Planning and Operation Framework of Smart Distributed Energy Resources in Emerging Distribution Systems

by

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Author Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Smart grid technologies have provoked a major paradigm shift in how power systems are planned and operated. The transition to a smarter system is happening gradually; however, researchers have reported that this transition is generally dealt with in a 'react and provide' manner. Proper planning studies allow for this transition to happen in a 'predict and provide' fashion. One part of planning this transition is envisioning the future system. Technical, social, environmental, and economical challenges are foreseen and tackled in the literature; however, no generalized planning framework has been developed that addresses the overall picture of different involved parties' interests and their anticipated (and often conflicting) interactions to properly plan for a better and fairer outcome. This work addresses the issue in several steps: 1) it provides a backbone framework architecture for asset sizing and allocation in the future smart distribution system (SDS), 2) it considers the daily optimal operation of these assets in the long-term planning problem, and 3) it considers the potential conflicts that exist in the long-term planning and on operational levels. This architecture requires the development of a framework capable of absorbing private investments, integrating new technologies, and promoting smart grid applications while remaining feasible for all involved parties.

A strategic analysis of each of those who have a stake in the system (stakeholder)'s involvement has been conducted. Proceeding from this analysis, deductions and conclusions about venues for promoting and allowing a smoother transition to the new paradigm are drawn. This analysis also highlighted potential conflicts that are showcased in two different case studies. Potential ways in which the conditions affect the planning procedure and how they can be overcome are proposed. The recommendations can be highlighted as follows: 1) promoting new smart grid technologies, 2) encouraging communications and cooperation between involved parties, 3) considering the daily optimal operation of assets to fully take advantage of their new active nature to better allocate them in the long-term planning problem, and 4) the consideration of stakeholders interests in the planning phase to better absorb investments and shift to the new paradigm.

To size and allocate assets in the long-term planning problem for the SDS, first, a building algorithm has been developed to size and allocate distributed generation (DG) units. This algorithm breaks the problem into two subproblems to overcome the modeling and computational challenges of the mixed-integer nonlinear programming problem. The first subproblem is addressed using heuristic optimization techniques, namely a genetic algorithm, and the second involving deterministic analytical means of nonlinear optimization, utilizing the advancements made in branch-and-bound methods, and providing a proven global optimal solution to non-convex problems. Considering the daily optimal operation and electric utilities' as well as investors' objectives, the planning problem has been developed. The results show greater private investments absorption, reduced costs to both parties, and higher system performance due to decreased energy losses.

The expected increased numbers of customers opting to become resilient and have a more reliable service pose several operational and planning challenges. In this work, a novel consensus-based algorithm is introduced as an economically efficient tool for coordinating prosumers' interactions, within the feasible solution region. Several objectives are targeted in this work; among these objectives, the global economic benefit maximization of all interacting prosumers is the most salient. This economic benefit comprises the total cooperative payoff of the interacting prosumers. Each prosumer has its own private bounds defining the range of power production and consumption.

A novel definition is proposed for prosumers' interactions in the hybrid microgrids. The developed scheme's importance stems from dramatic changes in the smart networks' paradigms. Individual prosumers' preferences are also recognized via the comprehensive mathematical modeling of the evolved AC/DC network. The results are provided for a basic two-prosumer scenario. However, these results highlight the potential of the proposed approach in a practical system setting. More sophisticated case studies (i.e., multi-power levels, multi-prosumers, and different system topologies) could also be studied using the proposed work.

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بِسمِ اللّٰهِ الرَّحمٰنِ الرَّحِيمِ

إِهدَاء

لأَبي فَايز و أُمي إِشرَاق

لزوجَتي منَار

و بنَاتي زينَة و بسمَة

أُحبكم

Dedication

To my parents, *Faiz* and *Eshraq*.

To my wife, *Manar*.

To my children, *Zaina* and *Basma*.

I love you.

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List of Abbreviations

ABC

artificial bee colony optimization. *p:* 31

AC

Alternating Current. *pp:* xx, xxiii, 5–7, 28–30, 77–79, 95, 96, 98–105, 110–112

ANM

Active Network Management. *p:* 78

BAU

Business As Usual. *pp:* 26, 27, 111

CIGRE

Conference Internationale des Grandes Reseaux Electriques [International Conference of Large Electric Grids]. *p:* 11

DC

Direct Current. *pp:* xx, xxiii, 5–7, 28, 77–79, 95, 96, 98–105, 110–112

DG

distributed generation. *pp:* viii, xix, xx, xxii, xxiii, xxix–xxxi, xxxiv–xxxviii, 5, 6, 24, 25, 27–31, 36–40, 51–56, 58–60, 63, 65–72, 75, 76, 79, 96–99, 101–103, 108, 109, 111, 112

DISCO

Distribution Company. *pp:* 25, 34

DM

Decision Maker. *pp:* 42, 44

DSO

Distribution System Operator. *pp:* 18, 21, 34, 36

GA

genetic algorithm. *pp:* 31, 36, 64

GENCO

Generation Company. *pp:* 18, 21

IEC

International Electrotechnical Commission. *pp:* 11, 14

IEEE

Institute of Electrical and Electronics Engineers. *p:* 10

IPP

Independent Power Provider. *pp:* 18, 36

LDC

Local Distribution Company. *pp:* xxii, 25, 33, 34, 41, 58, 59, 110

LP

linear programming. *pp:* 25, 29

NIST

National Institute of Standards and Technology. *pp:* 13, 35, 110

NLP

nonlinear programming. *pp:* 30, 32, 108

NPV

Net Present Value. *pp:* 54–59

NSGA-II

non-dominated sorting genetic algorithm II. *pp:* 36, 110

OPF

Optimal Power Flow. *pp:* 25, 29–32, 53, 63, 108

PEV

Plug-in Electric Vehicles. *pp:* 19, 21, 96

PSO

particle swarm optimization. *p:* 31

PV

Photovoltaic. *pp:* 40, 96

SA

simulated annealing. *p:* 31

SDS

smart distribution system. *pp:* vii, viii, 2–6, 9, 10, 13, 16, 18–20, 22, 23, 28, 31, 34, 35, 41, 44, 49, 50, 53, 60, 75, 78, 107–111

TSO

Transmission System Operator. *pp:* 18, 21

TVPP

Technical Virtual Power Plant. *pp:* 25, 34, 36

Variables

$A_{(l)}$

a variable multiplier denoting the size of required line upgrade. *pp:* 57, 62

$C_{\mathrm{UP}_{(l)}}$

cost of upgrading line l in \$. *p:* 57

$I_{(i,j,y)}$

current in line between bus i and j (A or pu). *p:* 37

$I_{(l,h,d,y)}$

current in line l at hour h, day d, and year y (A or pu). *p:* 62

Ω

vector of decision variables. *pp:* 36, 37

$PF_{(i,dg,h,d,y)}$

minimum allowed power factor for DG dg in bus i at hour h, day d, and year y. *pp:* 39, 40, 60

$P^{Unused}_{(i,dg,h,d,y)}$

active power curtailed of DG dg in bus i, at hour h, day d, and year y (MW). *p:* 56

$\delta_{(j,h,d,y)}$

angle of the voltage at bus j (rad). *pp:* 38, 39, 61

$\delta_{(i,h,d,y)}$

angle of the voltage at bus i (rad). *pp:* 38, 39, 61

$\kappa_{(i,dg,y)}$

binary decision variables to place DG of technology dg at bus i and year y. *pp:* 38, 59

$\Psi_{(i,dg,h,d,y)}$

decision variable for curtailed power in bus i at hour h, day d, and year y ($\Psi_{(i,dg,h,d,y)} \in [0, 1]$). *p:* 60

$S^{inj}_{(i,dg,h,d,y)}$

injected total power after curtailment, power factor incorporation, and renewable availability. *pp:* 60, 61

$\varpi_{(i,dg,y)}$

variable size of allocated DG of technology dg. *pp:* 38, 59

$V_{(i,h,d,y)}$

magnitude of the voltage (V or pu) at bus i. *pp:* 37–39, 61, 62

$V_{(j,h,d,y)}$

magnitude of the voltage (V or pu) at bus j. *pp:* 38, 39, 61

$I_{(l,y)_{max}}$

maximum allowed current to flow in line l at year y (A or pu). *p:* 62

$P_{g_{(i,h,d,y)}}$

active power purchased from grid in bus i, at hour h, day d, and year y (MW). *pp:* 38, 39, 56, 61

$P_{(i,h,d,y)_{(loss)}}$

active power loss measured at bus i, hour h, day d, and year y (difference between produced power and demand) (MW). *p:* 57

$P_{(i,dg,h,d,y)}$

produced active power for DG of technology dg in bus i at hour h, day d, and year y (MW). *pp:* 38, 39, 55, 60, 61

$Q_{g_{(i,h,d,y)}}$

reactive power purchased from grid in bus i, at hour h, day d, and year y (MVAR). *pp:* 39, 40, 56, 61, 62

$Q_{(i,h,d,y)_{(loss)}}$

reactive power loss measured at bus i, hour h, day d, and year y (difference between produced power and demand) (MVAR). *p:* 57

$Q_{(i,dg,h,d,y)}$

produced reactive power for DG of technology dg in bus i at hour h, day d, and year y (MVAR). *pp:* 39, 40, 55, 60, 61

$S_{(i,dg,y)}$

allocated DG of technology dg at bus i and year y (MVA). *pp:* 37–40, 54, 59, 60

$y_{\left(\mathrm{UP}_{(l)}\right)}$

year at which line l is upgraded. *pp:* 57, 62

$\mathrm{UP}_{(l)}$

binary decision to upgrade line l. *pp:* 57, 62

Parameters

$C^{\text{Unit}}_{(base)}$

base cost of upgrading lines per unit length ($/km). *p:* 57

$I^{CAP}_{(l)}$

current carrying capacity of line l (A or pu). *p:* 62

$LH_{(l)}$

length of line l (km). *p:* 57

$P_{D(i,h,d,y)}$

active demand for bus i at hour h, day d, and year y (MW). *pp:* 38, 39, 61

P^{Max}_{g}

maximum active power the grid can inject into the grid connected bus (MW). *pp:* 39, 61

P^{Rev}_{g}

maximum reverse active power allowed into the grid connected bus (MW). *pp:* 39, 61

$P_{dc,Li}$

DC aggregated load connected at bus i. *p:* 98

Q_g^{Max}

maximum reactive power the grid can inject into the grid connected bus (MVAR). *pp:* 40, 62

Q_g^{Rev}

maximum reverse reactive power allowed into the grid connected bus (MVAR). *pp:* 40, 62

V^{target}

targeted voltage level. *p:* 37

V_{max}^{spec}

specified maximum voltage (V or pu). *pp:* 37, 62

V_{min}^{spec}

specified minimum voltage (V or pu). *pp:* 37, 62

$Y_{(i,j,y)}$

magnitude of the Y-bus matrix admittance (℧ or pu). *pp:* 38, 39, 61

r

effective discount rate (discount and inflation) [2]. *pp:* 37, 54–57

$\theta_{(i,j,y)}$

angle of the Y-bus matrix admittance (rad). *pp:* 38, 39, 61

$C_{(i,dg,h,d,y)}^{APower}$

active power cost for DG dg in bus i, at hour h, day d, and year y (\$/MW). *p:* 55

$C_{(i,h,d,y)}^{APower}$

active power cost from grid in bus i, at hour h, day d, and year y (\$/MW). *p:* 56

$C^{Capital}_{(i,dg,y)}$

capital cost of every allocated DG of technology dg at bus i and at year y (\$/MVA). *pp:* 37, 54

$C^{Fuel}_{(i,dg,h,d,y)}$

fuel cost for DG of technology dg in bus i, at hour h, day d, and year y (\$/MW). *p:* 55

$C^{OM}_{(i,dg,y)}$

operation and maintenance cost for DG of technology dg, at bus i and year y (\$/MW). *p:* 55

$C^{RPower}_{(i,dg,h,d,y)}$

reactive power cost for DG dg in bus i, at hour h, day d, and year y (\$/MVAR). *p:* 55

$C^{RPower}_{(i,h,d,y)}$

reactive power cost from grid in bus i, at hour h, day d, and year y (\$/MVAR). *p:* 56

$C^{Unused}_{(i,dg,h,d,y)}$

cost of curtailed power for DG dg in bus i, at hour h, day d, and year y (\$/MW). *p:* 56

$I_{(i,j,y)_{max}}$

maximum line current carrying capacity at year y between bus i and j (A or pu). *p:* 37

$Q_{D(i,h,d,y)}$

reactive demand for bus i at hour h, day d, and year y (MVAR). *pp:* 39, 61

S_{dg}^{max}

maximum DG size of technology dg (MVA). *pp:* 38, 59

S_{i}^{max}

maximum allowed total DG capacity in bus i (MVA). *pp:* 38, 60

$AF_{(dg,h,d,y)}$

availability factor for DG of technology dg in bus i at hour h, day d, and year y. *p:* 60

${C_{(i,h,d,y)}^{APower}}_{Loss}$

active power losses cost from in bus i, at hour h, day d, and year y ($/MW). *p:* 57

${C_{(i,h,d,y)}^{RPower}}_{Loss}$

reactive power losses cost in bus i, at hour h, day d, and year y ($/MVAR). *p:* 57

Sets and Indices

$\mathcal{DG}$

set for all DG technologies available. *pp:* 37–40, 54–56, 59–61, 69, 70

$\mathcal{D}$

set of all days considered as representing a year. *pp:* 37–40, 55–57, 60–62

$\mathcal{G}$

set of grid connected busses ($\mathcal{G} \subseteq \mathcal{I}$). *pp:* 39, 40, 56, 61, 62

$\mathcal{H}$

set of all hours considered as representing a day. *pp:* 37–40, 55–57, 60–62

$\mathcal{I}$

set of all buses $\mathcal{I} = \mathcal{J}$. *pp:* 37–40, 54–57, 60–62, 69, 70

$\mathcal{J}$

set of all buses $\mathcal{I} = \mathcal{J}$. *pp:* 38, 39, 61

$\mathcal{Q}_{dg}$

set of candidate buses for DG of technology dg ($\mathcal{Q}_{dg} \subseteq \mathcal{I}$). *pp:* 38, 59

Chapter 1

Introduction

"Planning is bringing the future into the present so you can do something about it now."

