ABSTRACT

Title of thesis: MODEL BASED SYSTEMS
ENGINEERING FOR A
TYPICAL SMARTGRID

Omkar Shalik Ninawe
Master of Science, 2019

Thesis directed by: Professor John S. Baras
The Institute for Systems Research

The complexity and heterogeneity of today's large *Cyber-Physical Systems* (CPS) is addressed by model based design. This class of systems is a direct consequence of our entry into the new era of systems characterized by high complexity, increased software dependency, multifaceted support for networking and inclusion of data and services form global networks. Cyber-Physical Power Systems such as SmartGrids provide perfect example to emphasis heterogeneity and complexity of today's systems. In this thesis we work towards augmenting the creation and demonstration of a framework for developing an integrated CPS modelling hub with powerful and diverse tradeoff analysis methods and tools for design exploration of CPS.

Model Based Systems Engineering for a Typical Smart Grid

by

Omkar Shalik Ninawe

Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park in partial fulfillment
of the requirements for the degree of
Master of Science
2019

Advisory Committee:
Professor John S. Baras, Chair/Advisor
Professor Mark Austin
Professor Jeffrey Herrmann

Dedication

To the creator of this life, Aai

Acknowledgments

I owe my gratitude to all the sentients who've helped me learn and make this thesis possible. Especially, I am thankful to my advisor, Dr. John Baras, a legendary engineer and teacher, who provided me with invaluable opportunities and guidance throughout these years. Working with Dr. Baras' group is the highlight of this degree.

I would also like to acknowledge Dr. John MacCarthy who has been a great teacher and Dr. Luigi Vanfretti who provided me with much needed support.

Lastly, I shall thank all those unsung souls who were with me in faith, in memories, in life - making everything worth it!

Table of Contents

List of Tables

List of Figures

List of Abbreviations & Acronyms

Abbreviations

CPS	Cyber-Physical Systems
SE	Systems Engineering
MBSE	Model Based Systems Engineering
LCM	Life Cycle Management
DSO	Distribution Service Operator
MoE	Measures of Effectiveness
KPP	Key Performance Parameter
BDD	Block Definition Diagram
IBD	Internal Block Diagram
AD	Activity Diagram
AI	Artificial Intelligence
SD	Sequence Diagram
UCD	Use Case Diagram
RD	Requiremnts Diagram
SMD	State Machine Diagram
SCOP	Second Order Cone Programming
SDP	Semi-Definite Programming
OPL	Optimization Programming language
MIP	Mixed Integer Programming
MIQP	Mixed Integer Quadratic Programming
LP	Linear Programming
EV	Electric Vehicle
UML	Unified Modelling Language
SysML	Systems Modelling Language
IEA	The International Energy Agency
IDE	Integrated Development Environment
ICE	Internal Combustion Engine
DC	Direct Current
ANN	Artificial Neural Networks
PMU	Phasor Measurement Unit
MEMS	Microgrid Energy Management System
ESS	Energy Storage System
BESS	Battery Energy Storage System
RES	Renewable Energy Sources
DR	Demand Response
EV	Electric Vehicles

DER	Distributed Energy Resources
DSM	Demand Side Management
ICT	Information and Communications Technology
DAE	Differential Algebraic Equations
INCOSE	International Council on Systems Engineering
UML	Unified Modelling Language
MARTE	Modeling and Analysis of Real-time and Embedded systems
BPMN	Business Process Model and Notation.
IDEF1x	Integration Definition for information modeling
SCADA	Supervisory Control and Data Acquisition
HVAC	Heating, Ventilation, and Air Conditioning
TOU	Time-of-use pricing
MGO	Microgrid Operator
RTP	Real-time pricing
VPP	Variable Peak Pricing
CPR	Critical peak rebates
CPP	Critical peak pricing
GHI	Global Horizontal Irradiance
PV	Photovoltaics
ENTSO-E	European Network of Transmission System Operators for Electricity
DSO	Distribution Service Operators
GPS	Global Positioning System

Acronyms

Indices & Parameters

g	Generator unit
n	Time-step [min]
Δn	Time between n and $n+1$
b	BESS unit
i	Bus number
τ	Social Cost of Carbon [$]
a	Quadratic term of cost function [$/kWh2]
b	Linear term of cost function [$/kWh]
c	Constant term of cost function [$/h]
a^{em}	Quadratic term of emission function of a Generator[ton/kWh2]
b^{em}	Linear term of emission function of a Generator [ton/kWh]
c^{em}	Constant term of emission function of a Generator [ton/h]
C^{up}	Start-up cost generating units [$]
C^{dn}	Shutdown cost generating units [$]
C^{emup}	CO^2 emission associated with shut-down of a Generator [ton]
C^{emdn}	CO^2 emission associated with start-up of a Generator [ton]
R	Ramp up/down rate of a generator [p.u./h]
T	Minimum up-time/downtime of a generator [p.u./h]
η^{ch}	Charging efficiency of ESS
η^{dch}	Charging efficiency of ESS
$PV_{i,n}$	Photovoltaic unit output [p.u.]
$PD^{c}_{i,n}$	Commercial active power demand [p.u.]
$PD^{r}_{i,n}$	Residential active power demand [p.u.]
PD^{rsmax}_{i}	Maximum total daily shiftable residential load [p.u.]

Variables

$PD^{rs}_{i,n}$	Residential shiftable active power demand [p.u.]
$P_{g,n}$	Active power from generating units [p.u.]
$Q_{g,n}$	Reactive power from generating units [p.u.]
$U_{g,n}$	Start-up decision (1 = start-up, 0 = otherwise)
$S_{g,n}$	Shut-down decision (1 = shut-down, 0 = otherwise)
$W_{g,n}$	ON/OFF decision (1 = ON, 0 = OFF)
$P^{ch}_{b,n}$	ESS charging power [p.u.]
$P^{dch}_{b,n}$	ESS discharging power [p.u.]
E_b	State of charge of ESS [p.u.]

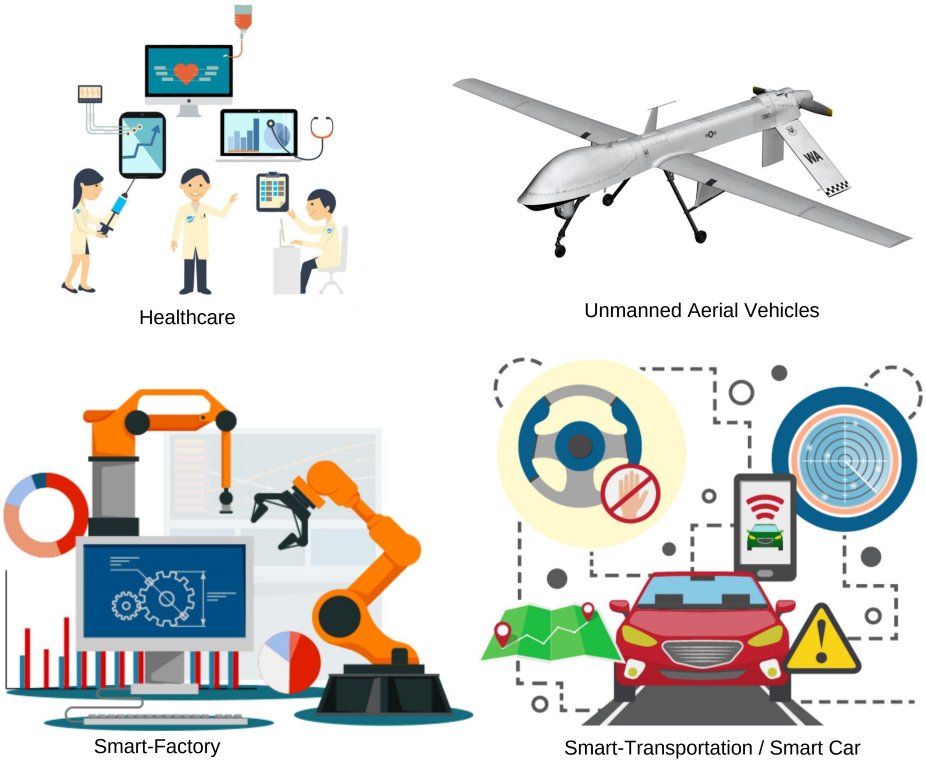
Chapter 1: **Introduction**

1.1 Motivation

The complexity and heterogeneity of today's large *Cyber-Physical Systems* (CPS) is addressed by model based design. This class of systems is a direct consequence of our entry into the new era of systems characterized by high complexity, increased software dependency, multifaceted support for networking and inclusion of data and services form global networks. Essentially CPS are engineered hybrid systems with physical components that follow the laws of nature and computational components that follow the rules of hardware and software logic.

With increasing number of components and interactions between them, the complexity of CPS rises exponentially unveiling emergent challenges in system design and control synthesis. Cross domain application of components give rise to integrated solutions such as SmartGrids, Smart buildings, Smart Transportation, Smart Manufacturing, Healthcare IT etc. pervasive in all areas of life and work today or in the immediate future.

Competitive pressure and societal needs drive industry to design and deploy airplanes and cars that are more energy efficient and safe, medical devices and systems that are more dependable, defense systems that are more autonomous and secure. Whole industrial sectors are transformed by new product lines that are CPS-based [1]. While presence of such composite systems hints mature technology that is not necessarily the case since methodologies for tackling challenges (design implementation, operation, and performance evaluation) presented by CPS are still in their infancy.


Healthcare

Unmanned Aerial Vehicles

Smart-Factory

Smart-Transportation / Smart Car

Figure 1.1: Examples of Cyber-Physical Systems across healthcare [2], manufacturing [3], defense [4] and transportation sectors [5].

Domain specific powerful tools such as $PSS^{\circledR}E$ [6] are preferred by engineers as they provide the ability to model systems with a software environment tailored for specific tasks.

However, given the inherent heterogeneity of CPS, interdisciplinary knowledge, interfaces for networking this variety of domains, and interoperability among tools is required. Effective realization of CPS is thus hindered by the lack of interfaces and standards for data and model exchange.

Increased software dependency on the other hand has created new challenges for engineers since representations of the cyber and physical parts of the system are different making it difficult to capture the interactions between the two.

Lastly, absence of formal ways to handle requirements is another hindrance to verifying safety and other operational characteristics of these systems.

These challenges can cause significant risks, produce failures and lead to loss of market.In serious cases, design flaws in safety critical situations could cost loss of life, significant property damage or damage to the environment; as is evident from the grounding of *Boeing 737 MAX* passenger airliner after a series of devastating accidents [7].

Rigorous research and investigation to facilitate development of a design framework and methodologies have been undertaken by consortia of academia and industry. Such efforts have led to creation of open standards and platforms [1] and design methodologies [8] for CPS. In this thesis, building on the framework developed and proposed in [1] we demonstrate how modern systems engineering languages (e.g. SysML) and tools can facilitate the systematic modeling of such complex systems, and on the other hand we develop tradeoff analysis methods for the design and operation of CPS *Smartgrid*.

1.2 Thesis Objectives

Extensive literature review revealed absence of a structured approach to optimize system architecture, manage the analysis and optimization of diverse measures of effectiveness (MoE), manage the various acceptable designs and most than anything else perform tradeoff analysis. Additionally, use of Model Based Systems Engineering (MBSE) as a structured approach to design and operate SmartGrids is missing. Accordingly the objectives of the work presented in this thesis are the following:

- Provide a SysML framework for modeling of SmartGrids as complex systems by representing grid structure and behavior [1].
- Develop appropriate multiview multilevel models of a microgrid to reflect component level structure and behavior of the grid.
- Formulate the tradeoff analysis problem for a typical microgrid for economic and sustainable operation with unit commitment, Energy Storage Systems (ESS), generation-demand, and reserve constraints taken into account.
- Perform tradeoff analysis on an example grid and perform design architecture synthesis. Interpret the results from a design and operational perspective of Smartgrids.

1.3 Contributions

As mentioned previously, use of Model Based Engineering as a structured solution for Smartgrid design and Operation is absent. Hence, we provide a SysML framework for the same. We represent the system structure and behavior using SysML constructs such as blocks, Block Definition Diagrams (BDD), Internal Block Diagrams (IBD), and Parametric Diagrams (PD).

Using the mathematical model developed of various components of a Smartgrid, we formulate a Mixed Integer Quadratic Program (MIQP) and solve Unit Commitment (UC) optimization problem with various grid component constraints in consideration for an example microgrid. Based on the MBSE approach we provide system architecture synthesis using tradeoff analysis on the example microgrid.

1.4 Organization

The rest of the thesis is structured as follows: Chapter 2 provides comprehensive information on the Systems Engineering and analysis tools used to enable the MBSE approach. We discuss the advantages, limitations and necessity of the distinct tools used.

Chapter 3 provides an overview of smartgrid instantiation i.e. microgirds along with in-depth description of a microgrid and its technologies. We discuss the basic building blocks of a microgrid and model the components based on their characterizations in consideration. We also provide SysML representations of various components

Chapter 4 presents an example model in consideration and the corresponding multiview models developed along with the formulation of a tradeoff analysis problem for the same. The obtained results of the tradeoff analysis are analyzed and discussed highlighting the importance of a possible integrated design environment.

Finally in Chapter 5 we discuss the results, summarize the main conclusions and suggest future research work.

Chapter 2: **Systems Engineering & Tools**

This chapter provides a review of Systems Engineering and the main tools relevant to this thesis. In Section 2.1 we provide overview of SE followed by short discussion on MBSE. We then discuss SysML and also present details regarding use of SysML in this thesis and limitations of the language. Section 2.3 describes the optimization solver CPLEX.

2.1 Systems Engineering

2.1.1 Overview

Systems Engineering (SE) is a systematic approach for efficient design of products and processes while satisfying the requirement, meeting the performance metrics and minimizing the risk. Challenges in development of modern systems as discussed earlier require a structured and all-encompassing approach for successful realization. This structured approach is a collection of processes, methods, activities, concepts, tools, and techniques altogether known as Systems Engineering.

