$$

The key decision for the microgrid depends on the feasibility of problem (3.4.1).

1. If (3.4.1) is feasible: no requirement for grid synchronization. Initiate demand response

2. If (3.4.1) is infeasible: initiate grid synchronization.

The vector form of (3.4.1) can be written as:

$$\begin{pmatrix} \mathbf{1}_{1\times|I|} & \mathbf{0}_{1\times2|I|} \\ \mathbf{K}_{2|I|\times|I|} & \mathbf{I}_{2|I|\times2|I|} \end{pmatrix} \begin{pmatrix} \mathbf{g}_{|I|\times1} \\ \mathbf{S}_{2|I|\times1} \end{pmatrix} = \begin{pmatrix} D \\ \mathbf{G}_{2|I|\times1} \end{pmatrix} \tag{3.4.2a}$$

where,

$$\mathbf{K}_{2|I|\times|I|} = \begin{pmatrix} 1 & 0 & 0 & ... & 0 \\ -1 & 0 & 0 & ... & 0 \\ 0 & 1 & 0 & ... & 0 \\ 0 & -1 & 0 & ... & 0 \\ ... & & & ... & \\ 0 & 0 & 0 & ... & 1 \\ 0 & 0 & 0 & ... & -1 \end{pmatrix} \tag{3.4.2b}$$

$$\mathbf{G}_{2|I|\times1} = \begin{pmatrix} \overline{G}_1 \\ -\underline{G}_1 \\ \overline{G}_2 \\ -\underline{G}_2 \\ ... \\ \overline{G}_{|I|} \\ -\underline{G}_{|I|} \end{pmatrix}, \text{ and} \tag{3.4.2c}$$

$$\begin{pmatrix} \mathbf{g}_{|I|\times1} \\ \mathbf{S}_{2|I|\times1} \end{pmatrix} \geq \mathbf{0}_{3|I|\times1} \tag{3.4.2d}$$

3.5 Linear Programming

Linear programming is a mathematical method for optimising operations given restrictions. Linear programming's basic goal is to maximise or minimise a numerical value. It is made up of linear functions that are constrained by constraints in the form of linear equations or inequalities. Linear programming is a popular technique for determining the most efficient use of resources. Linear programming is made up of two words: linear and programming. The term ”linear” refers to a one-dimensional relationship between many variables. The term ”programming” refers to the process of choosing the optimal answer from a set of options. This problem class is broad enough to cover a wide range of interesting and relevant applications, yet narrow enough to be achievable even with a high number of variables.

The requirement to address complicated planning problems in wartime operations prompted the development of linear programming as a field in the 1940s. Its growth accelerated significantly in the postwar period, as numerous businesses discovered that linear programming had practical applications. George B. Dantzig, who invented the simplex technique in 1947, and John von Neumann, who founded the theory of duality the same year, are widely considered as the subject's pioneers. The Nobel Prize in Economics was given to the mathematician Leonid Kantorovich (USSR) and the economist Tjalling Koopmans (USA) in 1975 for their contributions to the theory of optimal resource allocation, in which linear programming played an important role. Many sectors utilise linear programming as a typical method, for example, to optimally allocate a finite set of resources. Airline crew scheduling, shipping or telecommunication networks, oil refining and blending, and stock and bond portfolio selection are only a few examples of major application fields.

Linear programming can be used in a variety of engineering applications and power system businesses. Linear programming models can be claimed to be “tailor-made” for capital budgeting problems as it falters on the interrelation of capital budgeting and financing. Speific power engineering problems where Linear Programming can be used are in unit commitment or generation scheduling problems, reactive power allocation, power system planning etc.

Find a vector $\mathbf{x}$
that maximizes $\mathbf{c}^T\mathbf{x}$
subject to $A\mathbf{x} \leq \mathbf{b}$
and $\mathbf{x} \geq \mathbf{0}$.

Figure 3.1: A Typical Linear Programming Model

This is called the canonical form expression of a typical linear programming problem. The variables to be determined here are the components of x, c and b are given vectors (with indicating that the coefficients of c are used as a single-row matrix for the purpose of creating the matrix product), and A is a given matrix. The goal function is the function whose value is to be maximised or minimised (in this case). The constraints that specify a convex polytope over which the objective function is to be optimised are the inequality Ax b and x 0. When two vectors have the same dimensions, they are similar in this context.