— Alan Lakein

This chapter introduces the thesis topic in Section 1.1, and its structure is explained in Section 1.4. Moreover, the motivations behind the work are detailed in Section 1.2, and the formulated objectives precedes a general description of thesis problems in Section 1.3. The chapter is then concluded with a summary in Section 1.5.

1.1 Preamble

Time spent planning is time saved in execution is a well-known truism. For this reason, planning studies are very important for any project. They provide the general architecture and guidelines for other studies. In power systems, long-, medium-, and short-term planning are common practices and continue to be of great interest in research. Research in the areas of distribution and transmission networks planning has been primarily influenced by potential economic benefits. Although the planning studies provide lower overall costs for many project categories, many drawbacks still need to be addressed. The new technologies that are being integrated into power systems, interest in making power systems smarter, electrification of transportation, growing demand for energy in general, and need for cleaner and renewable energy also pose more challenges for planning studies. The drawbacks can be summarized under four umbrellas: 1) insufficiencies in the models representing loads and assets that are used in problem solving, 2) the exclusion of primary stakeholders of the new system paradigm, 3) technical or economic benefit-based drawbacks that arise from the failure to develop an optimal plan, and 4) the failure to provide a comprehensive planning framework that allows for a smooth transition to the new SDS paradigm (i.e., smart grid).

Studies in the areas of generation, transmission, and distribution systems planning have been steadily increasing in the past few decades as can be seen in Figure 1.1, which represents a Scopus database search yield of keywords related to planning, power systems, transmission, and distribution. Power system planning in the literature is studied from several perspectives, depending on the type project. For example, the sizing and allocation of conventional generation stations is one category of power system planning studies. Another area of planning in power systems is transmission and distribution system expansion. Depending on the regulatory, environmental, and technical requirements, specific expansions in certain parts of any power system are inevitable. However, planning studies that focus on upgrading existing systems and reinforcing them with emerging and existing technologies are of prime interest in this work. Classifications for these studies are found in the literature in several forms, and depending on the purpose, a particular classification criterion is chosen. For instance, chronological classification is commonly used to differentiate the depth of planning. Moreover, feeder and substation reinforcement are classified as long-term planning issues; thus, they can be considered top-level planning.

Therefore, a long-term SDSs planning framework that considers the optimal daily operation of the system and its components, as well as satisfying all system stakeholders with their coinciding or conflicting interests in a fair manner is needed. This work provides a general framework for planning SDSs, which means increasing the hosting capacity of distributed resources, integrating new technologies, overcoming any potential conflicts, and providing a socially and economically fair and feasible architecture for all stakeholders.

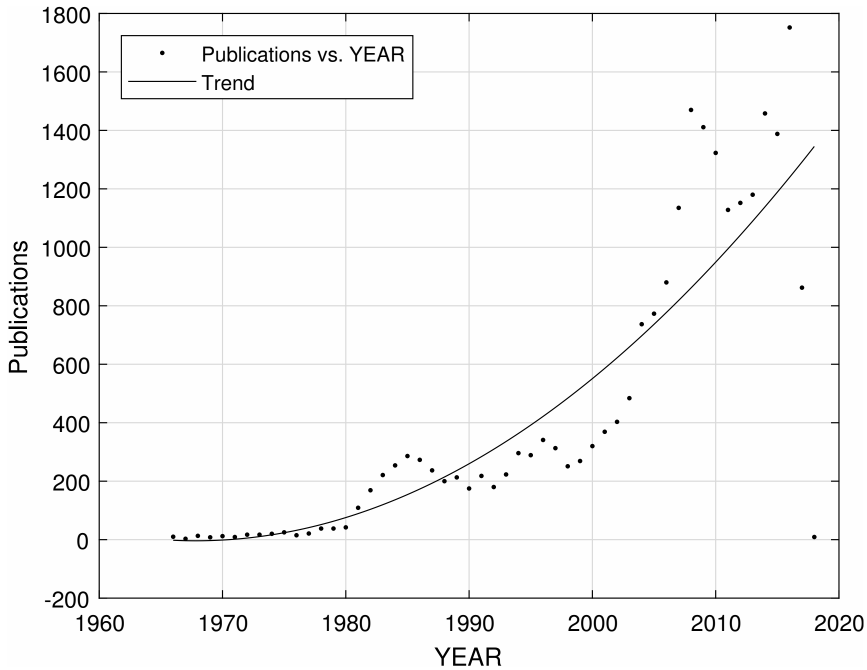

Figure 1.1: Publications on Power Systems Planning Studies

1.2 Thesis Motivations

This work aims to capitalize on existing distribution systems' assets and upgrade them at minimal cost by deploying smart grid technologies and distributed resources. The notions of capitalizing on existing assets and integrating distributed resources and emerging technologies into an SDS architecture are the prime motivations of this work, which can be summarized as follows:

- the lack of clarity of stakeholders' perceptions of SDSs and smart grid products in general;

- the conflicting nature of stakeholders, especially the financial aspect;
- the necessity for a feasible yet fair planning framework that is impartial to all parties from a third-party perspective for all stakeholders;
- the general notion of an investment-attracting environment and its contemporary importance;
- the need for a technically viable infrastructure that can accommodate existing and emerging technologies;
- the importance of capitalizing on the existing infrastructure;
- the evident need to be able to adapt to new SDS technologies;
- the pressing necessity of autonomy and independence for greater reliability and resiliency.

1.3 Thesis Objectives

It is expected that if all motivational challenges are overcome, then a generalized framework for long-term planning in SDSs can be developed. In doing so, a planning framework that considers the operational details of distributed resources and emerging smart grid technologies should be modelled. Moreover, potential conflicts that arise from the non-cooperative nature of most stakeholders in SDSs must be eliminated. To eliminate these conflicts, a cooperative decision-making infrastructure that works in a distributed fashion is essential. Key steps in reaching this goal are listed below:

- strategically analyze stakeholders' interests and their interactions to highlight potential conflicts and understand the future of SDS;

  - develop illustrative *long-term* planning case studies to showcase potential conflicts in the planning phase;
  - develop illustrative *operational* planning case studies reflecting potential conflicts and their effects on the overall long-term planning;

- develop an algorithm to provide optimal *long-term* sizing and allocation planning of distributed generation (DG);
  - consider daily optimal operation;
  - consider both electric utility's and investors' interests;
  - allow for the highest feasible investment absorption.

- design and develop cooperation methodology to overcome the anticipated conflicts;
  - cooperative to eliminate the contradictory nature of noncooperative schemes;
  - distributed to allow a more realistic approach to deal with isolated and grid-connected microgrids;
  - applicable to both AC and hybrid AC/DC systems for smoother transition to future systems.

The thesis objectives can be summarized by the aforementioned completed and future work. The ultimate goal of developing a generalized planning framework for SDSs that incorporate emerging smart grid technologies can be materialized by following the diagram shown in Figure 1.2.

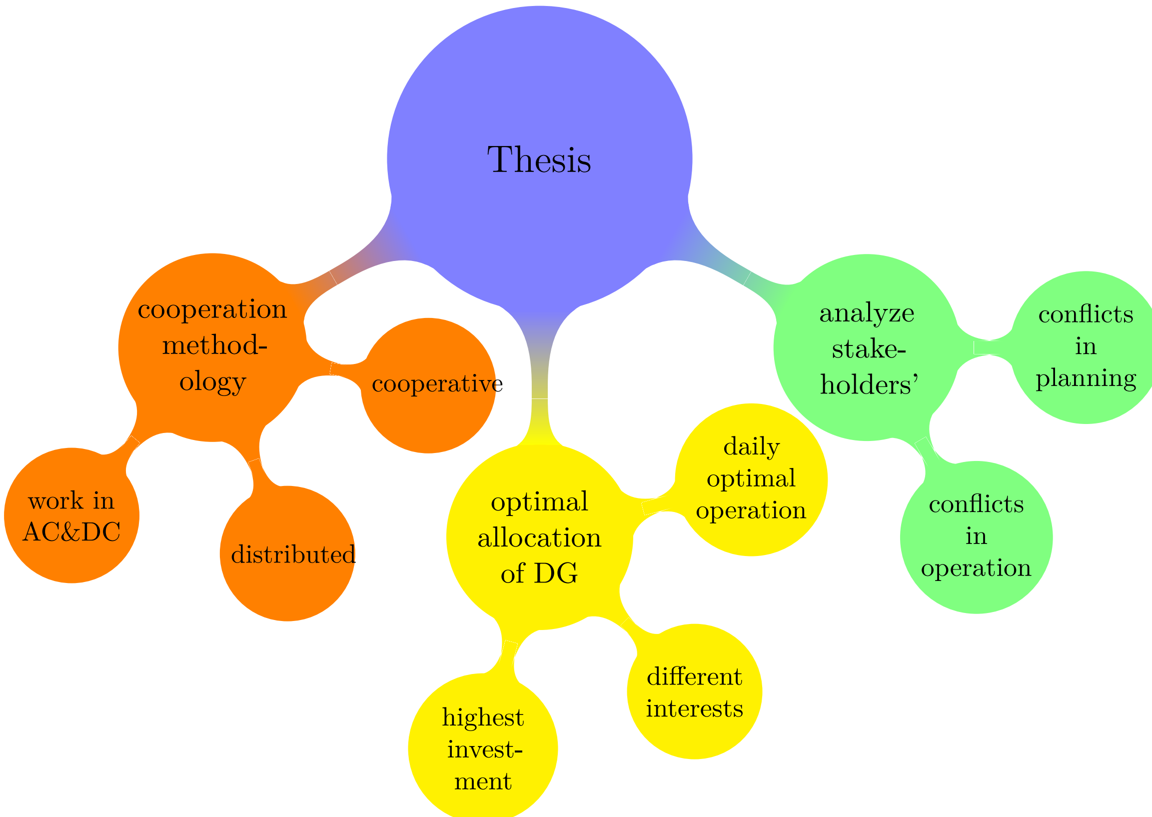

Figure 1.2: Diagram of All Anticipated Thesis Objectives

1.4 Thesis Structure

This work is divided into five chapters. An introductory section summarizing the topic and highlighting challenges, motivations, objectives and expected contribution is provided in Chapter 1. Following the introduction, Chapter 2 provides a literature survey of long-term planning and smart grid technologies' integration into distribution systems. In Chapter 3, a strategic analysis covering SDS stakeholders and the potential arising conflicts from their interaction is attempted. Long-term DG planning considering the daily optimal operation and different stakeholders' interests is formulated and showcased in Chapter 4. Chapter 5 introduces the developed cooperative autonomous interaction algorithm and demonstrates the actual technical realization of this proposed algorithm in an advanced system structure (i.e., a hybrid AC/DC system). The study and its contributions are then summarized in Chapter 6. Figure 1.3 poses a schematic of the thesis structure where solid arrows show the physical flow and the dashed ones represent the information flow.

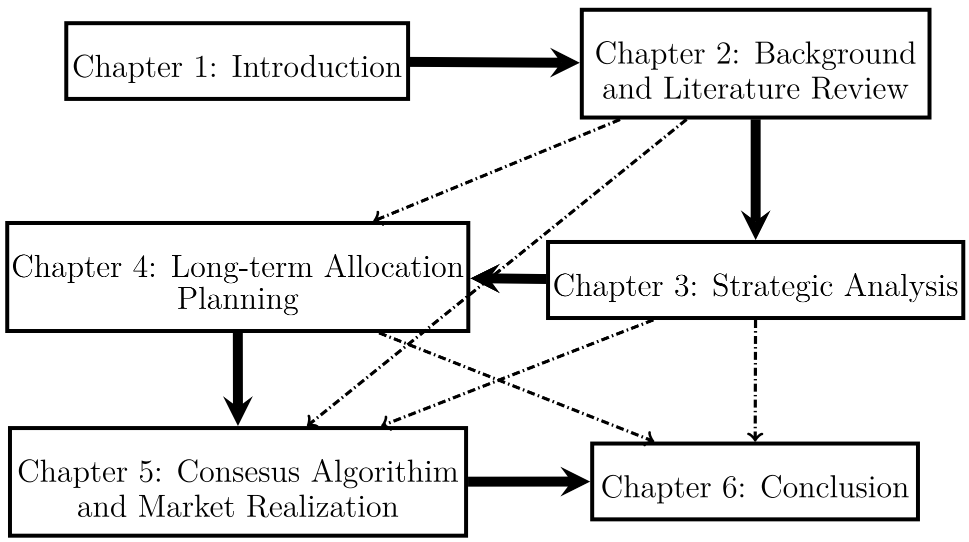

Figure 1.3: Thesis Structure

1.5 Chapter Summary

Chapter 1 introduced the work's motivations and objectives. It has established what the thesis will address in subsequent chapters and illustrated the structure of how the issues are addressed.