The increased significance of SE approach is due to higher performance requirements, short time to market, and faster technology development and opportunities for their insertion in a system. Primarily a synthesis tool, SE exists due to the complex and heterogeneous nature of todays systems. Development of a system as a consolidated solution with patch fixes in the form of incremental changes entail a significant rise in development cost as errors discovered in later stages of a product life cycle cause expensive redesign steps.

Over 70% of the product problems can be attributed to poor systems engineering [9]. Spanning across the entire life cycle of the product, SE has proven to be cost effective by realizing successful systems with reduced risk of significant failures. SE is applied across various domains including Automotive, Biomedical & Healthcare, Defense and Aerospace, Infrastructure, Space, Ground Transportation, etc. with varying levels. The iterative process of SE can be implemented using the preferred industry solution of *V lifecycle development model*.

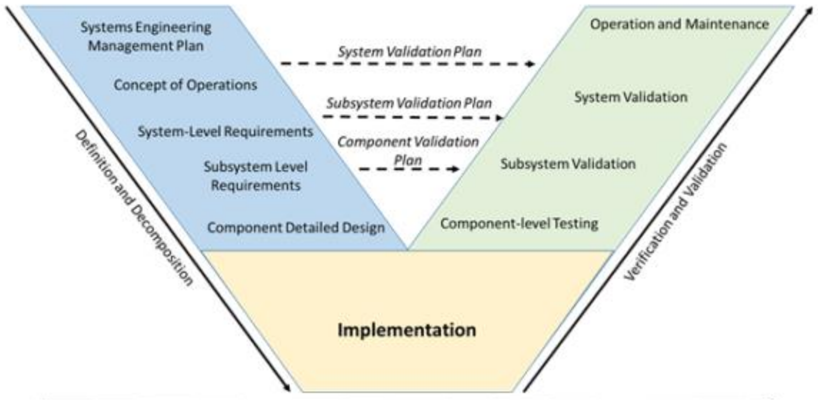


Figure 2.1: The V development life-cycle model (LCM). It is an extension of the traditional waterfall model, splitting the traditional model right into two sections viz., Design and Development on the left, and Integration and Testing on the right.

To allow for a complete solution the LCM's top-down design process starts with development of requirements phase all the way through validation phase of the obtained solution. Synthesizing the requirements, system conceptual design is built with increasing level of details on the left hand side of the V while simultaneously developing testing strategies at each level of abstraction. The right side of the V then builds on the integrated solution testing and performing Verification and Validation (V&V) at every level to obtain the engineered system. Thus the system is viewed as a hierarchical abstraction of components.

Different versions of the V-model exist; tailored according to the purpose. Fig. 2.1 however, represents a generic view of the V-model which fails to depict crucial details of the design process. The V-model fails to represent component reuse, iterative development behavior, parallel design development, and multi-domain nature of systems. One of the major disadvantages of this model is the delayed V&V phase which might contribute to expensive redesign procedures or in worse cases building wrong systems.

2.1.2 Model Based Systems Engineering

Successful realization of complex systems can be attributed to the adoption of Model Based System Engineering (MBSE) methodology. MBSE is the formalized application of modelling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases [10]. Traditional *document-*

centric methods of system development suffered from generic inefficiencies and inability to handle the stress of complexity of modern systems. MBSE has been advocated to counter the inefficiencies of the traditional approach while providing additional perks as mentioned in [11].

MBSE includes multiple modelling domains across life cycle and across various levels of the system. Benefits of MBSE translate into reduced design time, improved system quality, and affordable complex systems. Fig. 2.2 shows the basic steps of the MBSE process developed [1].

The design process is iterative and concludes when sufficiently satisfactory system design is obtained. Briefly put, the process executes system architecture by creating structural and behavior models of the system followed by allocation of behavior to structure.

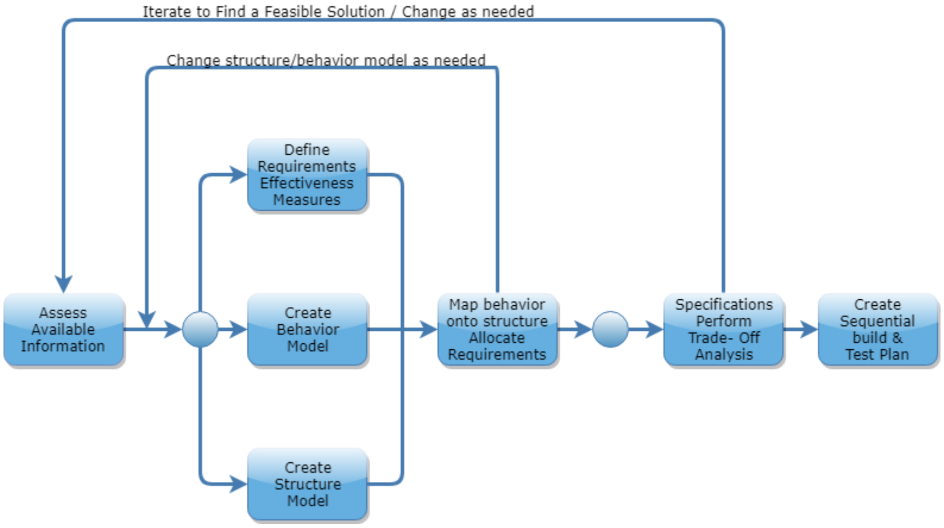


Figure 2.2: The MBSE process [1]. Depicts the iterative refinement and mapping of the SE process.

Recent research has demonstrated the use of *SysML* as a centerpiece abstraction for team-based system development, with a variety of interfaces and relationship types (e.g., parametric, logical and dependency) providing linkages to detailed discipline-specific analyses and orchestration of system engineering activities [1]. Hence to implement MBSE we use SysML in this work, details of which are presented in Section 2.1.

2.1.3 MBSE for Cyber Physical Power Systems

Cyber-Physical Power Systems (e.g. ***Smartgrids***) are the next stage in the evolution of power systems and promise unprecedented performance, reliability, safety, economic benefits, and environmental conservation. An excellent example of ultra-complex CPS, Smartgrids consist of power grids, energy resources, Information and Communication Technologies (ICT), and computational systems. Advances in the field of ICT such as- 5G and in the field of computation such as Self-learning Artificial Intelligence (AI) based systems have enabled grid automation and higher penetration of renewable energy resources. Insertion of novel technologies however presents novel challenges and possible emergent behaviors. For instance, increasing Renewable Energy Source (RES) penetration together with decommissioning of nuclear power plants is causing dangerous frequency variations in the girds creating a cascading effect to power infrastructure, increasing blackouts probability. Thus, rigorous and accurate modelling of the Smartgrids is essential to maximize our understanding and minimizing the risk and failure while deploying them.

Although model driven engineering has picked up significant pace, use of MBSE for modelling power systems is a recent affair with very few researchers explicitly stating MBSE as the development methodology. Another factor advocating model driven engineering is the fact that ENTSO-E, the European Network of Transmission System Operators for Electricity, in its regulations prescribe use of a common transmission model for grid development studies and network operation processes. At any given time, multiple Distribution Service Operators (DSO) each one with their preferred operating software, work together to operate the grid. Presence of different time scales in power systems along with model inconsistencies due to lack of standardized model exchange among various softwares used by DSOs further strengthens the case of MBSE.

OpenIPSL [12] is an open-source *Modelica* library for power systems developed by Vanfretti et al. It is a collection of component models of different types typically found in power systems and enables modelling a typical power system network comprising power generation, transmission, and power consumption.

Apart from the physical network model, power systems also need to be modeled for:

- Telemetry and Supervisory Control and Data Acquisition (SCADA) system
- The telemetered view via the SCADA system
- The analyzed view via the load flow program
- A simulated view for performing what-if scenarios based on current data
- A simulated view for performing what-if scenarios based on current data

- A historical view for reviewing the cause of problems and network outages

- A model of the human operators making decisions

These views of the system can be modeled in SysML, albeit use of SysML in power engineering is uncommon. A ***Microgrid*** is an instantiation of SmartGrids which shall form the base of the tradeoff analysis presented in the thesis. With slight abuse of notation, we use Micrograms and SmartGrids interchangeably henceforth.

2.2 Introduction to SysML

INCOSE's efforts to customize UML for systems engineering applications resulted in the development of SysML; a general-purpose graphical modelling language that supports the analysis, specification, design, verification and validation of complex systems including but not limited to cyber-physical, hardware, software, personnel, procedures, facilities, and other man-made and natural systems. [13].

SysML, a robust and standardized language enables effective encapsulation of system requirements, structure, and behavior. Developed as an extension of the software-centric UML, it incorporates additional diagrams befitting the needs of today's system engineers. Although several domain specific languagues like UML, MARTE, BPMN, and IDEF1x do exist for practicing MBSE, SysML's generic constructs are applicable across varied domains similar to Modelica.

SysML includes nine types of diagrams [13], seven of those are a direct inheritance from the UML while Requirements and Parametric Diagrams are the two aforementioned enhancements. Each of these provides a different view of the system being modelled.

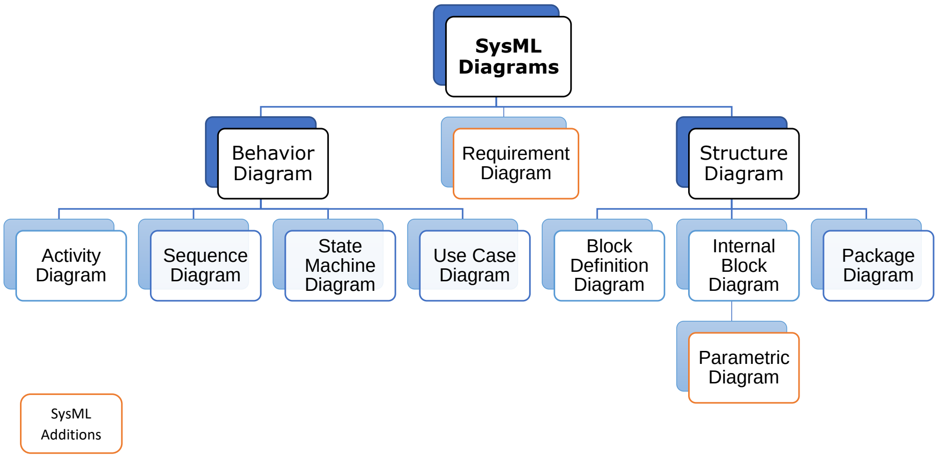


Figure 2.3: SysML Diagram types. Darker shades denote broad categorization of the diagrams while lighter shades denote the actual diagrams types.

- ***Package Diagram***: Similar to UML, your Package diagram is a tool for hierarchical organization of the system elements being developed. These diagrams are unusable for any kind of mathematical analysis and aid system development simply by representing high level structure and organization of the model.

- ***Block Definition Diagram*** (BDD): A BDD is one of the two major structural diagrams which represents the system architecture through SysML's basic entity the blocks, their composition, and the relationships between them.

- ***Internal Block Diagram***(IBD): The other important structural diagram, an IBD specifies the connections and interfaces between the internal parts of a single block.

- ***Parametric Diagram***: A parametric diagram enables engineering analysis by providing constructs for mathematical modelling of constraints on property values of the block.

- ***Activity Diagram***(AD): An AD captures system behavior by representing the ordered flow of executing actions and data/energy transformation through them.

- ***Sequence Diagram***(SD): SD captures behavior of the system in terms of sequence of messages exchanged between system components.

- ***State Machine Diagram***(SMD): The SMD represents all the possible transitions of a system or system component through its states.

  grammar check kar

- ***Use Case Diagram***(UCD): A UCD is an important behavioral diagram inherited form the software engineering industry. It specifies the how a user shall make use of the system to accomplish his/her goals.

- ***Requirements Diagram***(RD): One of the two additions over UML, RD provide framework for specifying requirements and their composition.

Several commercial (e.g. *Cameo Systems Modeler* and *IBM Rational Rhapsody*) and free open-source (e.g. *Papyrus* and *Modelio*) tools are available for SysML modelling. The choice of tool for this thesis work is Cameo Systems Modeler.

2.3 Introduction to CPLEX

The IBM ILOG CPLEX Optimizer solves integer programming problems, very large linear programming problems using either primal or dual variants of the simplex method or the barrier interior point method, convex and non-convex quadratic programming problems, and convex quadratically constrained problems (solved via second-order cone programming, or SOCP) [14].

For the platform proposed in [1], CPLEX forms the core optimization engine. The full IBM ILOG CPLEX Optimization Studio consists of the CPLEX Optimizer for mathematical programming, the CP Optimizer for constraint programming, the Optimization Programming Language (OPL), and a tightly Integrated Development Environment (IDE). Interfaces to C++, C#, Java, Python and connectors to Excel, MATLAB are provided via a modelling layer called **Concert**. However the studio lacks integration with system modelling tools such as SysML, Modelica, UML etc. Availability of such an integration of a modelling tool with a power solver would drastically enhance system design development by aiding rigorous engineering analysis as is pointed out in [1].

Over the period of more than four decades the CPLEX suite has been developed as a congregated solution to meet a wide range of user's needs. As such we shall make use of this tool for solving mathematical programming problems in which some or all of the variables assume integer values. Such problems are known as **mixed integer programs (MIP)** because they combine numerical and boolean variables in the objective function and in the constraints. A sub-category of MIP is

Mixed Integer Quadratic Programs (MIQP) with a quadratic term in the objective function, and linear terms in the constraints. The mathematical formulation of the optimization problem presented in this thesis is a multi-objective MIQP.

By default, CPLEX can solve MIQPs where the restriction of the problem to its numerical and boolean variables is a *quadratic program* (QP) [14]. If this assumption is not satisfied, CPLEX will return the error CPXERR_Q_NOT_POS_DEF. To allow optimization of non-convex problems CPLEX offers the parameter *optimality target* which can instruct CPLEX to search for a globally or locally optimal solution.