3.5.1 Industry Solvers and Algorithms

With the previous paragraphs very clearly mentioning the prowess of Linear Programming, it is bound to have a number of proprietary softwares or solvers that can aid engineers and scientists in solving complex application specific linear programming problems with ease. Some of the most common solvers used in solving linear programming problems are CPLEX, XPRESS, Gurobi etc.

The **FICO Xpress** optimizer is a commercial optimization solver for linear programming (LP), mixed integer linear programming (MILP), convex quadratic programming (QCQP), second-order cone programming (SOCP), and their mixed integer cousins. Xpress contains a general-purpose nonlinear solver, Xpress NonLinear, which comprises a sequential linear programming technique (SLP, first-order method), as well as Artelys Knitro (second-order methods). The primal simplex method, the dual simplex method, and the barrier interior point approach can be used to solve linear and quadratic programmes. The branch and bound approach and the cutting-plane method are used to solve all mixed integer programming versions. The IIS (irreducible infeasible subset) method can be used to examine infeasible problems. Xpress includes a built-in tuner for automatic control setting tuning. Xpress contains its modelling language Xpress Mosel and an integrated development environment called Xpress Workbench. Mosel has distributed computing capabilities that allow it to solve numerous scenarios of an optimization problem in concurrently.Robust optimization approaches can tolerate input data uncertainty.

CPLEX is another solver that can allow solution of linear programming problems. Using IBM ILOG CPLEX Optimizer's sophisticated algorithms, we can make precise and logical conclusions for planning and resource allocation problems using a distributed parallel approach for mixed integer programming as well as flexible, high-performance mathematical programming solvers for linear programming, mixed integer programming, and other applications.

Gurobi is a cutting-edge optimization tool built from scratch to take use of modern architectures and multi-core processors, employing the most advanced implementations of the most recent optimization algorithms to solve your models quicker and more reliably. In addition to best-in-class performance, Gurobi offers a wide range of interfaces, access to industry-standard modelling languages, flexible licensing with transparent pricing, and superb, easy-to-reach optimization expert support. Typically these solves default to dual simplex (and have a very robust dual simplex implementations) [1, 2]. This means that search space and constraint spaces are switched internally by the dual simplex solver once. Hence, it would be faster to solve a problem in lower search space dimensions and higher number of constraints (when using a commercial solver), as it would result in a faster run time.

In our application as posed in (3.4.2), the following holds true:

1. Number of Variables: $3|I|$
2. Number of Constraints: $2|I| + 1$

We would aim to switch the search space and constraint dimensions, as this would reduce the run time with commercial solvers.

Simplex Method

The Simplex algorithm (or Simplex method) is a popular method for solving Linear Programming (LP) optimization issues. Because many of them will be transformed to LP and solved using the Simplex algorithm, the Simplex algorithm can be viewed of as one of the basic phases in solving the inequality problem. George Dantzig devised the Simplex algorithm, which was inspired by the idea of gradually downgrading to one of the convex polyhedral vertices. The term ”simplex” may refer to the top vertex of the simplicial cone, which is a geometric representation of the constraints in LP issues.

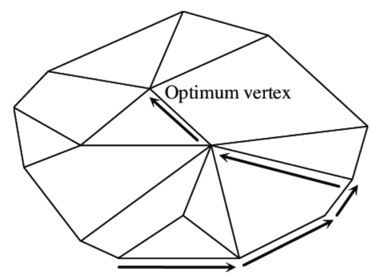


Figure 3.2: Optimization evolution of the simplex algorithm

Chapter 4

Case Study of IEEE 33 Bus Microgrid

4.1 Introduction

We now discuss an IEEE 33-node system employed to validate the presented method of distribution reconfiguration. [9]

Case I: General Case

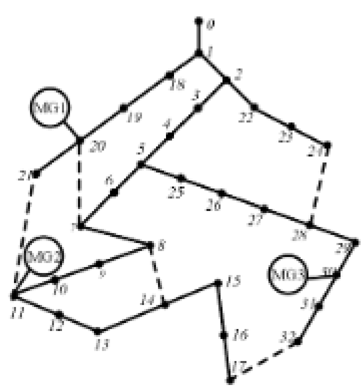


Figure 4.1: IEEE 33-node system with no microgrids

The IEEE 33-node system with no microgrids is shown in the figure 4.1. It contains 33 nodes and 5 tie lines, all with switchers. The first node is treated as the source node. There are three MGs connected to node11, node 20 and node 30. The capacities that MGs can supply to the distribution are respectively 100kW, 150kW, 400Kw. 50% loads connected to node 29 and node 32 are thermal loads. It is assumed that all branches have sectionalizing switchers.