Chapter 2

Background and Literature Review§

"If I have seen further than others, it is by standing upon the shoulders of giants."

— Isaac Newton

Chapter 2 is divided into several sections: Section 2.2 provides a background of the topic and summarizes the SDS concept, provides related definitions, and explains functions; Section 2.3 describes studies involving stakeholders and their interactions; and Section 2.4 surveys the current literature concerning the adaptation of smart grids in the planning of future distribution systems (i.e., SDS). The survey conducted highlights several drawbacks of the current research and practices related to SDS planning. Finally, a summary of the chapter and gaps in the literature are provided in Section 2.5.

2.1 Introduction

In Chapter 1, the architecture, objectives, and motivations of this work were described. The provided description drives the attention toward many important areas of the literature:

§Parts of this chapter are published in [3].

the optimal long-term planning of distribution systems, the optimal operational planning of distribution systems, cooperative decision making, and conflict resolution. Therefore, the various optimal planning and operation approaches presented in the literature are surveyed and critiqued; then, interactions between the concept of an SDS with the mentioned approaches is analyzed. The features of an SDS are also studied. Finally, conflict resolution and cooperative decision-making are examined.

2.2 Background

In this section, background information for several topics is summarized. First, Section 2.2.1 provides the definition and functions of a smart grid. Then, in Section 2.2.2, general background information about power system components in the smart grid paradigm is summarized. This background provides a necessary panoramic overview of the topic, allowing for a more comprehensive understanding and hopefully yielding robust outcomes.

2.2.1 Smart Grid Definition and Functions

Smart grids have attracted significant attention lately. One may assess the level of attention by the numerous survey studies focused on highlighting a definition and the anticipated function of smart grids [4–10]. However, the definition of a smart grid can be summarized from its functions and anticipated objectives. Generally, a smart grid is referred to as the power system of the 20^{th} century transformed into the 21^{st} century digital age. From fast communication and bidirectional power flows to resiliency and smart operation, this new grid is obviously hyped in the literature. Moreover, several governmental and independent organizations that advocate for standardization and conceptualization of this future grid have been very active in recent years. For instance, countries such as the United States, China, Japan, Germany, and Korea, as well as the European Union have all developed or proposed roadmaps or mandates for smart grid structures. Agencies such as the Institute of Electrical and Electronics Engineers (IEEE), International Electrotechnical Commission (IEC), Conference Internationale des Grandes Reseaux Electriques [International Conference of Large Electric Grids] (CIGRE), and companies such as Microsoft have also shared this interest in a roadmap of proposals and standards [6, 11]. Several common functions can be found in the literature. These functions, although very ambitious, are somewhat technically viable and, in some cases, economically feasible; therefore, some could be applied in the near future. Some functions are a continuation of current practices, but with the help of smart grid applications and products, they

1. improve power quality and reliability;
2. optimize and defer the construction of back-up generation;
3. enhance the capacity and efficiency of existing electric power networks;
4. increase resilience to disruption;
5. enable predictive maintenance and self-healing responses to system disturbances;
6. seamlessly integrate renewable energy sources;
7. absorb higher investments from distributed energy sources;
8. increase the level of autonomous operation and maintenance;
9. reduce emissions and promote environmentally friendly technologies;
10. reduce oil consumption and dependence;
11. improve system security;
12. enable the transition to plug-in electric vehicles and new energy storage options;
13. enable more competition (consumer choice); and
14. enable emerging markets, services, and technologies.

2.2.2 Power System Components in the Smart Grid Paradigm

Although the system will be in a new (conceptualized) architecture, as reported in the literature [8], the physical power components, not necessarily in their traditional representation, will comprise the generation, transmission, and distribution of electricity. The overwhelming amount of literature devoted to distribution systems, in particular, is a product of the dire need to integrate these anticipated applications and technologies into these systems. However, most work in this area remains empirical because smart grid distribution efforts require a high level of analysis before implementation in the field (over 60% of surveyed articles in [7] were related to empirical research). Moreover, it is logical to draw this much attention to distribution systems given their market share. In [12], a survey was conducted and showed that the distribution sector constituted 25% of infrastructure spending for US electric utilities. The remaining 75% was for generation, environment, transmission, and other system components and services. In 2010, power systems in the US had $272,000$ km of transmission lines [13].

Research described in [14] has highlighted potential areas in the smart transmission grid as primarily involving 1) synchrophasor measurement, 2) data and communication, 3) coordination among power systems, and 4) security. Also, the authors suggested that most of the attention in related research is directed toward distribution systems and how consumers interact. For generation, bulk generation plays a vital role in power systems as it relates to security, reliability, and stability. However, very limited contributions are made toward conceptualizing new and smarter roles of conventional generation in the smart grid. Apart from increasing efficiency and decreasing environmental impacts, conventional generation will gradually shift from carbon-producing reliable service toward an environmentally friendly source of stability and security in the smart grid.

2.3 Stakeholders

This section addresses three tasks: stakeholder identification and description, categorization, and an investigation of the relationship between them. Description and identification are performed and stated based on key players in the SDS paradigm. Categorization is then performed by means of an interest-influence matrix, where a relationship assessment is made possible through the actor-linkage matrix. According to National Institute of Standards and Technology (NIST), seven domains are suggested in their conceptual framework [1]. These domains are used as a starting point for stakeholder identification and description in the following section and illustrated in Figure 2.1.

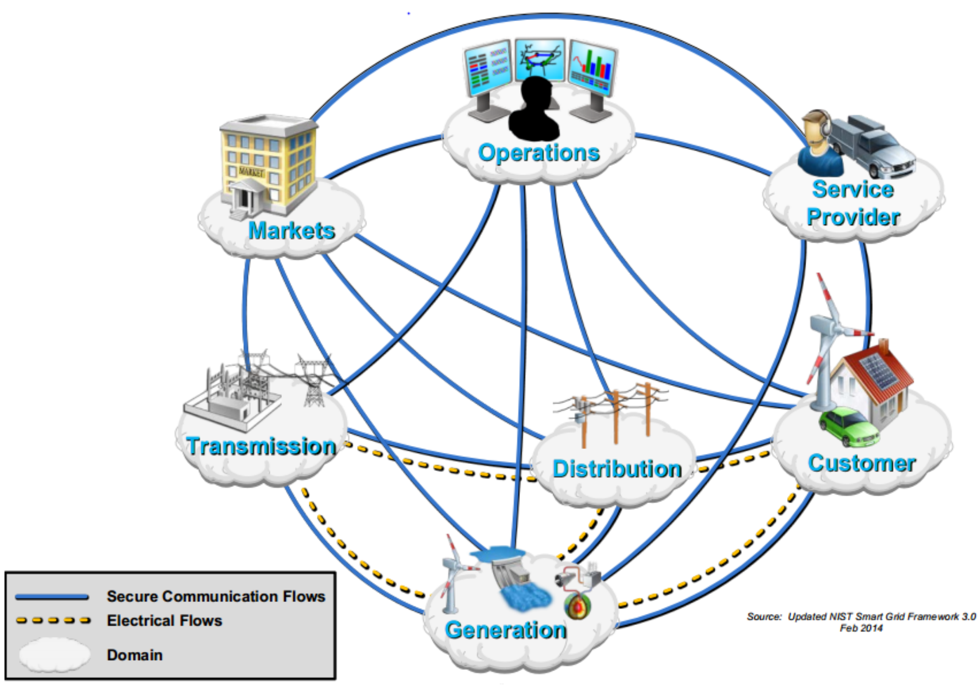

Figure 2.1: The NIST Conceptual Model for a Smart Grid [1]

2.3.1 Stakeholder Analysis

Many standards that have been developed or are under development require refinements or are recommended for different areas concerning the transformation to and operation of smart grids [15]. Work in [11] surveyed the standardization efforts and recommendations for smart grids. They stated that IEC TC 57 SIA is a good smart grid standardization framework because it incorporates several standards. However, the authors also emphasized that the standards prevent certain stakeholders from being involved in the process. Moreover, they concluded with the notion that for a smart grid to become a reality, substantial efforts toward cooperation and integration are important.

The term stakeholder is relatively new in the world of system and business development and management. Reportedly, it was first invented in the 1960s as a derivation of the term shareholder [16]. This deliberate play on words emphasized the fact that other players have a role in the decision-making process of developing modern systems [16]. Generally, stakeholders are those who have a stake in a particular system.

A stakeholder analysis is very important and can help in several ways. It can provide an empirical understanding of those who are involved in a system [17] and can provide important empirical knowledge regarding stakeholder involvement in the process and the development of frameworks for the system [18]. This empirical knowledge may help policymakers understand the opportunities and help resolve conflicts. A stakeholder analysis is commonly used for formulating policy and analyzing complex and conflicting situations. Notably, a stakeholder analysis, especially in the identification phase, is a subjective and iterative process. Some stakeholders that may be regarded as important and are associated with a key role in a system at first may later become less or more involved. In [19], three different rationales for performing a stakeholder analysis are summarized: descriptive, normative, and instrumental. Moreover, [19] emphasized the fact that a descriptive rationale is very rarely for the mere sake of performing it and is usually performed as a first step before normative- or instrument-based studies are conducted. This is because the descriptive rationale only involves describing the relationship between a system and the players involved. It is important to mention that in the smart grid paradigm, the instrumental rationale is important since it assumes a goal, and then an analysis is conducted based on this goal. For normative studies, on the other hand, reaching a common goal is part of the analysis. Thus, it is important to first describe all stakeholders and their relationships with the system (i.e., the smart grid). A summary of rationales, typologies, and methods is adapted from [19] and illustrated in Figure 2.2.

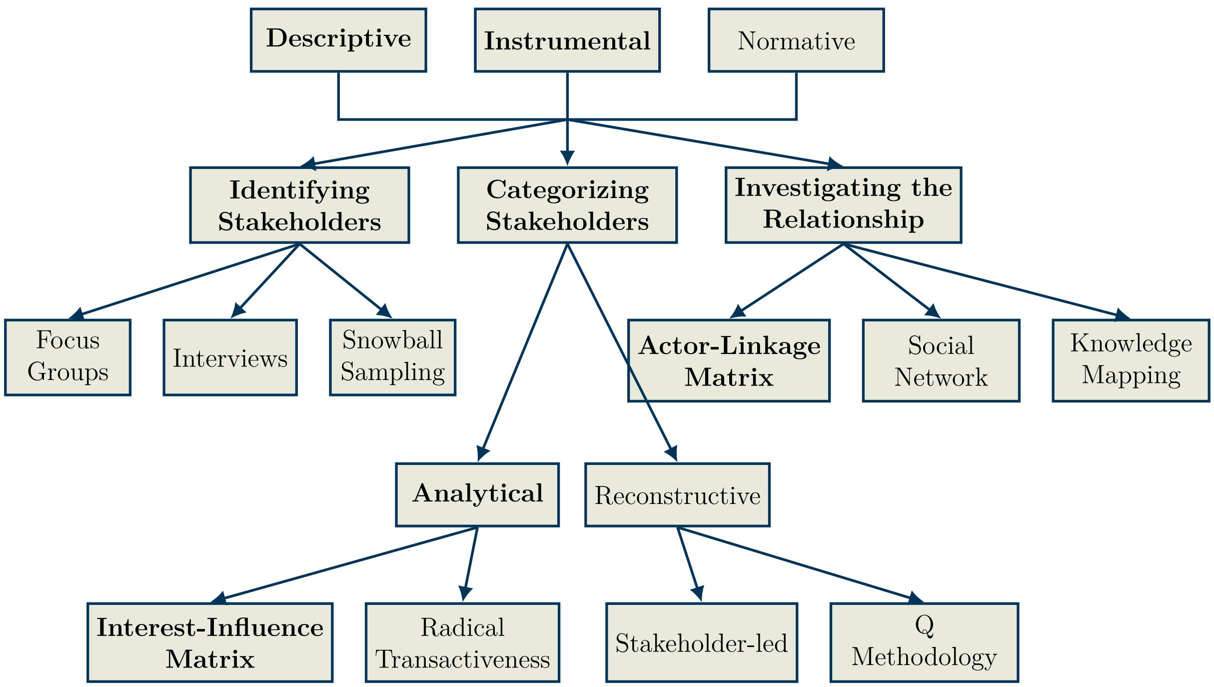

Figure 2.2: Summary of Rationales, Typologies, and Methods Used for Stakeholder Analysis

The wide range of methods used for stakeholder analysis are depicted in Figure 2.2; however, only two of them can be performed by a practitioner/researcher: interest-influence and actor-linkage matrices [19]. Therefore, these two methods will be adapted in this work. The interest-influence matrix is used for stakeholder categorization, where the actor-linkage matrix investigates the relationship between them. For stakeholder identification, the relevant literature is consulted to highlight key stakeholders in future distribution systems. The description, categorization, and relationship investigations are performed as a background for the strategic analysis conducted in Chapter 3.