The following formulation illustrates a mixed integer programming problem,

$$\begin{aligned} \min_{x} \quad & 0.5x_1^2 + x_1x_2 - 4y_1 + 2y_2^2 \\ \text{s.t.} \quad & x_1 + x_2 \leq 2 \\ & -2x_1 + x_2 \leq 5 \\ & 0 \leq \mathsf{x}, \mathsf{y} \\ & y \in \mathbb{Z}^2 \\ & x \in \mathbb{R}^2 \end{aligned} \tag{2.1}$$

where x, y are the set of optimization variables with integer or continuous values, $\mathbb{R}^2$ is 2-dimensional set of real numbers and $\mathbb{Z}^2$ is 2-dimensional set of integers.

In the MIP optimizer of CPLEX, based on the characteristics of the model, the solver decides which of the two algorithms to apply. The two main algorithms used, the **Branch & Cut algorithm** and the **Dynamic search algorithm** consist of the same building blocks: LP relaxation, branching, cuts, and heuristics.

In addition to the choice of algorithms , the IDE also provides several tools, techniques, and parameter selection such as, pre-processing, probing, heuristics, and tuning.

Chapter 3: **The Smartgrid**

This chapter serves as foundation of the system in hand, i.e. Smartgrid and presents background review of the technologies, and the operation and control mechanisms used. We provide in-depth description of primary grid operation, specifically Unit Commitment, to make use of that in later stages.

3.1 **Overview**

Edison's concept of distributed generation, - infeasible back then due to inadequacy of technology-, is one of the marked features of the future grids. With the weakening public support for Nuclear plants, increasing penetration of RES, and rising numbers of Electric Vehicles (EV), unprecedented problems have engulfed current grid operations. Owing to the volatile nature of RES grid stability is up in the air. Hence need of large storage systems and power reserves is felt. The changed dynamic behavior of the grid has led to dangerous frequency variations.

In order to counter the issues discussed, the future sustainable smartgrids shall have [15] centralized and decentralized generation, intelligence with ICT, dominating RES, smart loads, effective Demand Response (DR) programs, and bidirectional load flows. In the same way that the Internet revolutionized communication systems,

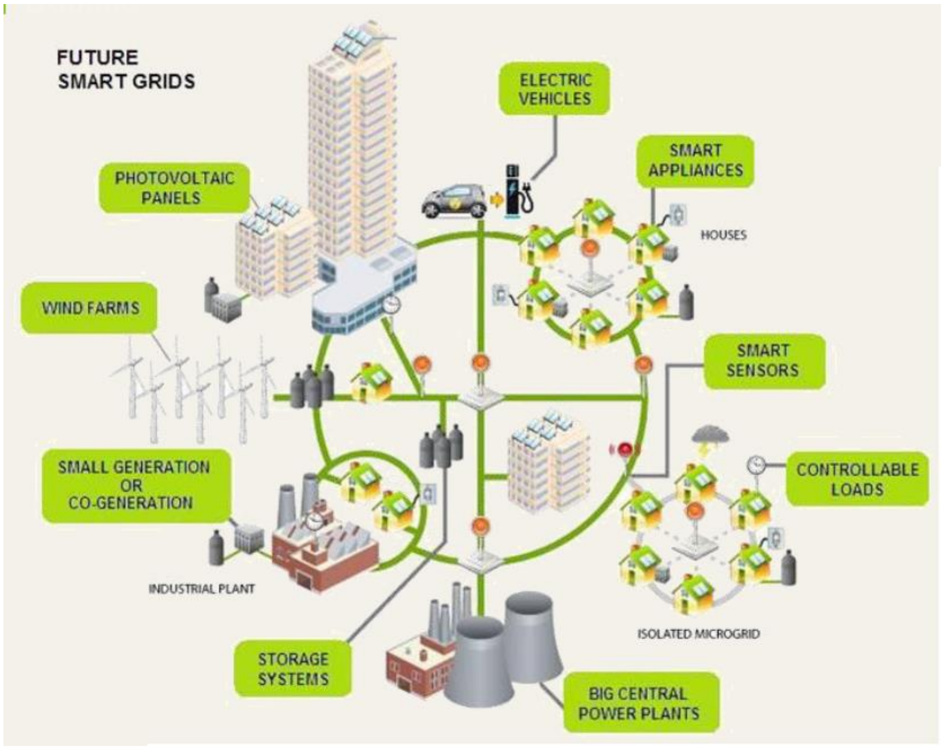


Figure 3.1: Future SmartGrid Concept [16]

integration of distributed generators powering relatively small power systems called micro-grids may be the only option to truly address the problems affecting power grids [17].

A Microgrid is a group of interconnected loads and Distributed Energy Resources such as distributed generators, energy storage systems, and controllable loads, within a clearly defined and local electrical boundary that can act as a single controllable entity with respect to the grid [19]. Modern microgrids are instantiation of the Smartgrids which incorporate key technologies as mentioned previously. They can be operated independently i.e. islanded mode or grid connected mode where the main grid may act as a complementary power source. Not only do micro-grids provide an apt solution to ultra-high power supply availability and cost efficiency in certain cases, but they are also capable of providing blackout resiliency to the grid. One such Microgrid-based blackout recovery solution is discussed in [20].

The number of installed microgrids is small, but it's growing in many regions around the world. The International Energy Agency (IEA) estimates that to achieve its goal of universal access to electricity, "70% of the rural areas that currently lack access will need to be connected using mini-grid or off-grid solutions [21]." As such we shall be focusing on the microgrids operating in off-grid or *isolated mode*.

This chapter is dedicated solely to address the structure and behavior of Microgrids. We start with the description of various technologies of microgrids. The characteristics and limitations of each component are discussed and a corresponding model of the component is provided. Operation and control mechanisms are discussed in the later part of the chapter which summarizes the microgrid behavior in consideration.

3.2 Technologies

3.2.1 Power Generation Sources

This section describes the distributed power sources present in a typical microgrid. We include pertinent details such as the characteristics and limitations of each source.

3.2.1.1 Microturbines and Internal Combustion Engines

Synchronous generators are the most widely used electromechanical power generation technology which convert mechanical power into electrical form and feed it into the power network. A simple three-phase synchronous generator consists of fixed stator with winding distributed across the stator periphery and a rotor connected to a mechanical input shaft with rotor winding excited by a Direct Current (DC) source. An external source such as a microturbine, an Internal Combustion Engine (ICE), or a windmill applies torque to the machine's shaft which rotates the rotor. The DC excitation in the field winding creates a magnetic field which turns as the rotor rotates thus, producing three phase emfs in the stator winding which surround the rotor as shown in Fig. 3.2.

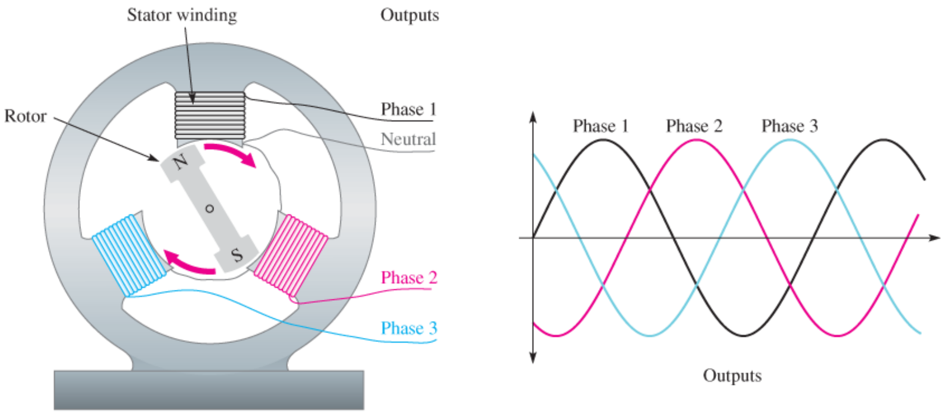


Figure 3.2: Synchronous generator and the 3-phase emf induced.

Since synchronous generators are the heart of the electromechanical conversion technologies mentioned earlier, irrespective of the mechanical driver, the generator structure and behavior models remain the same with slight variations i.e. generators can be modeled based on the significant physical characteristics which fortunately remain the same across most types. These variations are of particular interest to us since they form the design space and shall be used later in Section 4.2. Among several DERs, we will focus on the characteristics of ICEs and Microturbines which also makeup the majority of DER in microgrids around the globe.

Internal combustion engines are becoming increasingly important to help improve the grid efficiency and endure reliability and safety. These are particularly important in isolated regions of earth and where intermittent nature of RES contributes to unreliable power supply. In fact, according to the Alaska Energy Authority, 94 percent of electrical generation in rural Alaska comes from diesel generators, and this is not likely to change significantly in the immediate future [22].

ICEs are characterized by low operation and maintenance cost, quick startup, compact size, short run cycle requirements, and low cost. Another advantage of this technology is that these engines can designed to consume a wide variety of individual fuels orin the case of dual-fuel unitsto be capable of using gaseous fuels (such as natural gas or propane) as well as liquid fuels such as diesel [22]. However, the efficiency of ICEs tend to be moderate to low at around 25% - 45% and higher gas emission levels as compared to other DERs. Hence, due to environmental policies in certain regions, the use of these engines as the primary power source is limited.

Gas Turbines are scaled down low power version of the traditional gas turbines used in large power plants. They evolved from piston engine turbocharges and airplane auxiliary power units, and have power output in the range of 25-500 kW. They are characterized by low emissions, moderately fast dynamic response, low maintenance intervals, and no vibrations. However, they suffer low power conversion efficiency, loss of power output and efficiency with higher ambient temperatures and elevation. Although microturbines have higher capital investment as compared to ICEs, they have several benefits as listed below [23]

- ***Distributed generation*** stand alone, on-site applications remote from power grids
- ***Quality power and reliability*** reduced frequency variations, voltage transients, surges, dips, or other disruptions
- ***Stand-by power*** used in the event of an outage, as a back-up to the electric grid
- ***Peak shaving*** the use of microturbines during times when electric use and demand charges are high
- ***Boost power*** boost localized generation capacity and on more remote grids
- ***Low-cost energy*** the use of microturbines as base load or primary power that is less expensive to produce locally than it is to purchase from the electric utility

- ***Combined heat and power (cogeneration)*** increases the efficiency of on-site power generation by using the waste heat for existing thermal process.

«block»
Generator

values
Active Power : power[kilowatt]{unit = kilowatt}
Quadratic cost coefficient a : Real
LinearCostCoefficient b : Real
LinearCostConstant c : Real
StartupTime : time[second]{unit = second}
ShutdownTime : time[second]{unit = second}
MinUpTime : time[second]{unit = second}
MinDownTime : time[second]{unit = second}
QuadraticEmissionCoeff aem : Real
LinearEmissionCoeff bem : Real
LinearEmissionConst cem : Real
StartupEmission Cemup : Real
ShutdownEmissionCemdn : Real
StartupCost Cup : $
ShutdownCost Cdn : $
ReactivePower : power[kilowatt]{unit = kilowatt}
ApparentPower S : apparent power[kilovolt ampere] [kVA]
StartupDecision : Real
ShutdownDecision : Real
 : Real
BaseVoltage : voltage
Current : electric current

operations
DispatchPower()
Startup()
Shutdown()
Emit()
Consume fuel()

Figure 3.3: Generic SysML block for a generator.

For smaller networks like microgrids, these generators are an excellent choice as they can provide power efficiently while countering the power deviations due to RES. Response time of the generators in a microgrid is considerably low with start-up, shutdown, and ramp rates in order of a few minutes. Cost is associated with frequent start-up and shutdown of the generators and is another important characteristic useful for trade studies. Finally each generator has a minimum uptime and minimum downtime value to ensure economic operation. All the relevant characteristics are modelled as value parameter in a SysML block for a generator as shown in Fig. 3.3.

3.2.1.2 Solar Energy

For 100% RES as the foundation for the future energy supply, Solar photovoltaic (PV) is among the top choices. In 2016 photovoltaics contributed 33.367 TWh to the grid and as of the end of 2017, the United States had over 50 GW of installed photovoltaic capacity. Photovoltaics are characterized by zero emissions and a sustainable source.

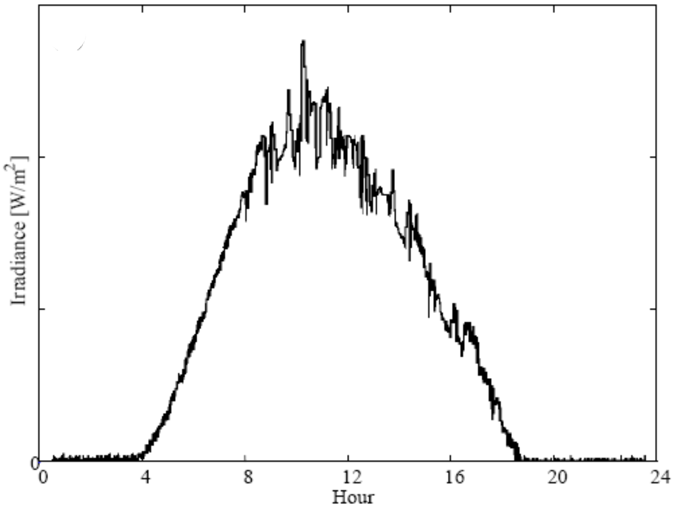


Figure 3.4: Daily solar irradiation diagram on a sunny day.

However, they are inherently unreliable due to intermittent supply and most importantly having low or non-existent inertial response. Additionally efficiency of the solar panels is still in its infancy, e.g. the highest efficiency achieved of a commercial mono-crystalline solar cell is just 22.8%.