Case II: Islands Partition

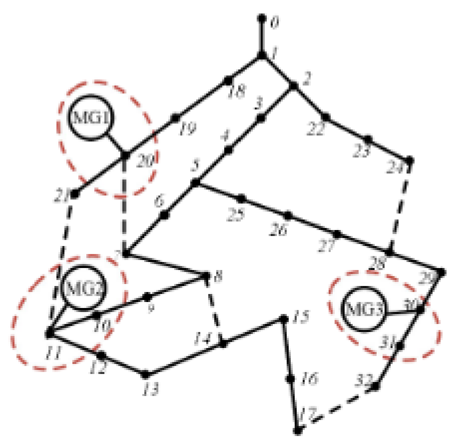


Figure 4.2: Island Partition

Based on the breadth-first search and depth-first search,the result of islands partition is give in figure 4.2. If a fault occurs in the feeder, the distribution will be separated into several islands. MG1 will support node 20; MG2 will support nodes 10 and node 11; MG3 will support node 30 and node 31.

Case III: Distributed Reconfiguration

In this paper, a fault occurring on branch 3-4 is considered. It will cause this branch out of service after fault. Calculation of the optimal solution of reconfiguration based on the result of island partition which is given in figure 4.3.

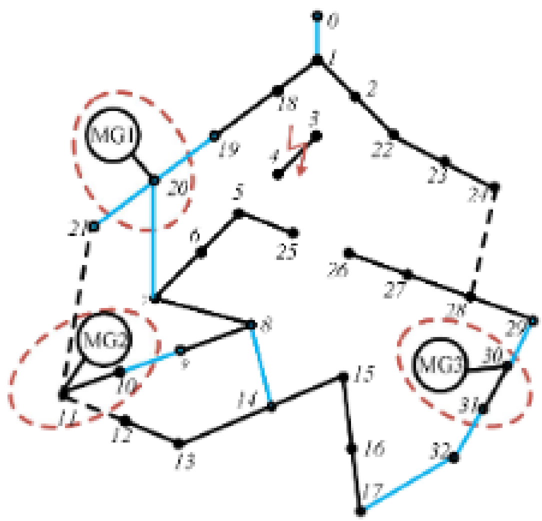


Figure 4.3: Distributed Reconfiguration

Rapid and accurate fault location is the basic premise for isolating the faulty section and restoring the service in the un-faulted region. According to figure 5, node 3 and node 4 are orphan nodes without any support when the fault in branch 3-4 occurs. Reconfiguration of the rest nodes can restore all the service. Before the reconfiguration, there are 3160kW loads cannot be satisfied. After the reconfiguration, only the loads of node 3 and node 4 cannot be satisfied which is 180kW.The reliability of power supply is greatly improved. And MGs no longer serve as islands, and they are restored to the running state before failure.

Chapter 5

Optimization of Demand Responsive Microgrid

5.1 Introduction

In this section we build up to Farka's Lemma through an explanatory proof.

Definition: The region generated by positive linear combination of a set of vectors is called a *Convex Cone*.

Let $\mathbf{A} = \left(a_1, a_2, ..., a_n\right)_{m\times n}$, then the convex cone generated by the column vectors of A can be written as $\{Ax|x \geq 0\}$. A representation of convex cone in $\mathbb{R}^m$ space can be seen in Fig. 1.

Farka's Lemma says: if there exists some $\mathbf{b} \in \mathbb{R}^m$, only one of the following possibilities can occur:

1. $\mathbf{b}$ lines in the convex cone, i.e, $\{\exists x \in \mathbb{R}^m|Ax = b \text{ and } x \geq 0\}$, or

2. $\mathbf{b}$ lies outside the convex cone

Case 2 is illustrated in Fig. 2. When $\mathbf{b}$ lies outside the convex cone, one can always draw a hyperplane passing through the origin that separates the convex cone and the vector $\mathbf{b}$. Let this hyperplane have a normal called $\mathbf{y} \in \mathbb{R}^m$. The hyperplane can thus be written as: $\{x \in \mathbb{R}^m|\mathbf{y}^T x = 0\}$. One one side of the hyperplane lies

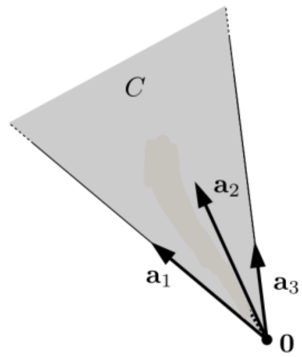


Figure 5.1: Convex Cone: Illustration [Adapted from [3]]