2.3.2 Stakeholder Identification and Description

Stakeholders can have a significant impact on future SDSs by the role they play. Stakeholders' roles in affecting the integrity and successful operation of the system are described. Moreover, stakeholders will be directly involved in envisioning the future distribution system. Proceeding from the seven domains described in [1], stakeholders are identified and described.

Cities, Politicians, and Legislators. As policymakers and lawmakers, these stakeholders have an instrumental rationale in mind for moving the system toward a certain direction. Policies designed to reduce environmental impacts and fossil fuel dependence are key factors in forming the architecture of a future system. Politicians are also in direct correspondence with end customers and their needs: the creation of jobs, private investment absorption, and conducting ethical business models. The supervisory role of these stakeholders also guarantees the consideration of less influential stakeholders in the future paradigm.

Regulators. Proceeding from strategic policies and governmental roles, the technical actions of implementing such laws and transforming them into effective regulations are the key functions of these stakeholders. Along with other stakeholders, they are responsible for the successful integration and transformation of new technologies.

Emerging Markets and Businesses. Emerging markets are crucially significant in the successful planning of SDSs. Many technologies and smart grid products are economically infeasible without a proper introduction and architecture that facilitates their deployment. Conventionally, a limited number of markets are associated with the power industry; however, with the changing roles of many stakeholders and the new capabilities smart grid applications propose, many new markets will evolve.

Electrical Transportation Manufacturing Industry. Electric vehicle researchers and producers have been developing new technologies at a very rapid pace. Building a planning framework that considers the fast-moving pace of electric vehicle technology development and how they can be integrated into future systems is important. Promoting such technologies requires strong communication between industries, policymakers, regulators, and, of course, end customers.

Car Parking Industry. As the number of electric vehicles increases, the parking industry will inevitably respond by either accommodating charging facilities or developing new business models. The parking industry has a key interest in new smart technologies, as reported in a survey conducted by [20].

Electrical Equipment Manufacturing Industry. This industry will continue to be in demand for as long as electricity is needed. However, as the system becomes smarter, there will be less need for conventional equipment. Early involvement of this sector can promote the faster adaptation of newer technologies and secure the industry's market share in future smart systems.

Electrical Installation and Maintenance Personnel. Moving forward without considering these very important players will result in devastating results. Therefore, early involvement and training concerning future technologies and products will increase these personnel's interest in switching to a company that implements smart systems. According to the literature, there exists, at least in the US, a negative correlation between distribution companies' revenues and the number of employees [12].

Asset Owners and Investors. Creating jobs and enabling new areas for development and investment cannot be achieved without the direct consideration of owners' needs in SDSs. Proper market structures and planning frameworks can significantly affect the level of private investments absorbed by SDSs.

Generation Company (GENCO) or Independent Power Provider (IPP). Although they may seem to be in natural conflict with self-sufficient systems, generation companies have provided and will continue to provide one critical service apart from energy: security. Concentrated bulk generation will not be obsolete in the near future. For technical, geopolitical, environmental, and economical reasons, generation companies must be considered key stakeholders in the success of developing a SDS.

Transmission System Operator (TSO). The technical burden of operating transmission systems is undertaken by these stakeholders. Ensuring the safe, reliable, and economic delivery of power to distribution systems embodies this player with a critical role in future plans. The development of a geographical area is directly proportional to its electrical transmission capabilities.

Distribution System Operator (DSO). Smarter options will inevitably increase the involvement of DSO in a SDS. It is foreseen that more responsibilities will be handed over to DSOs. However, the payback will increase along with the responsibilities.

Residential Customers. Although customers do not currently play an active role, smart grid applications and markets will significantly make their role more active. With electric vehicles, small-scale distributed generation, active energy management, and the introduction of demand-side management (DSM), this passive nature will evolve into critical decision-making power. Thus, customers are generally regarded as key stakeholders in future

SDSs. An example of how SDSs equipped with smart grid products and applications can significantly affect residential consumption is proposed in [21].

Commercial Customers. Like residential customers, the roles of conventional commercial customers will change. The relatively higher demand of commercial customers can adversely or positively affect the planning process.

Industrial Customers. The interests of industrial customers are not very different from other customers. They, like other customer types, can suffer from outages and poor reliability. For a system that provides more service options with increased resiliency and reliability, factories and bulk customers will be among the first supporters. Also, their involvement, along with residential and commercial customers, will eventually play a significant role in the concept of smarter citizens for smarter systems.

Vehicle Owners. As increased transportation electrification needs create greater penetration levels of electric-based vehicles (i.e. Plug-in Electric Vehicles (PEV)) into distribution systems, many technical and economic challenges arise [22]. With these challenges in mind, planning an SDS, in principal, must meet and accommodate the technical and geopolitical needs of these stakeholders. Electric vehicle owners should also be considered a key stakeholder, as they are anticipated to greatly affect the transition into a smarter grid. For instance, the discharging capabilities and distributed nature of these vehicles require concentrated attention to fully take advantage and utilize them in a smart grid environment.

2.3.3 Stakeholder Categorization

Plotting the aforementioned stakeholders in an interest-influence matrix yields four stakeholder categories, as shown in Figure 2.3. It is clear from the figure that the most important category is ‘Manage Closely.’ This category contains the most influential and most interested stakeholders in a SDS. They can provide key instruments to enable this transformation. For the ‘Keep Satisfied’ category, significant influence can be made on the successful transformation to a smart distribution, but with low interest. Customers and the electrical equipment industry should be monitored because they affect the system, especially with the anticipated changing roles.

The ‘Keep Informed’ category poses the fewest challenges since stakeholders in this category are already open to a SDS. For a successful planning methodology, moving the ‘Keep Satisfied’ category toward a higher interest region is necessary. The ‘Monitor’ category also needs to be moved to a higher interest region. These can be achieved by direct and strong communication that promotes the new concepts and advertises the benefits associated with such a transformation. The following section examines the communication and feedback levels among these categories. It is important to mention that this process is iterative and subject to changes according to the practitioner/researcher or when the study is conducted.

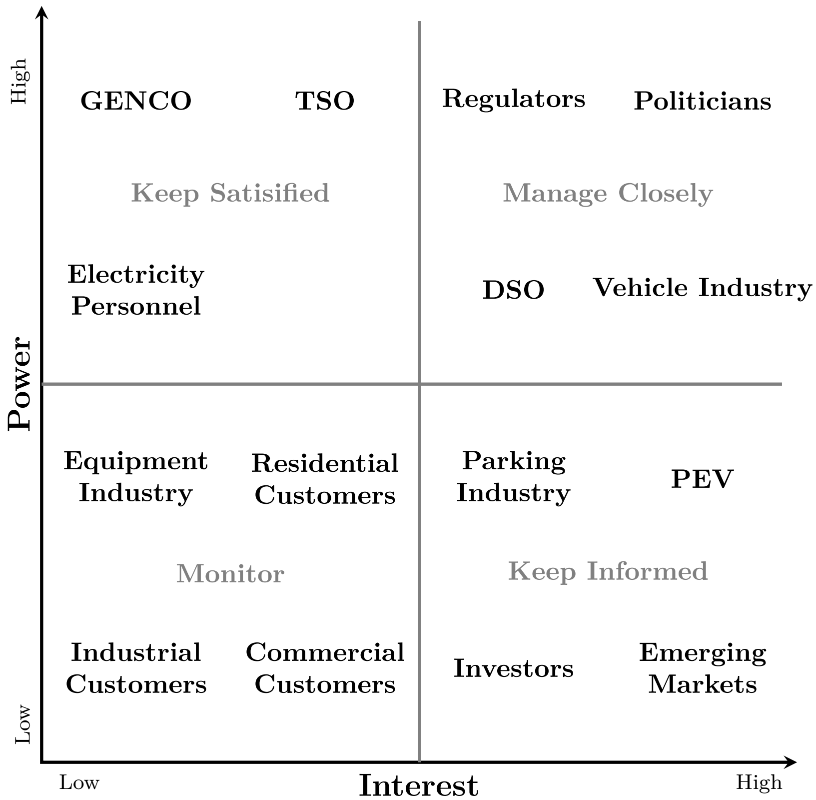

Figure 2.3: Stakeholder Influence-Interest Matrix

2.3.4 The Investigation of Stakeholders' Relationships

Like the categorization process, the relationship among stakeholders is also iterative. However, in this work, insights and conclusions about the relationship are drawn from surveys conducted in Ontario, Canada [23,24]. The relationships between the categories, in general, is summarized in Table 2.1 (i.e., actor-linkage matrix). One of the important insights gained from this matrix is that increased feedback and communication between the 'Keep Informed' and 'Monitor' categories are advised. Furthermore, since the 'Keep Informed' category is already highly interested in a new smart system, higher levels of communication and interaction are very advantageous with the 'Keep Satisfied' group.

Table 2.1: Stakeholder Actor-Linkage Matrix

Category	Monitor	Keep Informed	Keep Satisfied	Manage Closely
Monitor	——	L	H	H
Keep Informed	L	——	L	H
Keep Satisfied	H	L	——	H
Manage Closely	H	H	H	——

L: none-to-low communication and feedback
H: medium-to-high communication and feedback

2.4 Planning

From a background of ‘predict and provide’ to a ‘react and provide’ or ‘fit and forget’ perspective, distribution system planning has been of central interest with major importance given to network planners. Planning for future distribution systems requires a deep understanding of the technologies and players being introduced and integrated into the system. In the previous section, an analysis of SDS stakeholders was performed. It provided several insights; among them is the requirement to satisfy several stakeholders that will emerge in the system in the foreseeable future.

2.4.1 Overview

Although planning studies have existed for as long as there have been distribution systems, they have not become easier to design. More challenges have recently arisen with the development of new paradigms, causing planners to become more reactive than active [25]. Planning is probably the most critical step in designing and implementing new systems (or subsystems). Using short-term or operational planning, updates are gradually made to the planning manuals [25]. However, writing these manuals requires a comprehensive understanding of the system and the upcoming challenges. These challenges include accommodating rising loads and integrating renewable sources as well as emerging players into the system.

2.4.2 Distribution Systems Long-term Planning

The main objective of the long-term planning of distribution systems is accommodating the rising demand in an economical and reliable fashion. Planners face many challenges with the transition to a SDS, which will be discussed in Section 2.4.3.

In a survey conducted in 1997, authors in [26] summarized the planning and optimization models used in planning studies of distribution systems. A similar technique is used to categorize the literature of interest to the objectives of this work. This work assumes normal operation of distribution systems; therefore, planning for normal operation is of a centric interest. Although it is crucial, planning for emergencies and contingencies is outside the scope of this work. For planning under normal conditions, conducting single-period and multi-period planning studies are common practice. For a single-period, a single snapshot of the system is used to perform the study, including uncertainties in loads and generation. However, multi-period studies consist of either multiple single-period plans or a holistic approach that incorporates decisions made in one period and considers their effects on others. This work is primarily interested in multi-period studies and focuses on the advancements made in such cases. Researchers may also expand the categorization into expansion or reinforcement studies. Expansion studies optimally size and allocate new distribution system equipment, such as substations, feeders, and transformers, while serving technical and economic objectives and constraints. A reinforcement study provides reinforcing decisions on existing assets while addressing technical and economic objectives and constraints. Figure 2.4 summarizes the literature of interest that is related to this work's objectives.

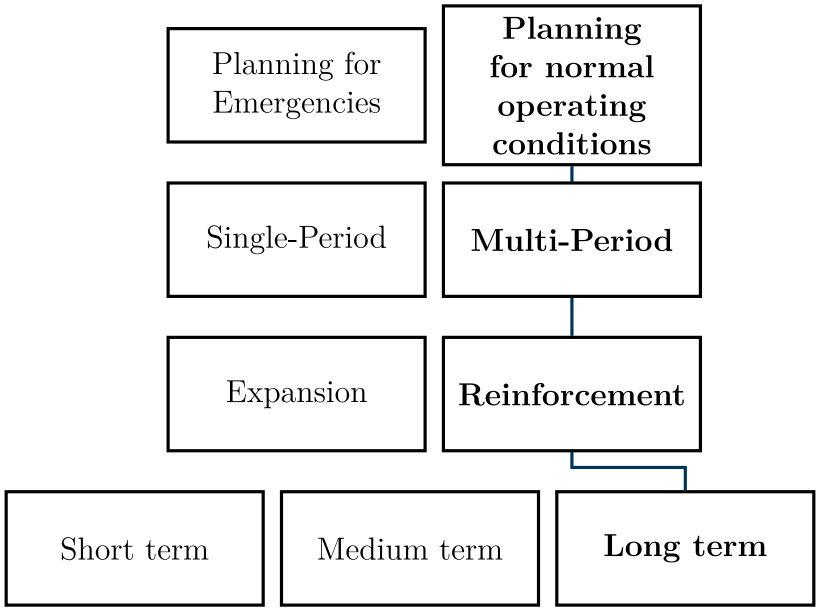

Figure 2.4: Summary of the Literature of Interest

2.4.3 Challenges in Planning Smart Distribution Systems

In the framework of distributed generation integration, the changing frameworks and the uncertainties of incentives can result in 'stranded costs' or assets [27]. These costs are directly related to countries' subsidy practices. For example, the decade-old practice in Germany (i.e., *Energiewende*) is expected to result in an increase of the already relatively (i.e., compared to the US and Canada) high tariff [27]. Because of these and other challenges, advanced and complex solutions that can result in more feasible plans are not adapted [28]. However, it is foreseeable that practice will overcome the difficulties of accepting new and complex planning frameworks as the planning problem becomes more complex [29].