Energy generated through PV is directly proportional to the solar irradiation received by the PV module. Based on the daily radiation profile we can model solar PV as energy sources in microgrids. Solar PV forecast can be generated using methodology combining spatial modelling and artificial neural networks (ANNs) techniques. An ANN based model is developed to predict the local global horizontal irradiance (GHI) based on daily weather forecasts in [24].

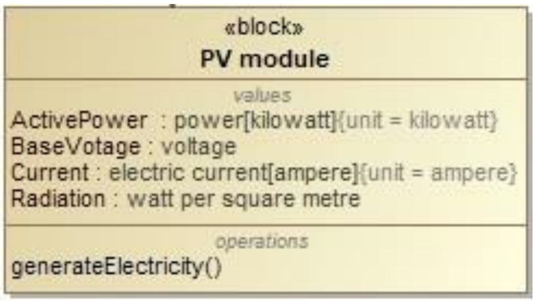


Figure 3.5: SysML block for PV module

Values for solar PV power generation at each node i are generated based on solar module power rating and the irradiation values based on the graph presented in Fig. 3.4 for the purpose of this thesis. Structure of a generic PV module can be illustrated as a SysML block as shown in Fig. 3.5.

3.2.2 Power converters and Sensors

Power electronic interfaces are responsible for controlled energy flow between the nodes of an electric network. power converters have enabled bidirectional energy flow with energy flowing towards consumer and also from the consumer into the network. In fact without converters it would be impossible to integrate network components like solar PV into the grid. These converters have very high efficiency and are robust, thanks to accelerated development of stationary power electronic system in the past decade [17]. These components however are safely ignored while performing power flow studies, owing to their high efficiency.

Phasor Measurement Unit (PMU) or Synchrophasors provide necessary network sensing for dynamic monitoring of transient processes in the network. These devices measure magnitude and phase angle of currents and voltages at a given node. The high-precision time synchronization (via GPS) allows comparing measured values (synchrophasors) from different substations far apart and drawing conclusions as to the system state and dynamic events such as power swing conditions [18]. Naturally, the grid is unbalanced due to dissimilar power demand and supply, hence causing frequency variations; PMUs are extremely important to implement voltage and frequency control techniques to stabilize the grid. PMUs are one the technologies that form *smart* in Smartgrids. Similar to the power electronic interfaces, these vital components are safely ignored while modelling for power flow studies. It is important to note the fact that the majority of the parameters in grid studies are accurately sensed only using these devices.

3.2.3 Smart Loads and Demand Response

One of the marked features of Smartgrids is the addition of active end nodes i.e. intelligent loads with capabilities to adjust power consumption. Smart meters and ICT infrastructure of smartgrids enables customers to participate in Demand Side Management activities by modifying their energy consumption. Consumers can-reduce their energy usage during critical peak periods when the electricity prices are high and shift their demand to off-peak periods by postponing activities involving heavy electrical usage to off peak time. Smart plugs, smart appliances and similar home energy management systems can also interact with the Microgrid Operator (MGO) and contribute to Demand Response (DR) programs. Demand response can be defined as the changes in electricity usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time. [25]. Various DR schemes for microgrids are discussed in [25]; these programs are already implemented by several utilities [26, 27].

Use of smart meters enable utilities to record electricity usage at a much higher time resolution thus enabling them to implement time-variant pricing and DR programs. Successful implementation of DR programs involving load shifting flatten the load profile peak by encouraging consumers to alter their demand pattern [28]. The demand shift may be activated by a signal from the MGO, such as dynamic pricing, peak load caps, etc.

Forms of time-based rate programs include [29]:

Time-of-use pricing (TOU) - typically applies to usage over broad blocks of hours (e.g., on-peak=6 hours for summer weekday afternoon; off-peak = all other hours in the summer months) where the price for each period is predetermined and constant.

Real-time pricing (RTP) - pricing rates generally apply to usage on an hourly basis.

Variable Peak Pricing (VPP) - a hybrid of time-of-use and real-time pricing where the different periods for pricing are defined in advance (e.g., on-peak=6 hours for summer weekday afternoon; off-peak = all other hours in the summer months), but the price established for the on-peak period varies by utility and market conditions.

Critical peak pricing (CPP) - when utilities observe or anticipate high wholesale market prices or power system emergency conditions, they may call critical events during a specified time period (e.g., 3 p.m.6 p.m. on a hot summer weekday), the price for electricity during these time periods is substantially raised.

Critical peak rebates (CPR) - when utilities observe or anticipate high wholesale market prices or power system emergency conditions, they may call critical events during pre-specified time periods (e.g., 3 p.m.6 p.m. summer weekday afternoons), the price for electricity during these time periods remains the same but the customer is refunded at a single, predetermined value for any reduction in consumption relative to what the utility deemed the customer was expected to consume.

San Diego Gas & Electric began transitioning residential customers to Time-of-Use pricing plans in early 2019. Leveraging these plans energy consumers can better manage and control their daily demand to reduce consumption cost. Fig. 3.6

depicts on of SDG&E's TOU pricing plans.

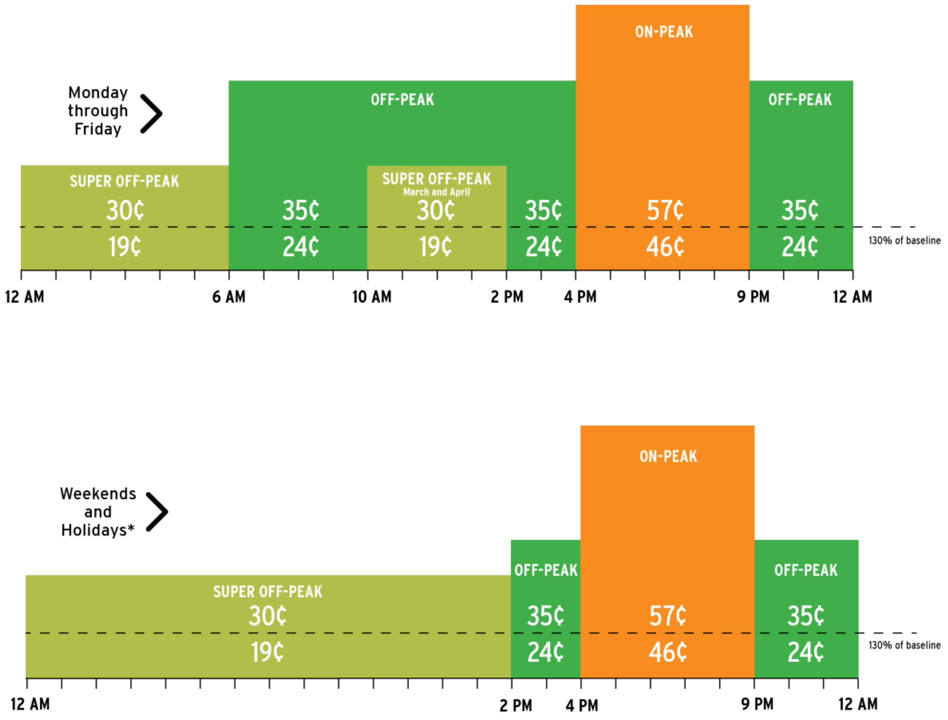


Figure 3.6: SDG&E's TOU-DR1 plan for Summer season spanning June1 - October31. Peak period is defined from 4pm - 9pm. The plan also includes baseline allowance [27].

To study the effects of DR program based on load shifting, we can model the behavior of these programs with part of residential load assumed to be shiftable. The controllable or shiftable part of the residential loads include infrequent usage of appliances like dishwashers, washing machines, and HVAC systems during certain seasons. The optimization problem here can be formulated with an objective to minimize total cost of electricity constraint by distribution of the load across the

24hr period. The constraint equation can be represented as,

$$\sum_{n} P_{i,n} \leq PD_i^{rsmax} \quad \forall i \tag{3.1}$$

where $P_{i,n}$ denotes load at node i at time n and PD_i^{rsmax} denotes maximum total daily shiftable load at node i.

3.2.4 Energy Storage System

Energy Storage System (ESS) in microgrids are essential to compensate for slow dynamic response by other DERs as well as continuously powering loads in absence of RES. Intermittent nature of RES and high availability requirements of microgrids make it absolutely necessary for ESS inclusion. In grid connected mode, power deficit from the local generation can be compensated by importing power from the grid, however, in isolated mode excess demand creates an imbalance which can be mitigated using ESS. ESS assist RES and help maintain power balance by storing energy during off-peak periods at lower costs. Use of ESS for frequency control in microgrids is discussed in [30].

Batteries, pumped-hydro, flywheels, and ultra-capacitors are some of the storage technologies currently in use. We will be focusing our discussion of ESS on just Battery Energy Storage System (BESS) since they are the most preferred choice of ESS in microgrids and other technologies such as pumped-hydro are not an option for all microgrids. Fig. 3.7 provides SysML block for a typical BESS system.

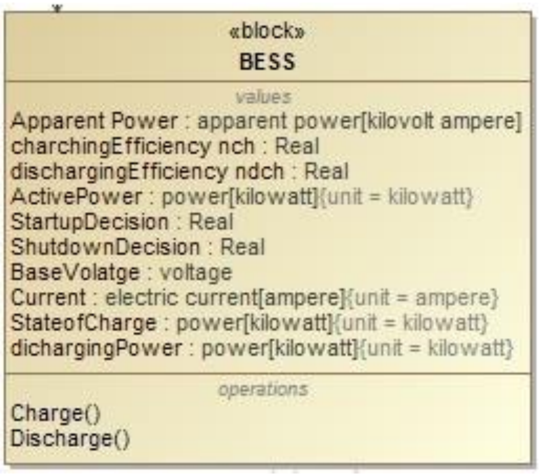


Figure 3.7: BESS SysML block

Types of Battery ESS are : Lead acid, Lithium Ion, Sodium Sulphur (NaS), Nickle Cadmium (Ni-Cd), and Nickel metal hydride (NiMH). They are characterized by relatively low cost, reduced environmental hazard, high reliability, and high deficiencies. However, Batteries suffer from poor life cycle, performance degradation over and losses at every step of charging and discharging.

Battery Voltage, Current rating and its storage capacity are all functions of its material and construction. State of Charge (SOC) is yet another important battery metric which is defined as the ratio of remaining capacity to the nominal capacity.

Eq. 3.2 and 3.3 depict SoC definition and the variation of $SoC(dSoC)$ that depends on time and capacity C_i.

$$dSoC = \frac{idt}{C_i} \tag{3.2}$$

$$dSoC = SoC - \int \frac{idt}{C_i} \tag{3.3}$$

Table.3.1 provides comparison among several types of BESS based on important economic and physical characteristics [17].

	Lead Acid	Ni-Cd	Ni-MH	Li-Ion
Cell voltage (V)	2	1.2	1.2	3.2 ($LiFePO_4$)
Specific Energy (Wh/kg)	1-60	20-55	1-80	3-100
Specific Power (W/kg)	< 300	150-300	< 200	100-1000
Energy Density (kWh/m^3)	25-60	25	70-100	80-200
Power Density (MW/m^3)	< 0.6	0.125	1.5-4	0.4-2
Discharge time range (min)	> 1	1-480	> 1	0.16- 60
Maximum Cycles	200-700	500-1000	600-1000	3000
Cost ($/kW)	200	600	1000	1100
Efficiency (%)	75	75	81	99

Table 3.1: Comparison of energy delivery profile technologies

3.3 Operation and Control Mechanism

Predominantly power system architecture can be classified into two types, centralized and distributed. Distributed systems have their control processing spread around its components while a centralized controller is responsible for the same in a centralized system. In a manner conventional power systems are centralized systems since power generation and control is localized to a single power plant that serves a large region. Decentralized or distributed architectures are more flexible as compared to their counterpart since they enable integration of different connection structures and component additions without frequent changes to the controller.While centralized structures present single point of failure and difficulties in integration of additional nodes, they provide more efficient management and coordination of DERs and hence are more suitable for microgrids.

3.3.1 Microgrid Energy Management System

The objective of a centralized Microgrid Energy Management System (MEMS) is to provide suitable set points to fulfill the demand, as control signals to the DERs and ESS units while minimizing the operational cost and maximizing RES usage. In a three-tier hierarchical control system for isolated microgrids, MEMS is also the highest hierarchical level in control [31]. Typical centralized MEMS for an isolated microgrid is presented in Fig. 3.8. Using PMUs, grid quantities like line voltage, line current, phase angle, and frequency at various node are acquired. These quantities may serve as input for power flow studies.

Based on demand forecast, DER characteristics, ESS capacity, and PV forecast, the MEMS proposed in [31] solves Unit Commitment mathematical problem to provide Load flow information, Generator and ESS dispatch schedule as output.

Unit commitment is an optimization problem that determines optimal schedule of DER and ESS units over a time horizon ranging from 24 hours to 168 hours with varying loads under different constraints and environments ahead of real-time

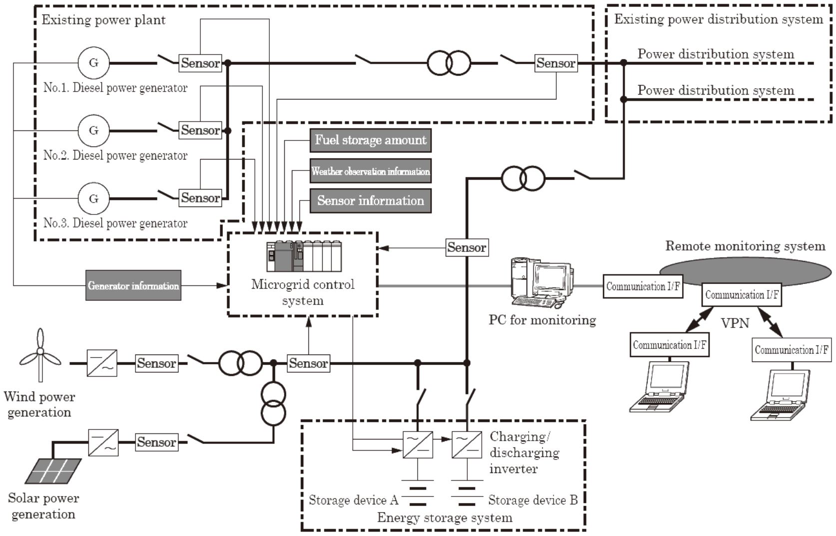


Figure 3.8: Centralized Microgrid Energy Management System [32]. Point of Coupling(PCC) provides connection to the main grid as shown in the top right corner.

application. The typical objective function is based on generation cost and is constrained by multiple considerations including load, spinning reserve, UC constraints, ESS constraints.