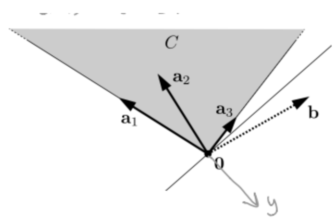


Figure 5.2: Convex Cone: Case 2 of Farka's Lemma [Adapted from [3]]

the convex cone and the other side of the hyperplane lies the vector $\mathbf{b}$. This can be represented by the following algebraic condition: $\{A^T\mathbf{y} \geq 0$ and $\mathbf{b}^T\mathbf{y} \leq 0\}$, i.e the inner product of any vector in the cone and y will have the opposite sign to the inner product of $\mathbf{y}$ and $\mathbf{b}$.

5.2 Problem Reformulation

It can be noticed that problem (3.4.2) is written as the first case of Farka's Lemma when the problem is feasible. If we rewrite the problem (3.4.2) as the second case of Farka's Lemma and look for its infeasibility, then the problem would (switch the search space dimensions and constraint space dimensions) become easier to solve for the solver with default settings.

5.3 Test System

The problem was solved for a microgrid with 1100 demand responsive devices and 200 generation-load imbalance cases. The primal problem (3.4.2) was solved first and then the same problem reformulated as the second case of Farka's Lemma was solved. All the problems were solved in MATLAB 2020b on a i7-7700K system with 32 GB of RAM. The test results were evaluated for statistical significance in the run-time improvements.

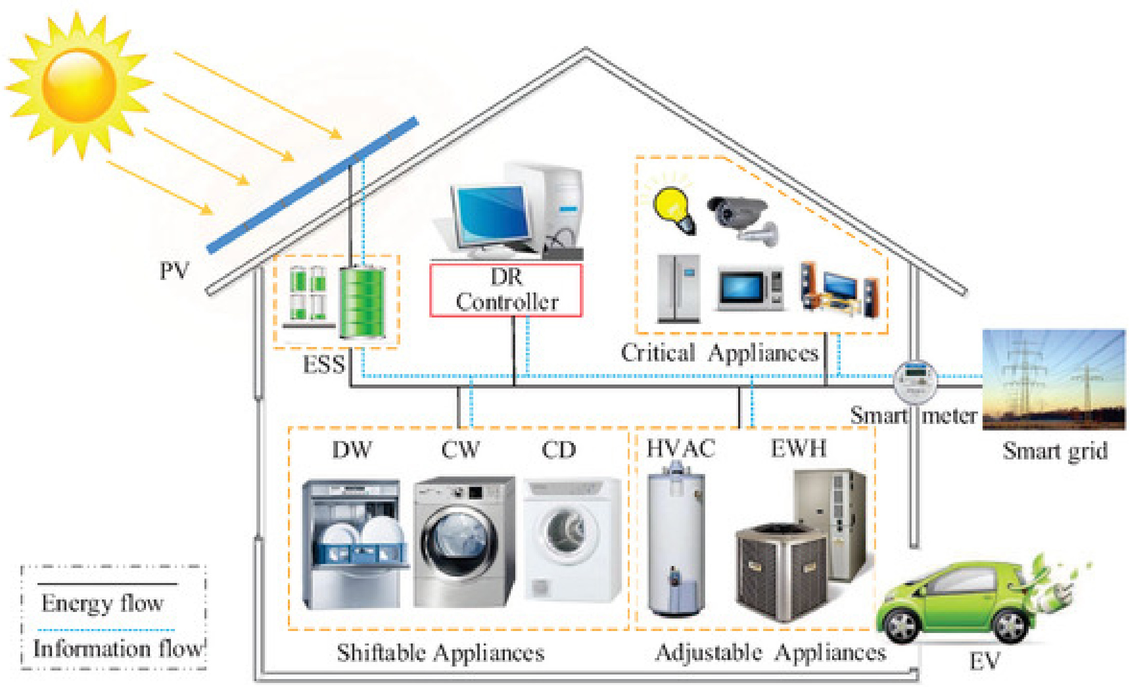


Figure 5.3: Demand Response Microgrids

Device Type	**1st hr rating(kW)**	**No. of devices**
Dryer	1.2	18
Dishwasher	0.7	28
Cloth Washer	0.5	100
Oven	1.3	32
Iron	1.0	150
Vacuum Cleaner	0.4	80
Fan	0.2	280
Kettle	2.0	40
Toaster	0.9	20
Cooker	0.85	59
Blender	0.3	66
Frying Pan	1.1	100
Coffee Maker	0.8	127

Table 5.1: Demand Responsive Devices

Given here we can see 1100 demand responsive devices with PV panel and battery storage installed with different types of appliances like critical appliance (eg. bulb, CCTV) , shiftable appliances (eg. washing machine, dishwasher) and adjustable appliances like HVAC. Here we can see in figure 5.3 that a DR controller is installed which takes care of demand response.