The authors in [29] have identified three planning tools that need to be used: stochastic techniques, multi-objective planning, and the operational details of the system. Numerous research articles have been developed to tackle the operational details of distributed resources. These studies confirm that the operational details of DG can significantly affect the size and placement of the installed unit. For instance, the optimal integration of wind-based generators into the system while considering the ramping effects is studied in [30]. Moreover, work performed in [31] and [32] examines the maximum installed capacity (i.e., hosting capacity) and its effects on power quality (i.e., voltage). Also, [33] proposed storage concepts to best allocate them based on voltage sensitivity analysis. Work in [34] studies phase unbalancing caused by the integration of small single-phase units (e.g., microFIT). For power curtailment, [35] studied the benefits of optimally operating installed DG systems, and the work concluded that there are two main benefits: voltage support at peak loading and minimum power curtailment at minimum loading, yielding a greater hosting capacity. The work used linear programming (LP)-based Optimal Power Flow (OPF) in a single-year period. While sufficient for the purpose of validation, allocation and sizing problems require a more complex representation of loads and DG as well as a suitable algorithm to solve the resulting mixed integer (linear or nonlinear) problem over a longer time span. Generally, one may conclude that as more distributed resources (i.e., DG, storage, and capacitors) are integrated into the system, the smart grid technology investments become more economically feasible [36].

However, the operational details pertaining to distributed generation (both dispatchable and non-dispatchable) power curtailment while satisfying reverse power constraints, among other technical constraints in a long-term planning framework, are still needed. This need is seen from two perspectives:

1. local distribution company (LDC), Distribution Company (DISCO), or Technical Virtual Power Plant (TVPP) perspective: the entity that holds the technical overview of the system and ensures adequate resources and efficient operation.

2. Producer/Customer(Consumer): usually referred to in the literature as prosumers [37] are the customers/consumers and producers of electric power and mostly interested in the economic benefit of investment and the absorption of their investments.

LDCs or DISCOs (or TVPPs, as suggested in [38]) can offer incentives to private investors (or prosumers) to place distributed sources in optimal locations to improve the voltage profile or power quality and reliability of service, or all of these, as described in [39]. Moreover, in addition to political, regulatory, and environmental drivers, accommodating rising loads and integrating renewable sources and emerging players into the system are additional incentives to move to a smarter system [40].

Several studies target some aspects of the emerging smart grid concepts. In [29, 41], planning studies in active distribution networks are surveyed. The studies identified several planning tools, including techniques that account for the contradicting nature of goals amongst stakeholders (players). The studies concluded that new planning frameworks that incorporate new concepts and envision the future in the process are needed. An example of these concepts is the active distribution network concept. This concept poses several challenges, such as the future regulatory and technical aspects of integrating the active players into the system. Figure 2.5 shows the anticipated future of control schemes for different system players [40]. Business As Usual (BAU) planning will result in an increased passive loads and traditional transmission and generation capacities to meet these demands. This practice can be optimized with the incorporation of active management capabilities.

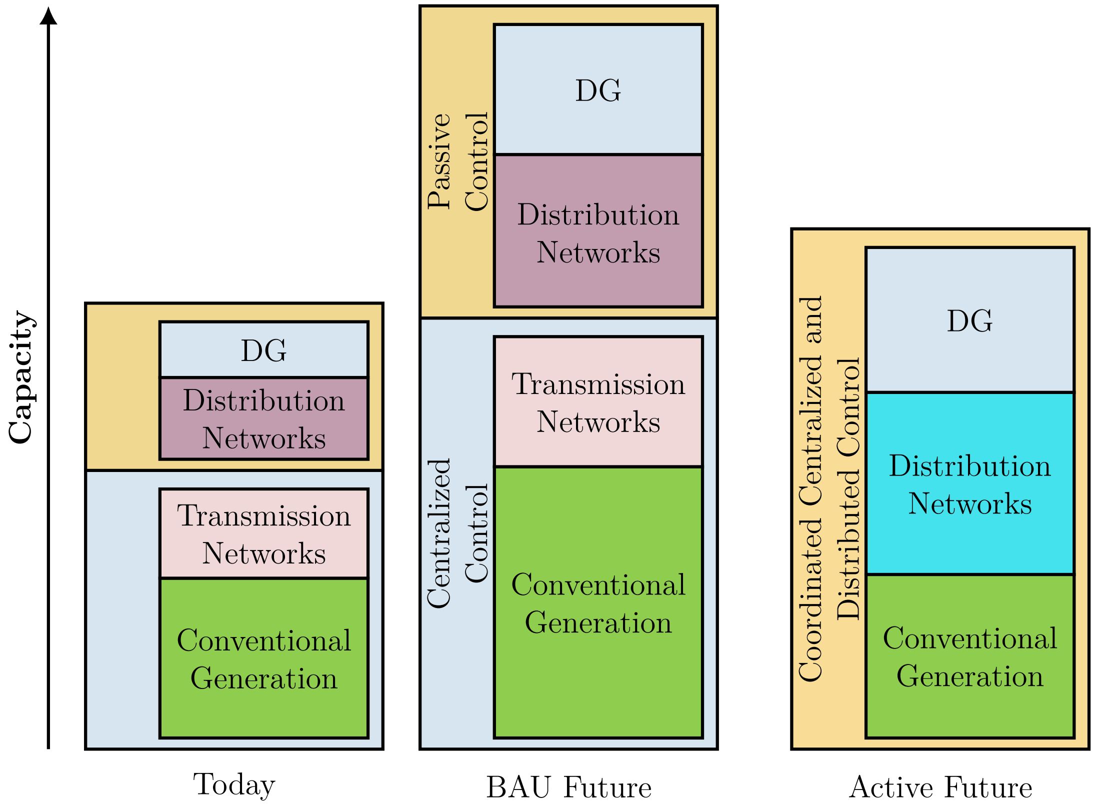

Figure 2.5: The Future of Control Schemes in Power Systems

2.4.4 State-of-the-Art Asset Planning Techniques

Many planning frameworks are proposed in the literature. They mainly differ in their approach to three main criteria, namely the technique used in the planning, the purpose (i.e., the objective), and the modeling of the system. For the objective, several approaches have proposed single objective formulations, where many others have formulated and proposed multiple-objective planning frameworks. These objectives can be either technical or financial. A wide range of techniques are found but primarily fall into two categories: numerical and analytical. However, the combination of an objective (or multiple objectives) and a technique for the optimal planning of distribution systems is the norm.

Another area where works proposed in the literature differ from each other is the modeling of the system and its components. Depending on the objective, the suitable (from the authors' perspectives) depth of representation is chosen. For instance, load uncertainty modeling, distributed generation uncertainty modeling, SDS concepts (active components), control, and time-frame are some examples of the differences that occur in representing the system under study. For practicality, assumptions are usually considered in this criterion of differences whenever a framework is conducted and causes different system awareness levels among these frameworks.

In [42], a comparison of deterministic-based and heuristic-based techniques was conducted. The study assessed the performance of optimally planning DG and state-of-the-art techniques in both worlds (i.e., deterministic and heuristic). Results showed that branch-and-bound-based mixed-integer nonlinear programming resulted in the highest percentage of feasible designs. Compared to DC power flow models, which are faster and converge almost every time in linearized but not feasible designs, the non-linearized model still suffered from speed and feasible outcomes. This means that using AC power flow, if properly incorporated into the planning problem, can be a preferable option with advanced solvers. However, since this paper only focuses on assessing performance, it still sufferes from providing a planning framework for freely sizing and allocating DG units, and other assets were not within the scope. Therefore, further investigation with optimal DG sizing and allocation are advised. Moreover, it is also noticeable that the genetic algorithm used in [42] can benefit from incorporating an advanced AC power-flow solver.

In [43, 44], analytical approaches were used on power losses. For a single snapshot of load and generation, these analytical approaches can be performed for a specific objective, and it can only be applied to one asset at a time. Moreover, this step allocation of units may result in network sterilization and not allowing higher investment absorption. This approach also cannot facilitate the operation of the installed assets, which is highly advised for active system planning.

Exhaustive methodologies were used in [45–47]. For a single problem such as power losses, this technique explores most of the possible solution space. It is obvious that this method favours assets of discrete sizes that do not necessarily cope well with the of technology enhancements used in developing these assets (e.g., photovoltaic). Although these techniques increase in computational intensity with the more system-aware representation, time is not a primary problem for long-term planning if it provides a feasible solution. However, with the advancements in metaheuristic techniques, smart searching in the search space is possible.

In principle, using linear programming techniques requires linearization of the power flow. For discrete-based assets, [48,49] reported an insignificant error although it will always entail a degree of error. With the objective to minimize annual generation curtailment, work in [35] employed a linear power flow technique. However, work in [50] used AC power flow for linearized sensitivity studies. For non-firm generation, work in [51] utilized an LP-based model to optimize DG allocation with relaxed voltage constraints, whereas in [52], the power flow was used in its traditional AC fashion. Both works reflect the great potential for LP models' fast response over other techniques when considering the operational aspects of assets. However, this is not a problem in a long-term off-line planning framework.

AC OPF is commonly deployed for economic dispatching. In [53], the traditional formulation of a nonlinear programming-based OPF is found, and it is widely appreciated by both academia and industry because of the vast ready-made and advanced methods to solve them. The method also entails a great aspect, which is the capability of adhering to constraints and specific objectives. For instance, work in [54] modifies a traditional technique to minimize power losses. Another objective can be found in [55], where the objective is to minimize energy losses. Moreover, this has been extended to more recent objectives, such as increasing the DG hosting capacity of a system [56, 57]. However, the aforementioned objective-oriented techniques suffer from two conventional assumptions: the passive representation of DG and peak load modeling. Although it is sufficient for traditional systems, smart grid applications require a more system-aware model that can, first, reflect and take advantage of the active nature of the new systems, and second, utilize the advanced optimization techniques that allow for different generation and loading scenarios to be considered.

In [58], work considering some of these features is proposed to allocate maximum DG capacity. Security problems and voltage steps are examples of more complicated objectives. However, work concerning these objectives can also be found in the literature [49, 59, 60]. A major weakness in the traditional nonlinear programming (NLP)-based AC power flow or OPF is that it cannot incorporate, in its traditional framework, integer programming. Work in [61] developed a mixed-integer NLP-based planning framework. The potential complexity of such development increases significantly with the size of the system as the number of variables and constraints increase dramatically. Additionally, for multi-period studies, the burden is further extended. Aggregation techniques are developed in [49, 62]. However, with reduced periods representing the system, system awareness and accuracy may be compromised. Also, it will be insufficient to fully represent an optimal hourly or half-hourly optimization of assets in long-term asset planning.

In [63–66], stochastic planning of assets is proposed. For reliability purposes, three main techniques are found in the literature, namely, 1) Monte Carlo simulations-based [67], 2) analytical-based [68], and 3) hybrid [69] techniques. However, these techniques also suffer from drawbacks. First, they require an enormous amount of data that is magnified with the larger systems. Besides, it requires a very high technical background to translate the data into plans, which, in turn, complicates the decision-making process. Moreover, they require an adequacy analysis of several system states, which is part of the optimization framework [70].

Proceeding with different objectives and different techniques, an area of planning is developed with a new modification. It employs multiple objectives that can better represent the system and/or utilize the new smart applications [68,71–73]. This branch of the planning framework usually utilizes Pareto set (frontier) optimization, such as in [39,73,74]. Different techniques are then used to assess this set, such as in [75]. A Pareto set can be reached by optimizing each conflicting objective individually or by constraining each objective by the other objectives until the frontier is reached.

Tuning is a major issue in metaheuristic algorithms, along with the number of iterations. Without careful and appropriate tuning, finding a good (near optimal) solution within a reasonable period of time may not be accomplished. This inherent lack of a guarantee that a global optimal solution will be reached requires multiple successive iterations to reach an acceptable solution. For DG allocation, a particle swarm optimization (PSO)-based technique is proposed in [76]. Artificial bee colony optimization (ABC) algorithms were also used for several objectives [77, 78]. However, a tendency towards favouring genetic algorithms (GAs) is found in the literature [39, 79–81]. This may be due to the simplicity of solution representation. Although the authors proved that simulated annealing (SA) outperformed GA in [82], the issue of tuning and the optimal setting of the algorithm arises. GA is also applied to optimal investment planning [83], and GA-based frameworks are found in the literature solving multiple objective problems with very complex objectives considered [62,83–86]. Moreover, this tendency to favour GA is also found in single technical-, environmental-, and economical-based objective optimization problem-solving [62, 85, 87–89].