With UC in consideration, cost to the grid operator can be summarized by the following formulation [28],

$$Cost = \sum_{g,n} [(a_g P_{g,n}^2 \Delta n + b_g P_{g,n} + c_g W_{g,n}) \Delta n + C_g^{up} U_{g,n} + C_g^{dn} S_{g,n}] \tag{3.4}$$

where quadratic terms a_g, b_g, and linear term c_g represent coefficients of cost function, decision variables $P_{g,n}, W_{g,n}, S_{g,n}$, and $U_{g,n}$ represent active power, on/off decision , shutdown decision, and startup decision respectively for each generator g at time interval n. Parameters C_g^{up} and C_g^{dn} denote the cost associated with generator startup and shutdown and Δn represents time interval in hour between n and $n+1$.

All the decision variables except the ones representing power are logical variables assuming binary integer values of 1 or 0 denoting on/off decisions. Complete list of parameters and variables along with their definitions is provided in Abbreviations and Acronyms section. Sample values for the parameters is provided in Appendix A.

The objective is subjected to bounds on variables and linear constraints associated with generation limits, generator constraints, co-ordination constraints, power balance and BESS constraints.

Engineering constraints in UC problem limit the power levels while satisfying the load conditions. Flow limits on active and reactive power are generally enforced as,

$$\underline{P}_g W_{g,n} \leq P_g \leq \overline{P}_g W_{g,n} \quad \forall g, n \tag{3.5}$$

$$\underline{Q}_g W_{g,n} \leq Q_g \leq \overline{Q}_g W_{g,n} \quad \forall g, n \tag{3.6}$$

where variable Q_g represents the reactive power from generating unit and the bars denote specified upper and lower limits on the corresponding quantities. However, we shall make use of only Active power P_g constraint in our analysis.

Ramp-up and ramp-down rates for a given generator g are the same and hence denoted by R_g. The following constraints characterize generator's loading behavior.

$$P_{g,n+\Delta n} - P_{g,n} \leq R_g \Delta n + U_{g,n+\Delta n} \underline{P}_g \quad \forall g, n \tag{3.7}$$

$$P_{g,n} - P_{g,n+\Delta n} \leq R_g \Delta n + S_{g,n+\Delta n} \underline{P}_g \quad \forall g, n \tag{3.8}$$

Each generator g is characterized by similar minimum uptime and downtime values denoted by T_g. The following constraints ensure that every time generator g is started or shutdown it stays on/shut for minimum prescribed time.

$$\sum_{n:n-T_g}^{n-1} W_{g,n}\Delta n > T_g S_{g,n} \quad \forall n > T_g \tag{3.9}$$

$$\sum_{n:n-T_g}^{n-1} (1 - W_{g,n}\Delta n) > T_g U_{g,n} \quad \forall n > T_g \tag{3.10}$$

Co-ordination constraints ensure that opposing binary decision variables ($S_{g,n}$, and $U_{g,n}$) do not assume same value at a given time instance n.

$$U_{g,n} - S_{g,n} = W_{g,n} - W_{g,n-\Delta n} \quad \forall g, n \tag{3.11}$$

$$U_{g,n} + S_{g,n} \leq 1 \quad \forall g, n \tag{3.12}$$

The power balance constraint ensures that total power from generation units, RES, and BESS units matches the residential and commercial load.

$$\sum_g P_{g,n} + \sum_i PV_{i,n} + \sum_e (P^{dch}_{e,n} - P^{ch}_{e,n}) = \sum_i [PD^c_{i,n} + PD^r_{i,n} + PD^{rs}_{i,n}] \forall n \tag{3.13}$$

DR constraints as explained in Section 3.2.3. are modelled as,

$$0 \leq \sum_{n} PD^{rs}_{i,n}\Delta n \leq PD^{rsmax}_{i} \quad \forall n \tag{3.14}$$

$$\underline{PD}^{rs}_{i} \leq PD^{rs}_{i,n} \leq \overline{PD}^{rs}_{i} \quad \forall i, n \tag{3.15}$$

Finally, the BESS constraints include limits on charging/discharging and State of Charge ($E_{b,n}$), constraints on energy balance and co-ordination constraints to prevent simultaneous charging and discharging.

$$E_{b,n+\Delta n} - E_{b,n} = (P^{ch}_{b,n}\eta^{ch}_{b} - \frac{P^{dch}_{b,n}}{\eta^{dch}_{b}}) \quad \forall b, n \tag{3.16}$$

$$P^{ch}_{b,n}P^{dch}_{b,n} = 0 \quad \forall b, n \tag{3.17}$$

$$\underline{E}_{b} \leq E_{b,n} \leq \overline{E}_{b} \quad \forall b, n \tag{3.18}$$

$$P^{ch}_{b,n} \leq \overline{P}_{b} \quad \forall b, n \tag{3.19}$$

$$P^{dch}_{b,n} \leq \overline{P}_{b} \quad \forall b, n \tag{3.20}$$

Unit commitment problem is restricted to obtaining minimum power generation set points ensuring minimum availability. This definition results in an objective of minimizing power generation cost while the only constraints are the UC constraints Eqn.3.5-3.12.

3.4 Summary

We've provided comprehensive text on the main technologies present in a microgird with brief description of every component. Generic SysML block diagrams for the components were provided and mathematical models of the relevant components were introduced. Based on these models we shall perform the tradeoff analysis in the next section.

Chapter 4: Microgrid Model Development & Tradeoff Analysis

4.1 Microgrid Energy Management System

4.1.1 System Description

To concretely illustrate robust tradeoff analysis potential we performed simulation experiments on a medium voltage microgrid network as shown in Fig. 4.1. Centralized controller, a Microgrid Operator (*not shown*) is connected to all the nodes in the network and is responsible for generation of grid operation signals. The grid assumes 10-bus hybrid network topology with 3 major generators at the centre and 3 ancillary generators, 6 solar PV modules, and 3 BESS units distributed throughout the network. The 6 Diesel generator units have a combined capacity of $7600kW$. Six solar PV modules can contribute for upto $2270kW$ power while the three BESS units have can provide support for upto $1167kW$. Power generation from the PV units is modelled as described in Section 3.2.1.2. Loads are broadly classified into Residential and Commercial type. 25% of the residential load is assumed to be shiftable to serve the DR implementation as explained in Section 3.2.3.

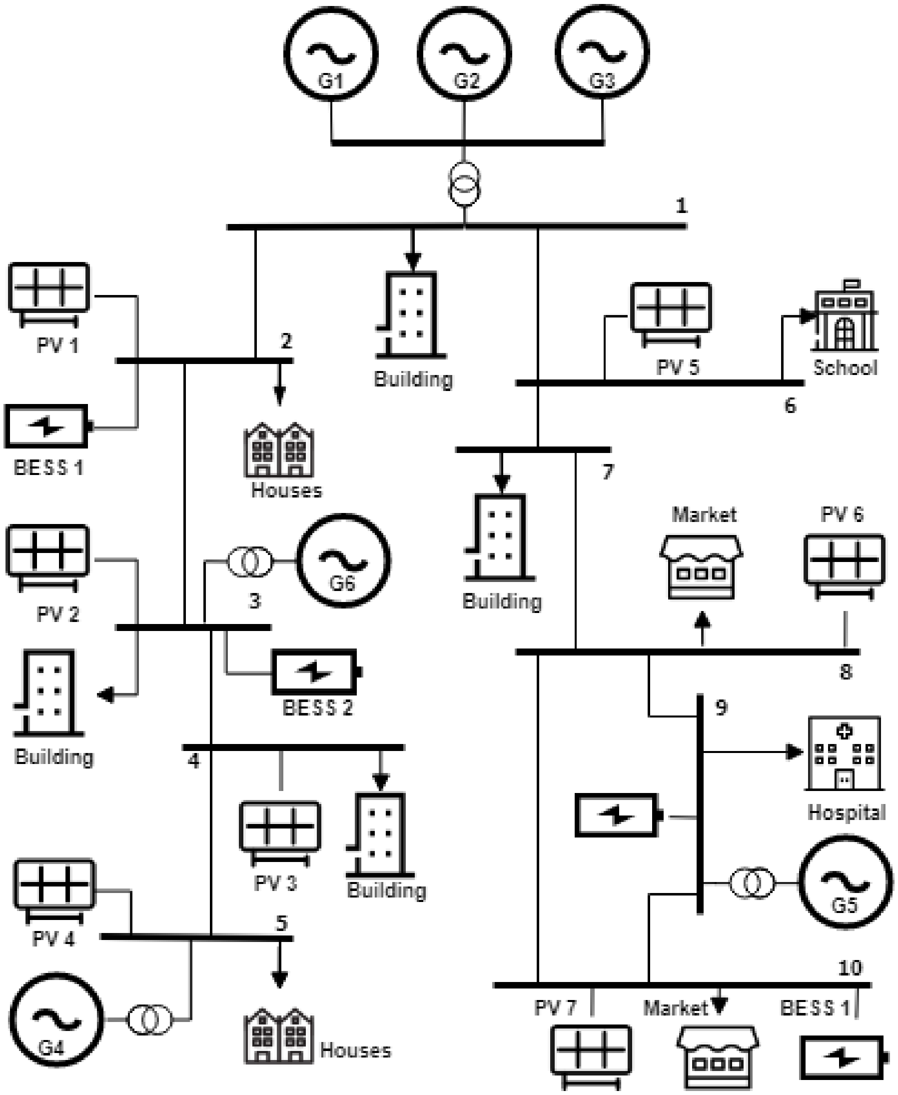


Figure 4.1: Example Microgrid network with DER and various types of loads

As depicted in Fig. 4.1 residential load is assumed to be from mid-rise apartments and small houses. Markets, Schools and Hospital are the 3 different types of commercial loads in the network.All the loads are modelled on the basis of data available form the U.S. Department of Energy, for the Baltimore-Washington Intl AP 724060 region [33]. Hourly resolution of data was linearly interpolated to result in 5min snapshots for 24hr period using simple MATLAB routine. Sample load profiles of different load types are presented in the following figures.

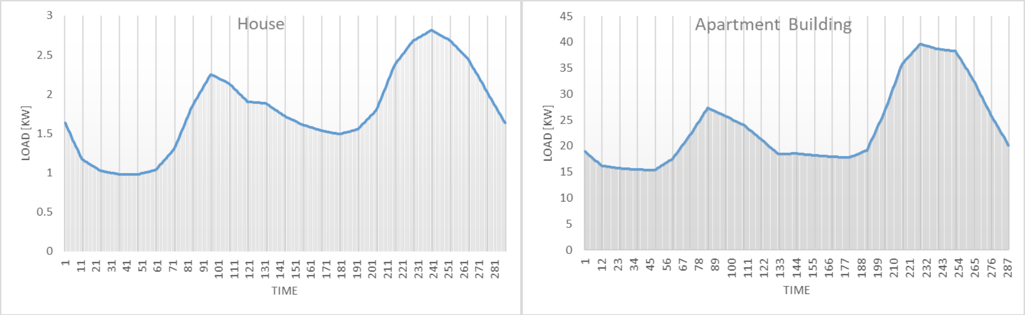


Figure 4.2: Residential loads: House(left) and Midrise-Apartment Building(right)

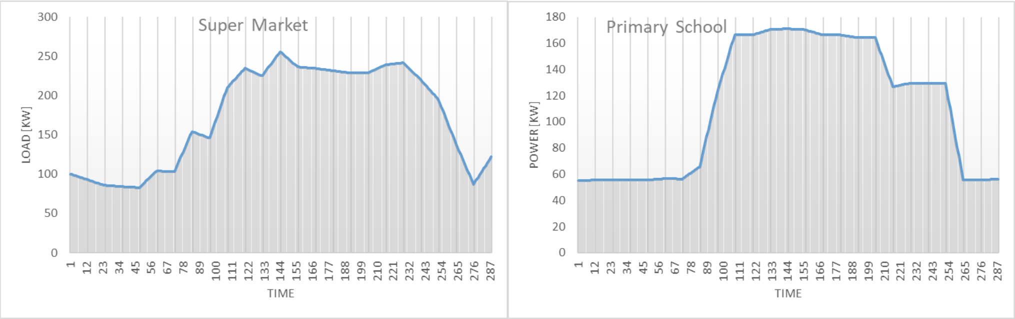


Figure 4.3: Commercial loads: Super Market(left) and Primary School(right)

As apparent in Fig. 4.3 the load curve for primary school is flat over non-operational hours while high plateau regions suggest relatively constant loads, thus accurately reflecting real-life behavior. Hospital loads depicted in Fig.

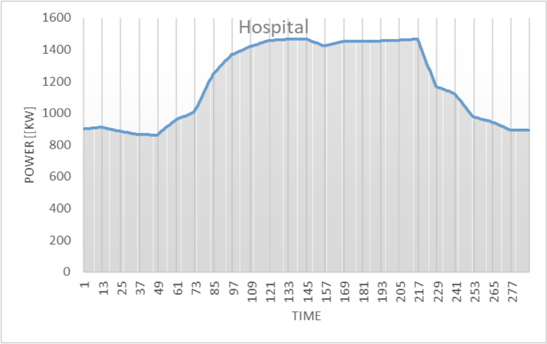


Figure 4.4: Commercial Loads: Hospital.