Chapter 6

Results & Discussion

The test results over 200 generation-load imbalance conditions clearly show (see figure 6.1) that the Farka's representation leads to a faster-run time. A Friedman's test was done to test the statistical significance of the reformulation on the run-times. A p-value of 0.0001 shows that the reformulation did make a significant effect on the run time.

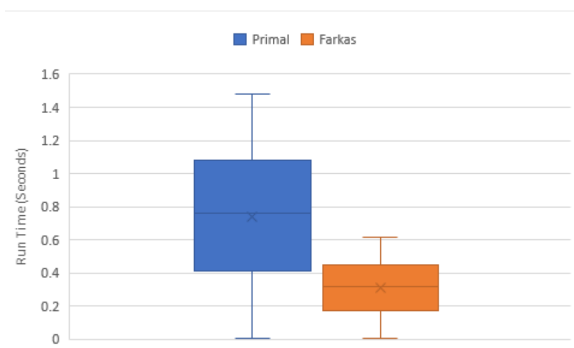


Figure 6.1: Statistical representation of run times

We tested our model with and without Farkas' lemma and found a noticeable difference in the run time (in seconds) between the primal approach and the novel approach (Farkas'). With this result we can identify soon whether our microgrid should be connected to utility grid or not.

Chapter 7

Conclusion & Future Work

Self-sufficient microgrids usually have an option to operate in both an islanded and grid-connected mode. However, the state management of a microgrid between islanded and grid connected operation is a complicated process.Therefore it is important to predict the requirement for such a mode transfer in advance so as to prepare the transition process of a microgrid operation model. We tried our method with and without Farkas' lemma by the aid of three different industry solvers : CPLEX, XPRESS and Gurobi and found out that our method compared to the primal method is very fast. This speed is achieved by the fact that we are able to identify soon whether our microgrid should be connected to utility grid or not.

The work has a number of possible future extensions. The Farkas Lemma concerns nonnegative solutions to linear inequalities. You would think that we can apply the Replacement Lemma here to a constructive proof of the Farkas Lemma, and indeed we can. But the choice of replacements is more complicated when we are looking for nonnegative solutions to systems of inequalities, and uses the Simplex Algorithm of Linear Programming.

Appendix A

Test Case without the use of Farkas' Lemma

```
clear all;
ngens = 1000;
pmin = 0.5*ones(1,ngens);
pmax = 10*ones(1,ngens);
A= [ones(1,ngens), zeros(1,2*ngens)];

Demand = ngens*10 - 99;
b = [Demand];



for i=1:ngens
    A=[A;zeros(2,3*ngens)];
    A(2*i,i)=1; %upper lim
    A(2*i,ngens + 2*i -1)=1; %upper lim
    A(2*i + 1, i) = -1; %lower lim
    A(2*i + 1, ngens + 2*i) = 1; % lower lim
```

```
    b = [b;pmax(i);pmin(i)];
end

lb = zeros(3*ngens,1);
f = zeros(3*ngens,1);
tic;
x=linprog(f,[],[],A,b,lb,[]);
toc;
```

Appendix B

Test Case using the Farkas' Lemma

```
clear all;
ngens = 1000;
pmin = 0.5*ones(1,ngens);
pmax = 10*ones(1,ngens);
A= [ones(1,ngens), zeros(1,2*ngens)];

Demand = ngens*10 - 99;
b = [Demand];



for i=1:ngens
    A=[A;zeros(2,3*ngens)];
    A(2*i,i)=1; %upper lim
    A(2*i,ngens + 2*i -1)=1; %upper lim
    A(2*i + 1, i) = -1; %lower lim
    A(2*i + 1, ngens + 2*i) = 1; % lower lim
```

```
    b = [b;pmax(i);pmin(i)];
end

m = length(A(:,1));
n = length(A(1,:));
Anew=[-A';b'];
bnew = [zeros(n,1);-1];
f = zeros(m,1);

tic
y = linprog(f,Anew,bnew,[],[]);
toc
```