2.5 Chapter Summary

In this chapter, a background and literature survey of SDSs and what the term may entail has been conducted. The chapter began with an introduction to the topic and the general motives behind it. The topic required further background understanding about what is envisioned in the smart grid as well as the role of power system components in this smart paradigm. These notions needed further investigation and understanding about the stakeholders of this envisioned SDS to properly explain how a generalized planning framework may be developed. Moreover, an investigation of the current planning literature was needed and conducted. It is now clear that any long-term planning framework that facilitates a smooth transition to a SDS while utilizing linearized OPF compromises accuracy.

Capitalizing on the capabilities of metaheuristic techniques and how NLP-based OPFs can enhance them are now of great interest to this work. With ever-advancing commercial solvers designed to address non-convex, nonlinear, and mixed-integer problems, as well as those with a large number of constraints and variables, challenging these solvers with even greater objectives becomes a natural progression.

Chapter 3

Strategic Analysis of Potential Conflicts in the Smart Grid Paradigm and Their Effects on Planning[§]

"Out beyond right and wrong, there is a field. I will meet you there."

— Jelaluddin Rumi

This chapter strategically investigates the relationship and interaction among future smart grid stakeholders. This is done to better understand and highlight potential conflicts and determine how to overcome them. The topic is first introduced in Sections 3.1 and 3.2, and then it addresses two main relationships: 1) between the LDC and investors in Section 3.3 and 2) among prosumers in Section 3.4. The chapter and its outcomes are then summarised in Section 3.5.

[§]Parts of this chapter are published in [90, 91].

3.1 Preamble

Assessing and developing any new framework is part of envisioning it. This futuristic approach allows for a greater response from all involved parties. The early involvement of parties in envisioning a system has often been reported to have a substantial impact on the success of any new system. Thus, this chapter attempts to strategically analyze and assess future SDS stakeholders and their interactions. In the following section, the process begins with the identification and analysis of future system stakeholders. This allows the analyst to become critically aware of the areas in which conflict may arise, and ultimately provide guidelines toward a generalized long-term planning framework that engages all stakeholders while eliminating any points that can damage the harmony of the interactions between them. However, to do so, a conflict analysis has to be performed for these arising conflicts.

3.2 Introduction

This work aims to investigate potential conflicts in future grids and their effect on planning distribution systems. Smart grid technologies are prevalent, especially in systems that look almost the same today as they did decades ago (i.e., power systems). Planning a transformation requires a comprehensive understanding of future challenges. Although the optimality and accuracy of planning techniques are evolving, many challenges are yet to be discovered and analyzed. In this chapter, potential conflicting goals in the smart grid are identified, and their impact on the planning process is analyzed. Two types of conflicts can arise with conventional planning techniques. The first involves potential conflicts between DSOs (e.g., LDC, DISCO, or TVPP) and prosumers), and the second involves potential conflicts among prosumers in the operation of SDSs. The research paths required to overcome these conflicts are described in this chapter.

For several important reasons, electric systems and all of their players are moving toward smarter systems (i.e., smart grids). The concept of the smart grid has been a central interest for many researchers in several fields as well as in practice; power engineers are no exception. They are at the core of this interest, as they are responsible for implementing and integrating the new technologies posed in the literature. Moreover, transforming decades-old technologies and business models to a smarter and more resilient infrastructure is not an easy task. To overcome any challenge, it first needs to be clearly identified and analyzed. Many challenges have been identified, and many more are foreseen, yet others are still hidden in the future. This work, among others, attempts to identify a problem that can cause conflicts in the planning frameworks of a smart system. For many years, power markets have been studied. Many research studies have aimed to enhance the transparency and performance of such markets. Policies, regulations, and technical standards are the most salient results of such research. However, as the structures and architectures of power systems change, so do the tools used to study them. An understanding of the future grid is based on several stakeholders' changing roles or perhaps even new ones coming into existence. For instance, in the future, customers of a grid are seen as playing different roles as they change from a passive player to a more active player. Prosumers increase the complexity from both technical and market perspectives [7]. In [9], the authors also suggest that a prosumer can be a collective or group of single physical entities (i.e., microgrids). Thus, their role can change from being a consumer to a producer in a short period of time, depending on self-interests. Furthermore, research in the area of bidirectional energy management is of interest [92]. This work aims to investigate the potential conflicts in future grids and their effect on planning distribution systems.

Although the NIST reports a consensus exists among stakeholders regarding interoperability standards [1], stakeholders are categorized differently regarding their interest and influence. This difference may be a reason for potential conflicts that arise in the long-term planning of SDSs. It is also important to capitalize on the strong communication relationships between categories to eradicate any potential conflict and further promote smart grid technologies. Proceeding from these insights, the following sections investigate potential conflicts between involved parties. The promotion aspect will be the subject of a future study.

Following the introductory section, an analysis of potential conflicts and their effect on planning studies is presented in Section 3.3 and Section 3.4. Section 3.5 offers conclusions and final remarks.

3.3 Conflict Between LDCs and Investors

The authors in [39] suggest that DSOs or TVPPs, as suggested in [38], can incentivize private investors to place distributed sources in optimal locations and improve the voltage profile, power quality, or both, as well as improve service reliability. These incentives may be similar in principle to the ones studied in the literature for IPPs, such as [93], or for the demand-side bidding strategy, such as in [94]. In the following section, a case study that examines the relationship between system costs and voltage profiles is conducted. Several insights regarding their effect on the long-term planning problem are duly drawn.

3.3.1 Problem Description and Formulation

Two objectives are studied in this case. The first is an index for the voltage profile described in Equation 3.2, and the second is the total costs, as Equation 3.3 describes. The multi-objective GA deployed here utilizes a controlled elitist variant of non-dominated sorting genetic algorithm II (NSGA-II) [95]). The costs considered in this problem are the line upgrade cost, DG capital costs, DG operation and maintenance costs, cost of energy losses, cost of purchased energy from the grid, and cost of surplus energy from DGs. This case study of a long-term planning problem can be defined by

$$\min_{\Omega} \left([f_1(\Omega) \;\; f_2(\Omega)] \right) \tag{3.1}$$

where Ω vector of decision variables and subject to constraints formulated in Equations 3.2 to 3.16

$$f_1(\Omega) = \sum_{y\in\mathcal{Y}} \sum_{d\in\mathcal{D}} \sum_{h\in\mathcal{H}} \sum_{i\in\mathcal{I}} \frac{\left|V_{(i,h,d,y)} - V^{\text{target}}\right|}{V^{\text{target}}}, \tag{3.2}$$

where $V_{(i,h,d,y)}$ is the magnitude of the voltage in (V or pu) at bus i in hour h, day d, and year y, and V^{target} is the targeted voltage level set by the operator; $\mathcal{Y}$, $\mathcal{D}$, and $\mathcal{H}$ are the sets of planning years, days, and hours; $\mathcal{I}$ is the set of system buses;

$$f_2(\Omega) = \sum_{y\in\mathcal{Y}} \frac{\sum\limits_{i\in\mathcal{I}} \sum\limits_{dg\in\mathcal{DG}} S_{(i,dg,y)} C^{Capital}_{(i,dg,y)}}{(1+r)^y}, \tag{3.3}$$

where $\mathcal{DG}$ is the set of available DG technologies; $C^{Capital}_{(i,dg,y)}$ capital cost of every allocated DG of technology dg at bus i and at year y (\$/MVA); $S_{(i,dg,y)}$ is allocated DG of technology dg at bus i and year y (MVA) and described in Equations 3.6 and 3.7, r is the effective discount rate (discount and inflation) [2];

$$V^{\text{spec}}_{min} \leq V_{(i,h,d,y)} \leq V^{\text{spec}}_{max} \ \forall i, h, d, y, \tag{3.4}$$

where V^{spec}_{min} and V^{spec}_{max} are specified minimum and maximum voltages (V or pu) according to regulations and standards;

$$I_{(i,j,y)} \leq I_{(i,j,y)_{max}} \ \forall i, y, i \neq j, \tag{3.5}$$

where $I_{(i,j,y)}$ is the current in line between bus i and j (A or pu) and $I_{(i,j,y)_{max}}$ is the maximum line current carrying capacity at year y between bus i and j (A or pu);

$$S_{(i,dg,y)} = \varpi_{(i,dg,y)} \times \kappa_{(i,dg,y)} \qquad \forall i \in \mathcal{Q}_{dg}, y \in \mathcal{Y}, \tag{3.6}$$

$$S_{(i,dg,y)} \leq S_{dg}^{max} \qquad \forall i \in \mathcal{Q}_{dg}, y \in \mathcal{Y}, \tag{3.7}$$

where $\varpi_{(i,dg,y)}$ is a binary decision variables to place DG of technology dg at bus i and year y and $\kappa_{(i,dg,y)}$ is a variable size of allocated DG of technology dg; S_{dg}^{max} is maximum DG size of technology dg (MVA); $\mathcal{Q}_{dg}$ is the set of candidate buses for DG of technology dg ($\mathcal{Q}_{dg} \subseteq \mathcal{I}$);

$$\varpi_{(i,dg,y)} : \begin{cases} \text{Integer}: & dg \text{ only available in steps} \\ \text{Continuous}: & \text{otherwise} \end{cases}$$
$$\forall\ dg \in \mathcal{DG},$$

$$\sum_{y \in \mathcal{Y}} \sum_{dg \in \mathcal{DG}} S_{(i,dg,y)} \leq S_i^{max}, \tag{3.8}$$

where S_i^{max} is the maximum allowed total DG capacity in bus i (MVA);

$$P_{g(i,h,d,y)} + \left(\sum_{dg \in \mathcal{DG}} P_{(i,dg,h,d,y)} \right) - P_{D(i,h,d,y)} = \sum_{j \in \mathcal{J}} V_{(i,h,d,y)} V_{(j,h,d,y)} Y_{(i,j,y)}$$
$$\cos\left(\theta_{(i,j,y)} + \delta_{(j,h,d,y)} - \delta_{(i,h,d,y)}\right) \forall i, j \in \mathcal{I}\ (\mathcal{I} = \mathcal{J})\ i \neq j, h \in \mathcal{H}, d \in \mathcal{D}, y \in \mathcal{Y}, \tag{3.9}$$

where $P_{g(i,h,d,y)}$ is the active power purchased from grid in bus i , at hour h , day d , and year y (MW); $P_{(i,dg,h,d,y)}$ is the produced active power for DG of technology dg in bus i , at hour h , day d , and year y (MW); $P_{D(i,h,d,y)}$ is the active demand for bus i at hour h, day d, and year y (MW); $Y_{(i,j,y)}$ is the magnitude of the Y-bus matrix admittance (℧ or pu);

$$P_{g(i,h,d,y)} = \begin{cases} P_{g(i,h,d,y)} : & i \in \mathcal{G} \\ 0 : & i \notin \mathcal{G} \end{cases} \qquad \forall i \in \mathcal{I}, h \in \mathcal{H}, d \in \mathcal{D}, y \in \mathcal{Y}, \tag{3.10}$$

$$P_{(i,dg,h,d,y)} \geq PF_{(i,dg,h,d,y)} \times S_{(i,dg,y)} \qquad \forall\ i \in \mathcal{I}, dg \in \mathcal{DG}, h \in \mathcal{H}, d \in \mathcal{D}, y \in \mathcal{Y}, \tag{3.11}$$

where $PF_{(i,dg,h,d,y)}$ is minimum allowed power factor for DG of technology dg in bus i at hour h , day d , and year y;

$$P_g^{Rev} \leq P_{g(i,h,d,y)} \leq P_g^{Max}\ \forall i \in \mathcal{G}, \tag{3.12}$$

where P_g^{Rev} and P_g^{Max} are maximum reverse and supplied active power at the grid connected buses ($i \in \mathcal{G}$) and $\mathcal{G} \subset \mathcal{I}$;

$$Q_{g(i,h,d,y)} + \sum_{dg \in \mathcal{DG}} Q_{(i,dg,h,d,y)} - Q_{D(i,h,d,y)} = -\sum_{j \in \mathcal{J}} V_{(i,h,d,y)} V_{(j,h,d,y)} Y_{(i,j,y)} \sin\left(\theta_{(i,j,y)} + \delta_{(j,h,d,y)} - \delta_{(i,h,d,y)}\right) \forall i, j \in \mathcal{I}\ (\mathcal{I} = \mathcal{J})\ i \neq j, h \in \mathcal{H}, d \in \mathcal{D}, y \in \mathcal{Y}, \tag{3.13}$$

where $Q_{g(i,h,d,y)}$ is the reactive power purchased from grid in bus i , at hour h , day d , and year y (MVAR); $Q_{(i,dg,h,d,y)}$ is the produced reactive power for DG of technology dg in bus i , at hour h , day d , and year y (MVAR); $Q_{D(i,h,d,y)}$ is the reactive demand for bus i at hour h, day d, and year y (MVAR);

$$Q_{g_{(i,h,d,y)}} = \begin{cases} Q_{g_{(i,h,d,y)}}: & i \in \mathcal{G} \\ 0: & i \notin \mathcal{G} \end{cases} \quad \forall i \in \mathcal{I}, h \in \mathcal{H}, d \in \mathcal{D}, y \in \mathcal{Y}, \tag{3.14}$$

$$Q_{(i,dg,h,d,y)} = \sin\left[\cos^{-1}\left(PF_{(i,dg,h,d,y)}\right)\right] \times S_{(i,dg,y)} \quad \forall\ i \in \mathcal{I}, dg \in \mathcal{DG}, h \in \mathcal{H}, d \in \mathcal{D}, y \in \mathcal{Y}, \tag{3.15}$$

$$Q_g^{Rev} \leq Q_{g_{(i,h,d,y)}} \leq Q_g^{Max}\ \forall i \in \mathcal{G}, \tag{3.16}$$

where Q_g^{Rev} and Q_g^{Max} are maximum reverse and supplied reactive power at the grid connected buses ($i \in \mathcal{G}$) and $\mathcal{G} \subset \mathcal{I}$;

3.3.2 Case Study

This case study is performed on a typical test system found in the literature [96]. The system, shown in Figure 3.1, is composed of residential, commercial, and industrial loads with different loading levels. The costs are adapted from [97], and the energy prices are based on the average hourly prices in Ontario over the past four years; the data were retrieved from [98]. The study is performed for a period of 20 years with a load increase of 10% per year. Three types of DGs are considered: wind, Photovoltaic (PV), and gas turbine.