4.4 have the highest peak load value of

approximately $1500kW$ among all the loads and exhibit behavior similar to other commercial loads.

We assume that the components are "ideal" i.e. losses are unaccounted for. Since the grid is considered to be in offline mode, in the event of inadequate power generation, load shedding will be implemented.

To understand the system structure from the tradeoff analysis point of view, we represent the grid structure using SysML block definition diagram and internal block diagram.

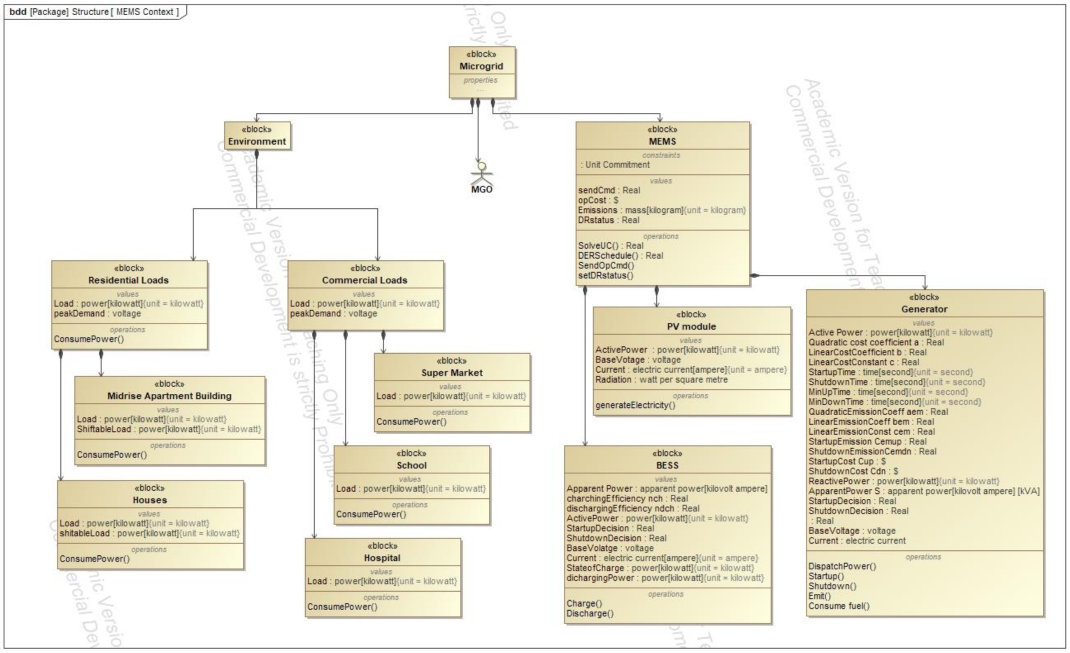


Figure 4.5: Block Definition Diagram SysML diagram for Microgrid system

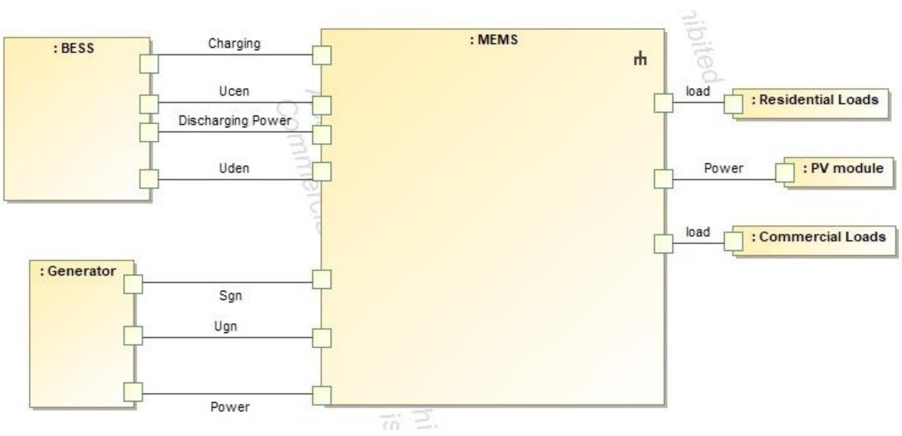


Figure 4.6: Internal Block diagram for Microgrid System

4.1.2 System Requirements

The system requirements can be crudely stated in the following manner.

Given a set of loads, together with their power and reliability requirements, the goal is to determine Microgrid architecture such that demand of the loads is always satisfied.

For the system in consideration, Safety requirements constrain power flow through network lines to avoid loss of power to any node.

Reliability requirements specify bounds on failure probabilities of the components and the system per se.

Performance specifications specify quality metrics that are desired for the system. Important system metrics such as cost of operation and emissions will be used to evaluate design choices.

4.1.3 Mathematical Model implementation

To assist decision making, tradeoff analysis is performed by experimenting on mathematically modelled primary system functions. Building on the component models discussed in previous sections, we form a complete grid model reflecting system function of Unit commitment. Microgrid UC model minimizes operational cost *opCost* to the grid operator while subjecting the objective to multiple constraints as explained in Section 3.3.1. The objective can be expressed as in,

$$opCost = \sum_{g,n}[(a_g P_{g,n}^2 \Delta n + b_g P_{g,n} + c_g W_{g,n})\Delta n + C_g^{up} U_{g,n} + C_g^{dn} S_{g,n}] \tag{4.1}$$

while constraining the objective with UC constraints (Eqn.3.5-3.12), Demand constraints (Eqn.3.13), Demand Response constraints (Eqn.3.14-3.15), and Battery Energy Storage System constraints (Eqn.3.16-3.20).

Following the exposition in [28], the total cost of emissions due to power generation form fossil fuel based DERs is calculated as the product of power generated and the social cost of carbon (SCC) [34]. Generator characteristics including emission associated with startup and shutdown are taken into consideration. The objective can be integrated into the UC model and is expressed as,

$$emCost = \tau[\sum_{g,n}[(a_g^{em} P_{g,n}^2 \Delta n + b_g^{em} P_{g,n} + c_g^{em} W_{g,n})\Delta n + C_g^{emup} U_{g,n} + C_g^{emdn} S_{g,n}]] \tag{4.2}$$

where τ represents SCC and is assumed to be 40\$/ton.

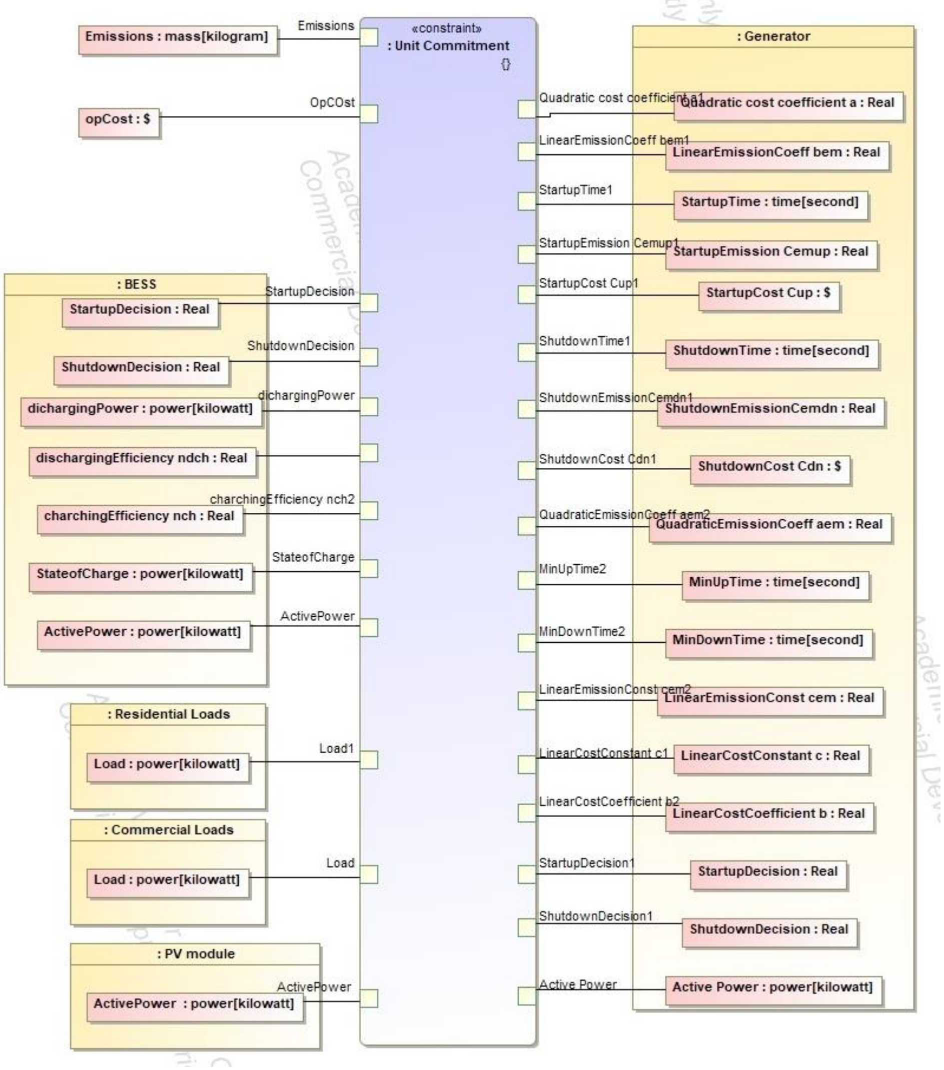


Figure 4.7: Parametric Diagram for Unit Commitment Constraint Block

Th above formulation presents a multi-objective problem with quadratic objectives and linear bounds and hence is a MIQP convex problem. For alternate non-convex formulations convex relaxation approaches such as semidefinite programming (SDP) and second order cone programming (SOCP) can be adopted [35].

The problem is coded in Optimization Programming Language and solved using the CPLEX IDE. Using the parametric diagram we can represent the Unit commitment problem in diagrammatic form as shown in Fig. 4.7

4.2 Tradeoff Analysis

4.2.1 Problem Formulation

Algebraic sum of the Cost model *opCost* and Emission model *emCost* form a single objective function to be minimized while subjecting it to the same constraints mentioned earlier.

$$J = opCost + emCost \tag{4.3}$$

Both objectives are weighted equally however, emphasis on any one of the two can be expressed by assigning weights to the objectives as,

$$J = \alpha opCost + \beta emCost \tag{4.4}$$

$$\text{where,} \qquad \alpha + \beta = 1 \tag{4.5}$$

At present we study the effect of DR, RES, BESS, and change in number of generating units while ranking both objectives equally.

4.2.2 Optimization Description

The model developed in the previous section reflects the behavior of a typical MEMS by solving the UC problem and generating optimal set points for grid operation. The optimization computes Cost of generation and corresponding emissions as output when provided input of generator characteristics, BESS characteristics, PV forecast, load profiles and bounds on the variables. Response model for the optimization depicted in Fig. 4.8 describes the relevant metrics and factors.

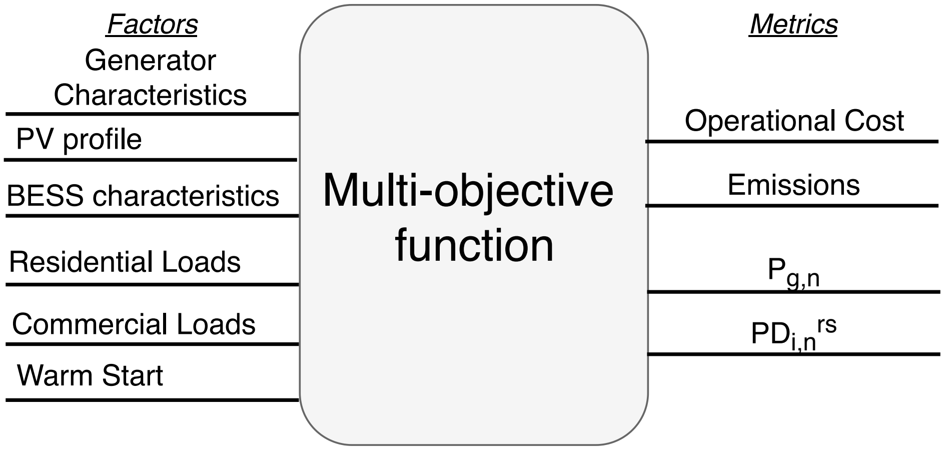


Figure 4.8: Simulation Response Diagram.

4.2.3 System Capabilities, KPPs, and MOEs

The objective of Microgrid operations can be summarized as providing requested power to the customers while maintaining high availability, and minimizing cost and hazardous emissions. Table.4.1 lists the ***Measures of Effectiveness(MOE)*** of the system in order of priority with 1 being the highest and 3 being the lowest. Each metric can be analyzed either deterministically or stochastically. Deterministically all the metrics can be calculated based on the mathematical models described in the previous sections. Stochastic approach resides to variations in load profiles based on some probability distribution.

Highest priority among system capabilities is its availability which ensures that

ID	Attribute	Metric
KPP 1	Generation Cost Reduction	Cost of Power generated through DER($)
MOE 1	Emission reduction	Emissions generated through DER(ton)
MOE 2	RES penetration	RES share in power generation(%)
MOE 3	Peak-period consumption reduction	Power generated through DER(kW)

Table 4.1: Prioritized MoE and KPP list for the simulation

power is dispatched and available to all the loads at any instance of time. This is ensured by the constraint Eqn. 3.13. Hence is always satisfied during the simulation runs given minimum configuration with just the major 3 generators.