Appendix C

IEEE 33-node System

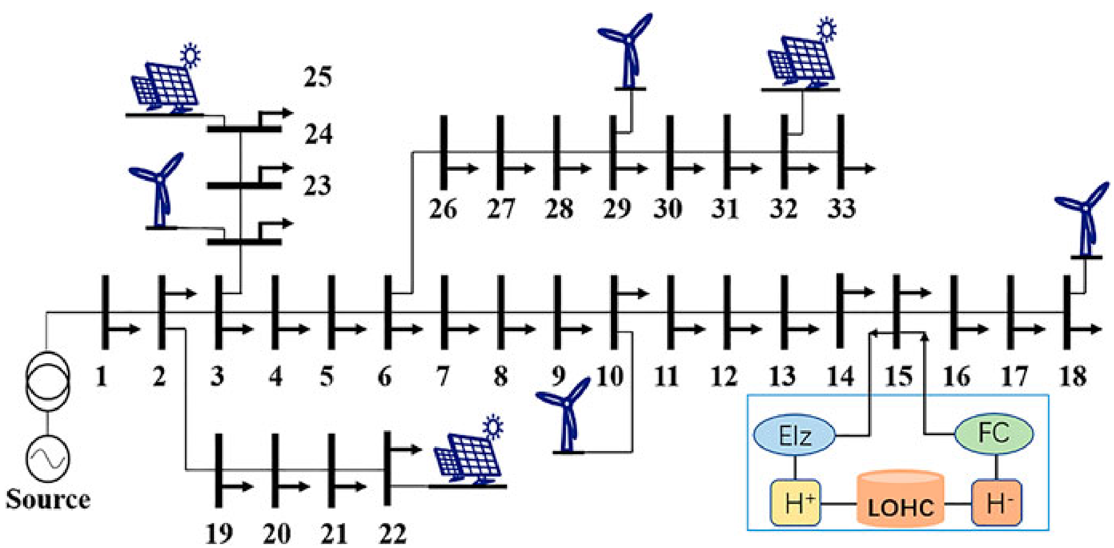


Figure C.1: IEEE 33-node System

Branch number	From bus	To bus	*R*	*X*	*U*	*U′*
1	1	2	0.0922	0.0470	0.8000	0.1000
2	2	3	0.4930	0.2512	0.4000	0.0100
3	3	4	0.3661	0.1864	0.1000	0.0600
4	4	5	0.3811	0.1941	0.5000	0.0600
5	5	6	0.8190	0.7070	0.2000	0.0200
6	6	7	0.1872	0.6188	1.0000	0.0300
7	7	8	0.7115	0.2351	1.0000	0.0100
8	8	9	1.0299	0.7400	0.8000	0.0200
9	9	10	1.0440	0.7400	0.7000	0.0200
10	10	11	0.1967	0.0651	0.4000	0.0200
11	11	12	0.3744	0.1298	0.1000	0.0300
12	12	13	1.4680	1.1549	0.3000	0.0400
13	13	14	0.5416	0.7129	0.5000	0.0100
14	14	15	0.5909	0.5260	0.2000	0.0500
15	15	16	0.7462	0.5449	0.6000	0.0900
16	16	17	1.2889	1.7210	0.2000	0.0900
17	17	18	0.7320	0.5739	0.6000	0.1000
18	2	19	0.1640	0.1565	0.7000	0.1000
19	19	20	1.5042	1.3555	0.9000	0.0200
20	20	21	0.4095	0.4784	0.5000	0.0800
21	21	22	0.7089	0.9373	0.1000	0.0700
22	3	23	0.4512	0.3084	0.5000	0.0400
23	23	24	0.8980	0.7091	0.4000	0.0200
24	24	25	0.8959	0.7071	0.3000	0.0700
25	6	26	0.2031	0.1034	0.8000	0.0900
26	26	27	0.2842	0.1447	0.2000	0.0600
27	27	28	1.0589	0.9338	0.8000	0.0500
28	28	29	0.8043	0.7006	0.8000	0.0200
29	29	30	0.5074	0.2585	0.7000	0.0200
30	30	31	0.9745	0.9629	0.5000	0.0400
31	31	32	0.3105	0.3619	0.1000	0.0600
32	32	33	0.3411	0.5302	0.4000	0.0200

Figure C.2: Bus Data of IEEE 33 Bus

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