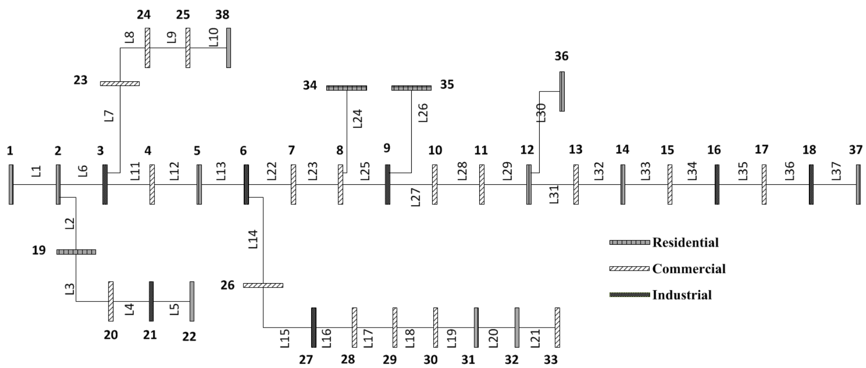

Figure 3.1: The 38-bus Test System Used in the Study of LDCs and Investors Conflict Case Study

3.3.3 Results

The design, with a minimum cost of \$653, 100 and a minimum voltage deviation sum of 2.82, is found at the utopia point; however, these minimums are paired in reality with a maximum cost of \$40, 330, 910 and a maximum deviation sum of 21.02. It is clear from Figure 3.2 that the objectives are conflicting, and the conflict can significantly impact the decisions made by planners. Enhanced voltage profiles can be attained with investments many times higher than the minimum costs resulting in possibly stranded assets. These investments can either be made by the LDC or a private investor, and an expected economic benefit is a reasonable rate of return on investment. However, since the minimum cost design satisfies voltage limit constraints, private investors are not interested in a low marginal contribution that enhances the LDC's performance with no acceptable rates of return on investments. The LDC is left with the decision to either pay for the necessary installations or face the burden of a system operating near voltage limits. Increasing the marginal contribution of installed units guarantees better rates of return and the higher absorption of private investments. This objective should be considered in planning SDSs; thus, the optimal operation of units is a necessary part of planning the allocation of these assets.

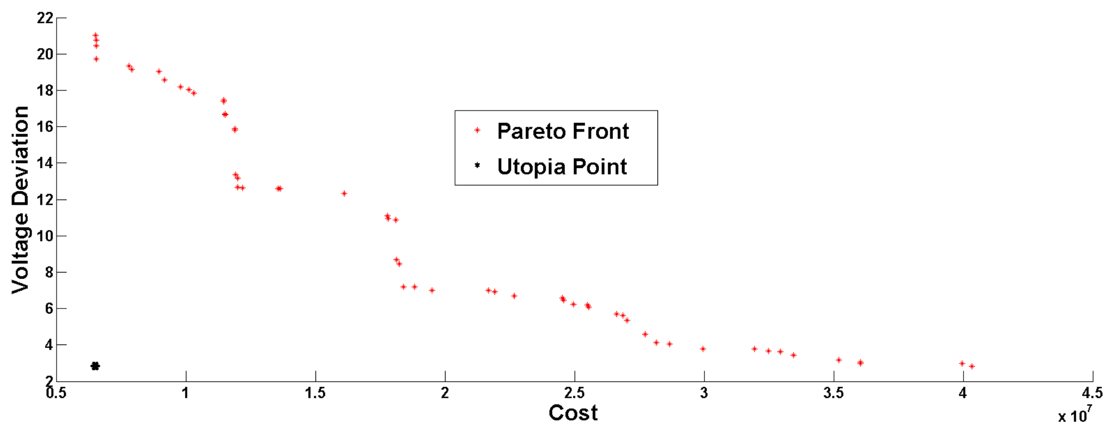

Figure 3.2: The Resulting Pareto Optimal Set

3.4 Conflict Between Prosumers

Given the insights gained from the previous case study in Section 3.3, further study is needed. In a case where a planner chooses to implement a design that provides minimum voltage, private investors pay more. Assuming that private investors will opt in on a design based on incentives, daily operations are yet to be analyzed. To generalize such cases, an example of a prosumer connected to a common service point is defined and studied. An analysis of which prosumer will respond and how equilibrium can be achieved is discussed in the following section.

3.4.1 Stability Definitions

A range of solution concepts (stability definitions) are defined within the paradigm of game theory to predict the possible output of an interaction. These stability definitions work as a case-based reasoning system that answers any what-if questions. The two solution concepts adopted in this work that evaluate the stability of a state for each Decision Maker (DM) are Nash stability [99, 100] and sequential stability (SEQ) [101]. For coalitional stability and equilibria, similar definitions are adapted from [102]. These definitions include Nash and SEQ coalitional stability. The definition of the reachable set and equilibria is slightly modified.

3.4.2 Case Study and Results

Figure 3.3 shows a general architecture of what a prosumer would be. At the service point, the utility or another player offers a price for power (1 MW in this case study). Both prosumers are able to respond to the request. Assuming two stages of generation and demand for both players, options can be summarized in Table 3.1. Moreover, due to the assumption of close geographical proximity, the price structure for service can also be assumed to be similar for both prosumers.

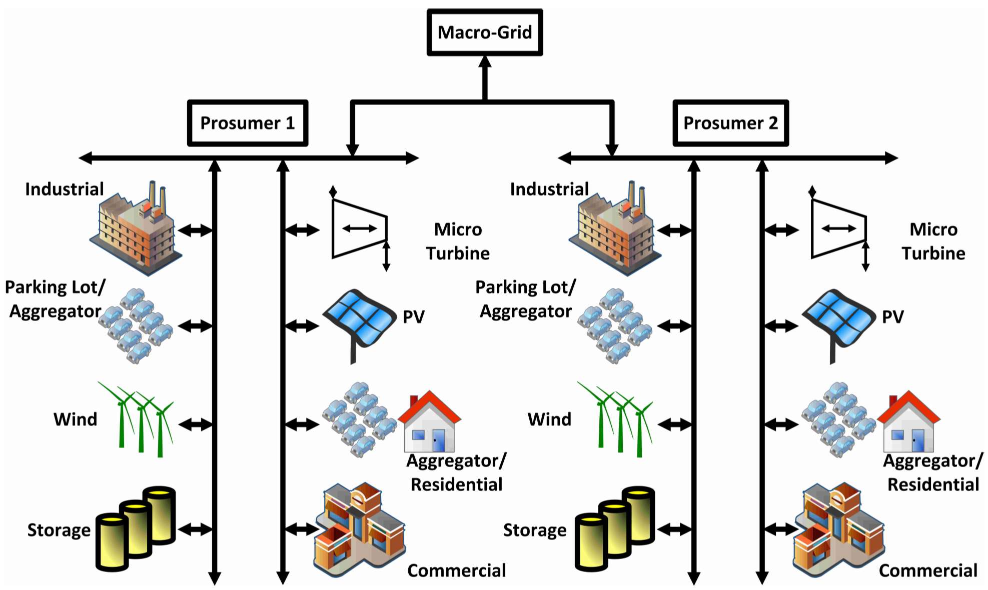

Figure 3.3: General Architecture of Two Prosumers

Table 3.1: Decision Makers and Options

DM	Options		DM	Options	
Prosumer 1	Sell 2	Yes No	Prosumer 2	Sell 2	Yes No
	Sell 1	Yes No		Sell 1	Yes No
	Idle	Yes No		Idle	Yes No
	Buy 1	Yes No		Buy 1	Yes No
	Buy 2	Yes No		Buy 2	Yes No

The combination of all options yields $2^{10} = 1024$ states. Removing the infeasible states, due to mutual exclusivity, will result in the elimination of 999 states; thus, the number of feasible states (i.e., players' points of view) is 25. The remainder of 25 does not guarantee market feasibility. If we assign weights, preference ranking can be conducted as in Table 3.3.

According to the definitions, Nash stability is a subset of sequential stability. Therefore, for a dynamic market, it is best to represent stable conditions by both sequential stability and Nash, so the rationality in a free market can be represented. However, it is important to mention that equilibria, from the perspective of a player, is not necessarily a market-feasible state. For a noncooperative, complete information, and dynamic game, the rationale that leads to an equilibrium (i.e., stable state) is not guaranteed to be a viable situation, whereas a free market is composed of a leader (i.e, the macrogrid) and followers (i.e., prosumers), which can be considered a Stackelberg competition.

In the case shown in Figure 3.4, only one state was stable. This very critical situation will increase in complexity if more players are considered (with similar price structures). Additionally, the stable state involves both prosumers opting 'yes' to 'Buy 2,' since prices are low. Moreover, one primary function of SDSs is the decentralization, which, in part, does not allow for a centralized authority to perform conventional optimization techniques.

This may not yield a market clearing status. However, if a coalition is considered between both prosumers, the results will be significantly different. Figure 3.5 clearly shows that increased chances of equilibria states arise. Since this is an ordinal analysis of the situation, random descending payoffs were assigned to options based on the preferences. Table 3.2 summarizes the list of feasible states for both prosumers.

Table 3.2: List of Feasible States

State	P1					P2					Mismatch
	S2	S1	I	B1	B2	S2	S1	I	B1	B2	
1	**Yes**	No	No	No	No	**Yes**	No	No	No	No	-5
2	No	**Yes**	No	No	No	**Yes**	No	No	No	No	-4
3	No	No	**Yes**	No	No	**Yes**	No	No	No	No	-3
4	No	No	No	**Yes**	No	**Yes**	No	No	No	No	-2
5	No	No	No	No	**Yes**	**Yes**	No	No	No	No	-1
6	**Yes**	No	No	No	No	No	**Yes**	No	No	No	-4
7	No	**Yes**	No	No	No	No	**Yes**	No	No	No	-3
8	No	No	**Yes**	No	No	No	**Yes**	No	No	No	-2
9	No	No	No	**Yes**	No	No	**Yes**	No	No	No	-1
10	No	No	No	No	**Yes**	No	**Yes**	No	No	No	0
11	**Yes**	No	No	No	No	No	No	**Yes**	No	No	-3
12	No	**Yes**	No	No	No	No	No	**Yes**	No	No	-2
13	No	No	**Yes**	No	No	No	No	**Yes**	No	No	-1
14	No	No	No	**Yes**	No	No	No	**Yes**	No	No	0
15	No	No	No	No	**Yes**	No	No	**Yes**	No	No	$+1$
16	**Yes**	No	No	No	No	No	No	No	**Yes**	No	-2
17	No	**Yes**	No	No	No	No	No	No	**Yes**	No	-1
18	No	No	**Yes**	No	No	No	No	No	**Yes**	No	0
19	No	No	No	**Yes**	No	No	No	No	**Yes**	No	$+1$
20	No	No	No	No	**Yes**	No	No	No	**Yes**	No	$+2$
21	**Yes**	No	No	No	No	No	No	No	No	**Yes**	-1
22	No	**Yes**	No	No	No	No	No	No	No	**Yes**	0
23	No	No	**Yes**	No	No	No	No	No	No	**Yes**	$+1$
24	No	No	No	**Yes**	No	No	No	No	No	**Yes**	$+2$
25	No	No	No	No	**Yes**	No	No	No	No	**Yes**	$+3$

Table 3.3: Preferences Rank

Most Preferred ⟶ Least Preferred

Options		**Payoffs**	
P1	P2	P1	P2
5	21	5	5
10	**22**	5	5
15	23	5	5
20	24	5	5
25	25	5	5
4	16	4	4
9	17	4	4
14	**18**	4	4
19	19	4	4
24	20	4	4
3	11	3	3
8	12	3	3
13	13	3	3
18	**14**	3	3
23	15	3	3
2	6	2	2
7	7	2	2
12	8	2	2
17	9	2	2
22	**10**	2	2
1	1	1	1
6	2	1	1
11	3	1	1
16	4	1	1
21	5	1	1