We illustrate in the results significance and feasibility of various technologies in our Smartgrid model by solving the model for different test cases over a period of 24 hour with 5 minutes intervals i.e. simulating the network by varying components mentioned in Table.4.2

4.3 Results and Discussions

Generator parameters and emission characteristics were adopted from [28] and can be found in Appendix. Microgrid was simulated for 24hr period with time step of 5min. All the simulations were coded and solved in CPLEX on Intel® Xeon® 3.5 Ghz processor with 16 GB memory. Computation time for most of the simulations was in the range of $150 - 300s$ with some exceptional cases where constraints were more tight the computational time was in the order of few hours. Relative MIP gap tolerance was set at 3% and all the results present an optimal solution.

Test ID	Grid Configuration
1A **(Baseline)**	Grid with **generation capacity (7,600 kW), BESS support (1,167 kW)**, **DR enabled**, and **PV generation (2,270 kW)**
1B	Baseline configuration with **DR disabled**
1C	Baseline configuration with **no PV generation**
1D	Baseline configuration with **no BESS support**
2A	Baseline configuration with **PV generation of 745 kW**
2B	Baseline configuration with **PV generation of 1,420kW**
3A	Baseline configuration with generators G1, G2, and G3 active and **generation capacity of 4,250 kW**
3B	Baseline configuration with generators G1, G2, G3, and G4 active and **generation capacity of 4,600 kW**
3C	Baseline configuration with generators G1, G2, G3, G4, and G5 active and **generation capacity of 5,500 kW**
3D	Baseline configuration with generators G1, G2, G3, and G6 active and **generation capacity of 6,350 kW**

Table 4.2: Test Cases

4.3.1 DER scheduling (KPP1 and MOE2)

DER dispatch based on the set points obtained form the optimization for Test case.**1A** yields the following optimal DER scheduling *stacked column* graph depicting share of 6 individual diesel generators, combined BESS units, and lumped sum of PV modules for a 24hr period. Fig. 4.9 represents the optimized scheduled obtained for test case 1A.

All but generator G4 and G3 provide power continuously for the 24 hour period. The short power dispatch discontinuity by generator G3 and G4 can be seen at around 3.30 AM depicted by a dip in the graph. Unimodal PV contribution curve during day time reflects solar radiation profile as described in Section 3.2.1.2. For test case 1A , with network consisting of all the DER sources available and

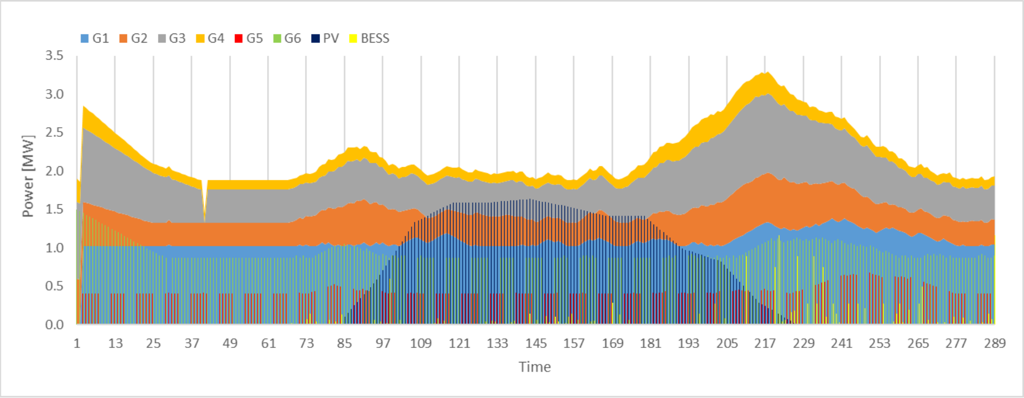


Figure 4.9: DER dispatch over 24hr period with time interval of 5min. Distinctly coloured area represents each DER's share.

DR enabled, generator **G1** and **G6** contribute more than 50% of the total power dispatch by the generators. Developed models are robust and provide easy options for accommodating different types of generators.

4.3.2 Significance of Demand Response (MOE 3)

Enabling DR techniques of load shifting definitely reduces operation cost and can be illustrated by comparing generation power dispatch from test case **1A** and **1B**. Since PV generation profile is static and BESS' contribution is significantly small, it is safe to assert that generation dispatch reflects the demand served accurately.

Cost reduction can be explained by the shifting of power to off-peak period where cheapest generator can dispatch necessary power, essentially increasing share of the cheapest generator in power dispatch. Effectiveness of DR can be further illustrated by comparing operational cost and emissions for the same network con-

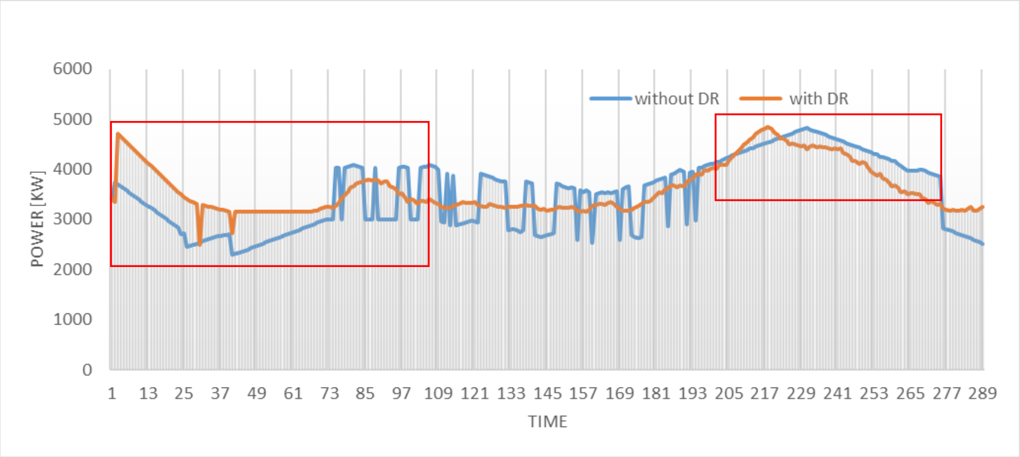


Figure 4.10: Effect of Demand Response. Peak-period approx. from 4PM-9PM is

figuration and switching DR option.

	with DR	without DR
Operating Cost ($)	18,675	19,105
Emissions (ton)	84.9	86.6
Cost reduction ($)	429.5	0
Emission reduction (ton)	1.7	0
Avg. load (kW)	3,608.8	3,506.1

Table 4.3: Effectiveness of DR strategy

4.3.3 RES Penetration (MOE 2)

MOE 3 *(RES penetration)* can be analyzed by studying effects of variations in PV capacity on the grid cost and emissions. Installed PV capacity is directly proportional to the power capacity of the grid with fixed installed generator configuration. In all the test cases, both emission and cost metric depreciate with increasing levels of PV capacity. The results for relevant test cases are summarized in Table 4.4, where we observe $> 13\%$ rise in cost and emission in absence of PV modules. It is apparent from the results that addition of PV brings down the operational cost and emissions however, the caveat here is that PV load profile was not modelled to be stochastic, neither have we focused on grid stability techniques such as frequency control, which provide more rational approach to PV sizing. Since frequency control is beyond the scope of this thesis, the obvious design choice for PV size would be of maximum PV capacity of 2,270 kW.

Test Case	Installed Capacity (kW)	Emissions (ton)	Cost ($)	% Emissions increase	% Cost increase
1A	2,270	84.9	18,675.9	0	0
2B	1,420	90.8	19,947.1	6.3	6.2
2A	745	93.7	20,582.7	9.1	9
1C	0	96.5	21,184.5	13.7	13.4

Table 4.4: Results of Test cases with varying PV levels

4.3.4 Effect of Generator selection (KPP1 and MOE 1)

Test cases 3A-3B along with the baseline, illustrate the effect of varying generation capacity on cost and emissions, essentially, these test cases help us making design choice for the generators.

Keeping the load conditions constant, generation capacity through generators was incrementally increased. Generator G1 and G6 having similar characteristics dominate the share of generation in every case as seen in Fig. 4.11

Increasing the share of RES translates to selection of design with maximum PV installed capacity. Hence, architecture synthesis for our case boils down to selection

Test Case	Installed Capacity (kW)	Emissions (ton)	Cost ($)	% Emissions increase	% Cost increase
1A	7.6	84.9	18,675.9	0	0
3A	4.52	86.8	19,853.2	2.2	6.3
3B	4.6	86.7	19,405.2	2.1	3.9
3C	5.5	81.2	18,011.1	-3.5	-3.5
3D	6.35	81.9	19,014.1	-3.5	1.8

Table 4.5: Summary of generator variation results.

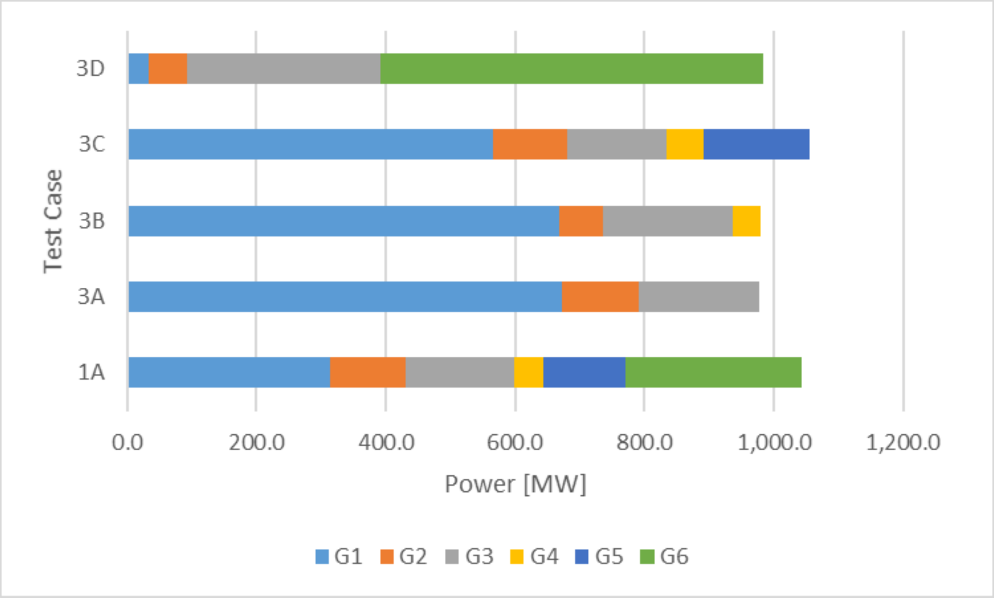


Figure 4.11: Individual generator share for each test case

of generator units. Since highest priority is assigned to reduction of cost followed by reduction of emission, we illustrate the effect of generator variation on these metrics in Fig. 4.12. Cost and emission values are scaled to provide comprehensive view of the results. Test case 3C provides lowest value for the objective and hence proves to be the ideal generator configuration.

Results of all the test cases are summarized in an emissions vs. cost scatter

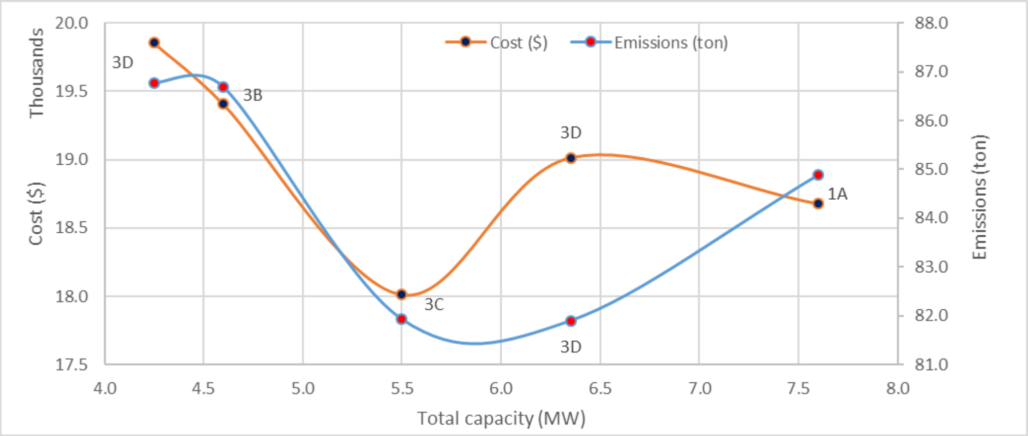


Figure 4.12: Comparison of design choices w.r.t. Cost, Emission, and Installed Capacity.

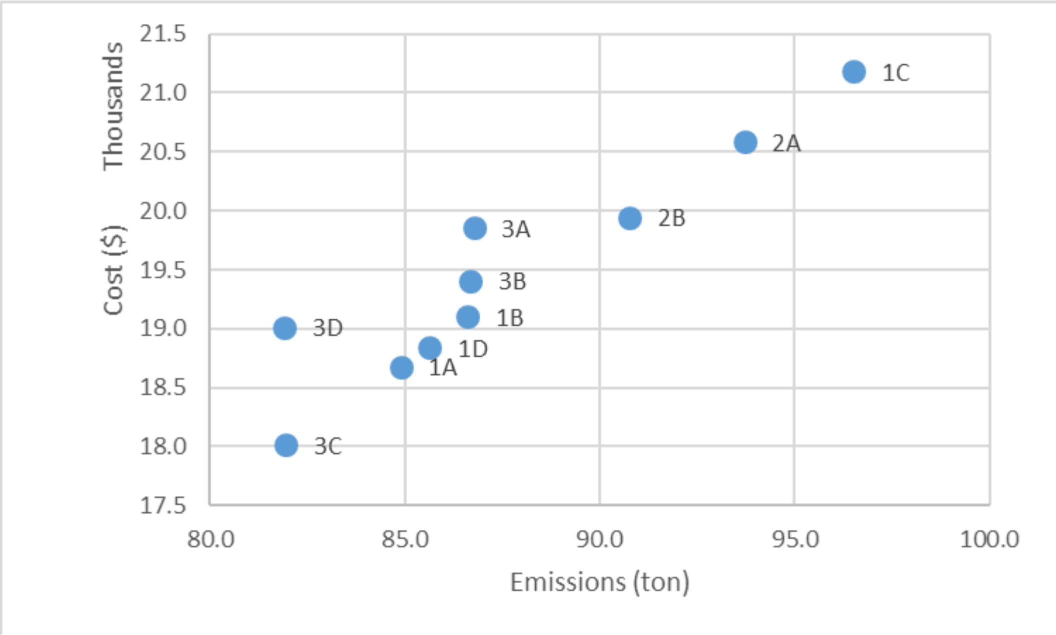


Figure 4.13: Emssions vs. Cost results for all the test cases.

plot as shown in Fig. 4.13. This pareto graph clearly indicates that design choice 3D, 3B, and 3A are suboptimal since they do not lie on the pareto surface, while design choice 3C provides lowest cost and lowest emissions.

In a similar fashion building on to these models we can perform other trade studies which can support analysis such as ideal BESS sizing, TOU rates, integration of wind energy sources etc.

4.4 Summary

We presented use of SysML for understanding microgrid structure. A tradeoff problem was formulated to optimize cost of operation and emission based on the mathematical modelling of components in the previous sections. Architecture synthesis was performed based on the results from tradeoff analysis. We also demonstrated use of powerful solver CPLEX which is widely used in the industry.

Chapter 5: **Conclusion**

5.1 Summary and Conclusions

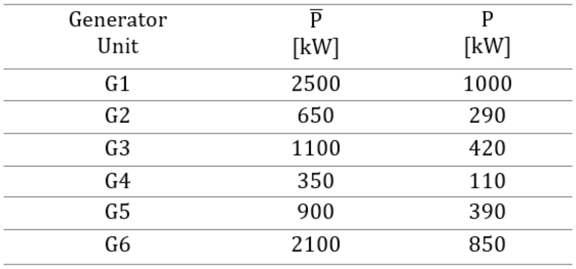
We offered an outlook over the application of our SE methodology: Model Based Systems Engineering. We argued that MBSE provides a structured and efficient approach to model high complexity systems.

A thorough description of a working Smartgrid instanstiation was provided with component level design fidelity. A comprehensive take on technologies that makeup future grids was provided. We developed structural model of the system using SysML and corresponding mathematical model describing behavior of the system. We then performed tradeoff analysis by optimizing the a multi-objective convex function over while taking component constraints into consideration. The MIQP representing the grid using powerful solver, CPLEX, advocating inclusion of such solvers in MBSE approach. Architecture synthesis was aided through the tradeoff analysis to further concertize importance of modelling while developing complex systems.

5.2 Future Work

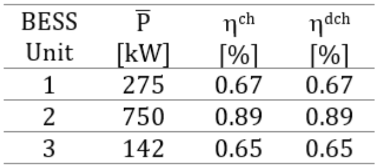
A big leap towards managing design of complex an heterogeneous systems is creation of an all-encompassing framework that is able to provide seamless exchange of data and ideas across different tools. On going construction of such a framework requires shifted focus towards tool interoperability and interfacing. Integration of CPLEX with modelling languages, especially SySML presents an interesting challenge, which when successful shall equip engineers with a robust design and development toolkit.

Appendix A: Example Microgrid network Data



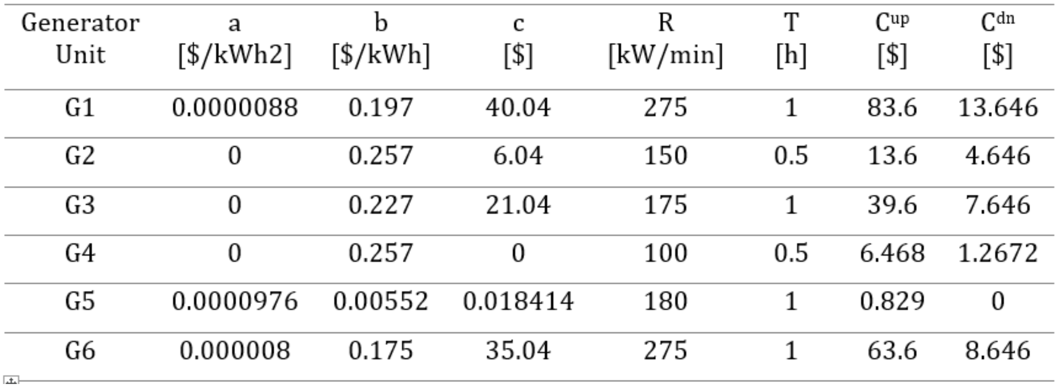
Generator Unit	$\overline{P}$ [kW]	P [kW]
G1	2500	1000
G2	650	290
G3	1100	420
G4	350	110
G5	900	390
G6	2100	850

Figure A.1: Generator power parameters



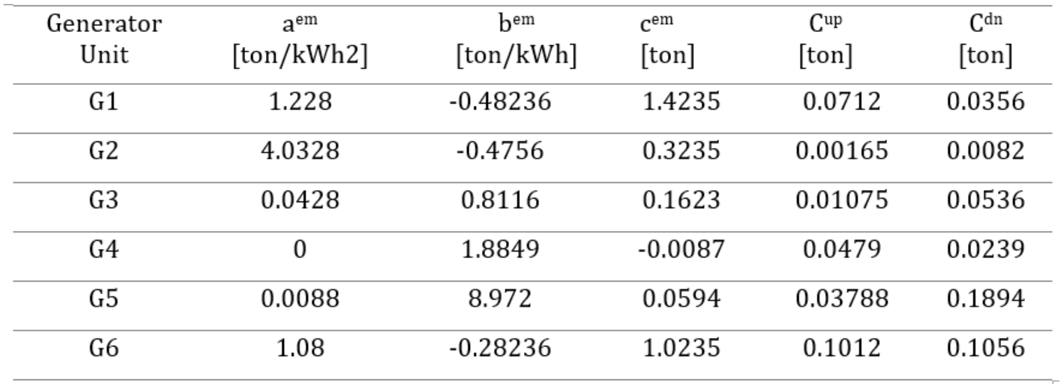
BESS Unit	$\overline{P}$ [kW]	η^{ch} [%]	η^{dch} [%]
1	275	0.67	0.67
2	750	0.89	0.89
3	142	0.65	0.65

Figure A.2: BESS parameters



Generator Unit	a [$/kWh2]	b [$/kWh]	c [$]	R [kW/min]	T [h]	C^{up} [$]	C^{dn} [$]
G1	0.0000088	0.197	40.04	275	1	83.6	13.646
G2	0	0.257	6.04	150	0.5	13.6	4.646
G3	0	0.227	21.04	175	1	39.6	7.646
G4	0	0.257	0	100	0.5	6.468	1.2672
G5	0.0000976	0.00552	0.018414	180	1	0.829	0
G6	0.000008	0.175	35.04	275	1	63.6	8.646

Figure A.3: Generator parameters



Generator Unit	a^{em} [ton/kWh2]	b^{em} [ton/kWh]	c^{em} [ton]	C^{up} [ton]	C^{dn} [ton]
G1	1.228	-0.48236	1.4235	0.0712	0.0356
G2	4.0328	-0.4756	0.3235	0.00165	0.0082
G3	0.0428	0.8116	0.1623	0.01075	0.0536
G4	0	1.8849	-0.0087	0.0479	0.0239
G5	0.0088	8.972	0.0594	0.03788	0.1894
G6	1.08	-0.28236	1.0235	0.1012	0.1056

Figure A.4: Generator emission characteristics

Bibliography

[1] J. S. Baras and M. A. Austin, Development of a Framework for CPS Open Standards and Platforms , The Institute for Systems Research, University of Maryland, College Park, ISR Technical Report, Feb. 2014.

[2] Health Professionals.[image].[Online].Available: `http://fuel-economy.info/?k=Health+Professionals+Scdhec` [Accessed 7 Mar. 2019].

[3] Factory Clipart industrialization 29. [image].[Online].Available: `https://clipart.wpblink.com/wallpaper-2824730` [Accessed 7 Mar. 2019].

[4] "General Atomics Mq1 Predador, Estados Unidos, General Atomics Mq9 Reaper", Gratispng.[image].[Online].Available:`https://www.gratispng.com/png-uw35qv/`.[Accessed 7 Mar. 2019].

[5] "Connected," Colorado Department of Transportation.[image].[Online]. Available:`https://www.codot.gov/programs/operations/intelligent-transportation-systems/assets_its/connected.png/view`.[Accessed 7 Mar. 2019].

[6] PSSE, Siemens 2017. [Online].Available: `https://w3.usa.siemens.com/smartgrid/us/en/transmission-grid/products/grid-analysis-tools/transmission-system-planning/Documents/Brochure_PSSE_EN_S4.pdf`.[Accessed 23 Mar. 2019].

[7] ASN Aviation Safety Database, Aviation Safety Network.[Online]. Available:`https://aviation-safety.net/database/type/index.php`.[Accessed 6 Nov. 2019].

[8] P. Nuzzo, "Compositional Design of Cyber-Physical Systems Using Contracts", Thesis, University of California, Berkeley, Aug. 2015.

[9] J.S. Baras, " Systems Engineering Principles. Part 2 of a short course on SE," The Institute for Systems Research, University of Maryland, College Park. Mar. 1996.

[10] "Systems Engineering Vision 2020," International Council on Systems Engineering (INCOSE), Ver. 2.03, TP-2004-004-02 2007.

[11] "From document-centric to model-centric," Eclipse Papyrus Case Study Series, CEA List, 2015.

[12] OpenIPSL.[Online].Available:`https://github.com/OpenIPSL/OpenIPSL`. [Accessed 27 Dec. 2018].

[13] S. Friedenthal, A. Moore, and R. Steiner *A Practical Guide to SysML*, Morgan Kaufmann OMG Press, 2012.

[14] IBM ILOG CPLEX Optimization Studio CPLEX Users Manual, IBM, Version 12 Release 8, 2018.

[15] L. Toma, "Key Concepts for Future Frequency definition and control," Challenges and solutions in Future Power Networks, RWTH Aachen University, Aachen (Germany), Mar. 2019.

[16] M. Pau, "Monitoring of Power Systems, "RESERVE and SOGNO PhD course,RWTH Aachen University, Aachen, Germany Mar. 2019.

[17] A. Kwasinski, W. Weaver, and R. Balog, *Microgrids and other Local Area Power and Energy Systems*, Cambridge University Press, Cambridge, UK, 2016.

[18] "Phasor Measurement Unit (PMU)," Siemens.[Online].Available:`https://w3.siemens.com`.[Accessed 25 Dec. 2018].

[19] R. Lasseter, Microgrid, in Proc. IEEE Power Engineering Soc. Winter Meet., vol. 1, , pp. 305308, Jan. 2002.

[20] F.Williams," ICT for Smart Energy," RESERVE and SOGNO PhD course, RWTH Aachen University, Aachen, Germany, Mar. 2019.

[21] "About Microgrids," Microgrid Institute. [Online]. Available:`http://www.microgridinstitute.org/about-microgrids.html`. [Accessed: 5 Nov. 2018].

[22] Fairbanks Morse Engines *Reciprocating Engine Generators and Microgrids: The Last Defense Against a Power Outage* Energy Efficiency Markets, LLC, 2016.

[23] B. L. Capehart, ”Microturbines,” Whole Building Design Guide, Dec. 2016.[Online].Available:`www.wbdg.org/resources/microturbines`.[Accessed: 3 Jan. 2019].

[24] B. Amrouche and X. L. Pivert, ”Artificial neural network based daily local forecasting for global solar radiation,” Applied Energy. vol.130 pp.333- 341, Oct. 2014.

[25] M.H. Albadi and E.H. El-Saadany, ”A summary of demand response in electricity markets,” Electric Power Systems Research, vol. 78, Issue 11, pp 1989-1996, Nov. 2008.

[26] ”Demand Response,” PJM Interconnection LLC.[Online].Available:`https://www.pjm.com/markets-and-operations/demand-response.aspx`.[Accessed: 1 Jan. 2019].

[27] ”Time-of-Use Pricing Plans,” San-Diego Gas & Electric Co. [Online]. Available:`https://www.sdge.com/whenmatters`[Accessed:26 Jun. 2019].

[28] B. V. Solanki, K. Bhattacharya and C. A. Caizares, ”A Sustainable Energy Management System for Isolated Microgrids,” in IEEE Transactions on Sustainable Energy, vol. 8, no. 4, pp. 1507-1517, Oct. 2017.

[29] Smartgrid, ”Time Based Rate Programs”.[Online].Available:`https://www.smartgrid.gov/recovery_act/time_based_rate_programs.html`.[Accessed 3 Jan. 2019].

[30] H. Jia, Y. Mu, and Y. Qi, ” A statistical model to determine the capacity of batterysupercapacitor hybrid energy storage system in autonomous microgrid,” in International Journal of Electrical Power and Energy Systems vol. 54, pp 516-524, 2014.

[31] D. E. Olivares, C. A. Caizares and M. Kazerani, ”A Centralized Energy Management System for Isolated Microgrids,” in IEEE Transactions on Smart Grid, vol. 5, no. 4, pp. 1864-1875, Jul. 2014.

[32] T. Kojima and Y. Fukuya, *Microgrid System for Isolated Islands*, Fuji Electric Review vol.57 no.4, 2011.

[33] U.S. Dept of Energy, Open Data Catalog, OpenEI.[Online].Available:`https://openei.org/doe-opendata/dataset`.[Accessed: 15 Feb. 2019].

[34] "The true cost of carbon pollution," Environmental Defense Fund.[Online]. Available: `https://www.edf.org/true-cost-carbon-pollution`.[Accessed : 5 May. 2019].

[35] D. K. Molzahn et al., "A Survey of Distributed Optimization and Control Algorithms for Electric Power Systems," in IEEE Transactions on Smart Grid, vol. 8, no. 6, pp. 2941-2962, Nov. 2017.