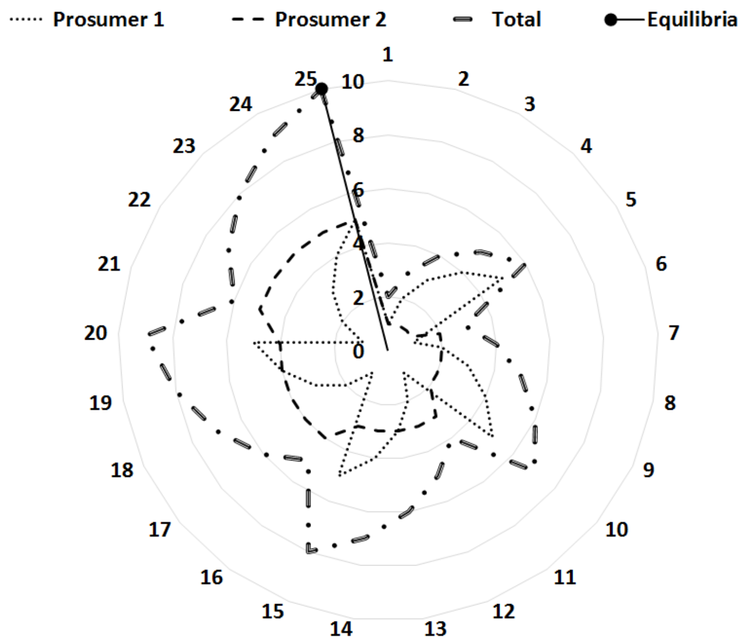

Figure 3.4: Payoffs and Equilibria While Prosumers Are Not Working Together

In similar cases, having similarly behaving prosumers fighting for resources (i.e., power or revenue) affects planning. Either of these cases should be eliminated from initial planning studies or cooperative or coalitional market structures should be worked toward, or both these approaches could be used. The equilibria obtained in Figure 3.4 is at the maximum total payoff. For this to happen, however, chronological agreements between parties need to be in place. At 25, both may receive the maximum, but it cannot be cleared in the market. A coalition stability analysis is performed using the Nash and sequential stability concepts, revealing that states, such as 10 and 22 (market feasible states), can achieve equilibrium if a coalition between prosumers takes place (as shown in Figure 3.5).

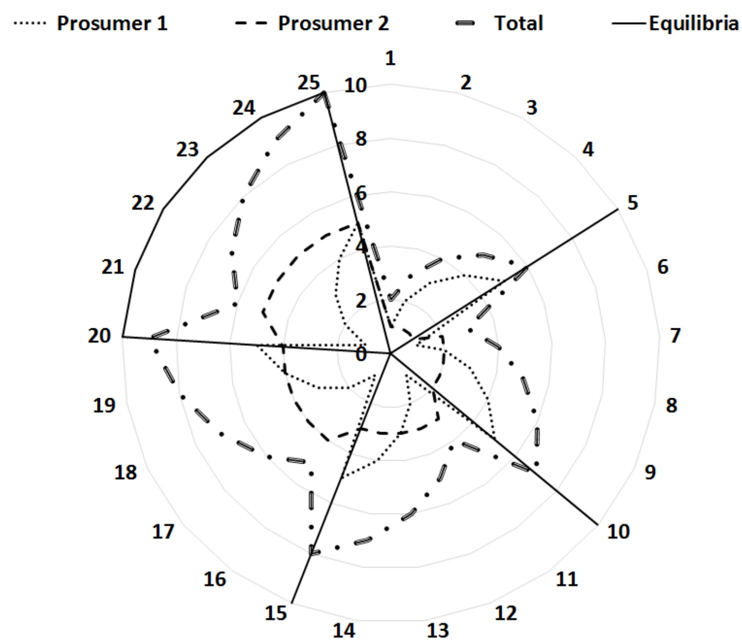

Figure 3.5: Payoffs and Equilibria While Prosumers Are Working Together

3.5 Chapter Summary

Several insights can be duly drawn from this strategic analysis, which first identified, categorized, and assessed the relationships between stakeholders and the two anticipated conflicts: the long-term planning level and the operation level. Feedback systems between different stakeholder categories have been seen as advantageous, especially for groups with lower interest in an SDS. Moreover, it highlighted the importance of keeping private investors continuously informed about new developments that lean toward their interests (i.e., smarter systems). Direct engagement and monitoring of all customer types are essential to a successful transition.

To conclude, contradictory goals can occur in a smart grid framework. These contradictions affect the planning process and should not be ignored [90]. As systems move toward multiple ownership and multiple stakeholders, planning entities must consider the goals of new stakeholders. Meeting conflicting objectives inherently involves compromises between parties; however, with smart grid technologies, ultra-fast communications and emerging markets and players make cooperation, coalition formation, and the optimal operation of assets necessary in the planning of future SDSs.

Chapter 4

Long-Term DG Allocation Planning Considering the Daily Operational Planning and Both Investor and Operator Interests[§]

"You can't solve problems until you understand the other side."

— Jeffrey Manber

Proceeding from Chapters 1 to 3, this chapter provides the backbone of a generalized planning framework. It addresses several objectives; however, it primarily provides an architecture for higher DG penetration into distribution systems utilizing smart grid technologies (i.e., active components). Thus, it can guide the route toward greater private investment absorption. The chapter is organized as follows: Section 4.2 introduces the work; the description and formulation are then detailed in Sections 4.3 and 4.4; Section 4.5

[§]Parts of this chapter are published in [103, 104].

proposes the algorithm developed to address the problem; an example case is then studied and discussed in Sections 4.6 and 4.7; contributions and summary of the chapter are highlighted in Section 4.8.

4.1 Preamble

A literature review exploring state-of-the-art planning frameworks and the techniques used was conducted in Chapter 2. It highlighted significant unexplored options in designing a planning framework. It first highlighted the need for greater attention to different stakeholders' interests that needs to be considered during the early planning stage. This early adaptation allows for the planners and their plans to become more predictive and comprehensive and require minimal operational updates. It also highlighted the untapped area of hybrid optimization techniques related to long-term planning that considers daily optimal operation over the planning period.

4.2 Introduction

An algorithm that maximizes the DG's hosting capacity in a system while lowering the overall system cost is proposed in this chapter. This algorithm considers several realistic aspects of long-term DG planning, such as the cost-effective design of feeder reinforcement. It allocates DGs and provides the type, size, location, and year of installation. Different DG technologies are used in the formulation. The complexity of the problem necessitates modeling the problem in a mixed-integer nonlinear programming fashion. Long-term planning is performed while considering the daily optimal operation of the allocated DGs. It also reselects different loading and renewable generation conditions to provide a more resilient plan. Active power management capabilities are also considered in the means of active power curtailment and power factor range (i.e., non-firm generation). A case study of a test system was conducted over a planning period of 20 years, with every year consisting of eight-day patterns and each day having 24 varying hours. The rationales that necessitated these numbers are as follows: 1) a long-term duration that reflects the multiple periods and duration of a planning problem, 2) a minimum amount of days representing a year to capture load and generation behavior considering that this algorithm will be further modified to incorporate different components in further studies, and 3) a time series representation that can take advantage of advanced solvers and be able to optimally operate components on a daily basis.

4.3 Problem Description

The allocation and sizing of DGs in distribution systems is a critical problem because they not only affect the cost of upgrading the system but may also lead to catastrophic technical performance of the system if not properly designed. The problem can be divided into two major subproblems:

- Allocation, type, sizing, and year of installation of the DG while satisfying physical and environmental constraints;
- Meeting technical constraints while minimizing operational costs (in terms of OPF).

The first subproblem introduces a mixed-integer component to the overall problem due to the decisions regarding placement and the integer steps of sizing. For the second subproblem, OPF introduces high nonlinearity because of the power flow equations. The binary decision of upgrading lines also causes an increase in the complexity of the overall problem. This problem, when studied for large systems and over long timespans, is computationally very challenging.

In an SDS, conflicting interests are inevitable due to the various characteristics and roles of players. However, planning a distribution system while considering various interests may resolve some of the potential conflicts. For instance, the absorption of private investment can be accommodated by enabling higher hosting capabilities in the system while benefiting the system operator (e.g., lowering paid incentives to DG owners [39]). Therefore, a description of all costs associated with all system players is presented. In the following sections (Section 4.3.1 to Section 4.3.7), descriptions of each cost venue are presented.

4.3.1 Distributed Generation Capital Cost

The first subproblem seeks to optimally allocate and size the DG unit in a timeframe that provides minimum capital cost. For each year, the amount of capital to be invested is calculated and summed over the study period. It is necessary to mention that any algorithm optimizing this cost must inherently favour larger units because of the $/MVA rate at installation. Moreover, changes mostly involve increases, as the amount to be paid as Net Present Value (NPV) decreases for larger units;

$$\mathrm{NPV}_{\mathrm{DG}}^{\mathrm{Capital}} = \sum_{y \in \mathcal{Y}} \frac{\sum_{i \in \mathcal{I}} \sum_{dg \in \mathcal{DG}} S_{(i,dg,y)} C_{(i,dg,y)}^{Capital}}{(1+r)^{y}}. \tag{4.1}$$

4.3.2 Cost of Fuel and Operation/Maintenance of Operating Distributed Generation Units

An important detail of the aforementioned operational details required for an enhanced planning framework is the operation and maintenance costs associated with every kW operated. This cost can be represented in several forms, such as $/kW or MW. Depending on the options and planning area infrastructure, several fuel-based DG technologies can be considered. It is always beneficial to consider less environmentally harmful technologies, such as gas or biomass. However, the operational costs associated with any fuel-based DG can be calculated based on the price of fuel of each technology at different locations as \$/kW or MW;

$$\text{NPV}_{\text{DG}}^{\text{Fuel}} = \sum_{y\in\mathcal{Y}} \frac{\sum\limits_{i\in\mathcal{I}} \sum\limits_{d\in\mathcal{D}} \sum\limits_{h\in\mathcal{H}} \sum\limits_{dg\in\mathcal{DG}} P_{(i,dg,h,d,y)} \times C^{Fuel}_{(i,dg,h,d,y)}}{(1+r)^y}; \tag{4.2}$$

$$\text{NPV}_{\text{DG}}^{\text{OM}} = \sum_{y\in\mathcal{Y}} \frac{\sum\limits_{i\in\mathcal{I}} \sum\limits_{d\in\mathcal{D}} \sum\limits_{h\in\mathcal{H}} \sum\limits_{dg\in\mathcal{DG}} P_{(i,dg,h,d,y)} \times C^{OM}_{(i,dg,y)}}{(1+r)^y}. \tag{4.3}$$

4.3.3 Cost of Active and Reactive Energy Purchased from Distributed Generation

According to [105], the cost of purchasing active energy from a DG is usually regulated. Therefore, as part of the operational detail, minimizing this cost for the overall benefit of the smart system is needed. It is important to mention that some of the allocated DGs can be used for ancillary services and must be compensated;

$$\text{NPV}_{\text{DG}}^{\text{APower}} = \sum_{y\in\mathcal{Y}} \frac{\sum\limits_{i\in\mathcal{I}} \sum\limits_{d\in\mathcal{D}} \sum\limits_{h\in\mathcal{H}} \sum\limits_{dg\in\mathcal{DG}} P_{(i,dg,h,d,y)} \times C^{APower}_{(i,dg,h,d,y)}}{(1+r)^y}; \tag{4.4}$$

$$\text{NPV}_{\text{DG}}^{\text{RPower}} = \sum_{y\in\mathcal{Y}} \frac{\sum\limits_{i\in\mathcal{I}} \sum\limits_{d\in\mathcal{D}} \sum\limits_{h\in\mathcal{H}} \sum\limits_{dg\in\mathcal{DG}} Q_{(i,dg,h,d,y)} \times C^{RPower}_{(i,dg,h,d,y)}}{(1+r)^y}. \tag{4.5}$$

4.3.4 Cost of Surplus (Unused) Energy from Distributed Generation

Given the description provided for the cost in subsection Section 4.3.3, any curtailed energy must be compensated to benefit all the players. This cost, if minimized, can reduce the waste of energy that can be harvested from distributed sources;

$$\mathrm{NPV}_{\mathrm{Energy}}^{\mathrm{Unused}} = \sum_{y\in\mathcal{Y}} \frac{\sum\limits_{i\in\mathcal{I}} \sum\limits_{d\in\mathcal{D}} \sum\limits_{h\in\mathcal{H}} \sum\limits_{dg\in\mathcal{DG}} P_{(i,dg,h,d,y)}^{Unused} \times C_{(i,dg,h,d,y)}^{Unused}}{(1+r)^y}. \tag{4.6}$$

4.3.5 Cost of Active and Reactive Power Purchased from the Grid

Unlike the cost associated with DG-purchased energy, energy purchased from the grid usually follows variable pricing. Depending on the independent system operator and regulations, different market structures exist. However, these prices usually reflect the market-clearing prices of bulk electrical energy. Reactive power support is essential to the optimal operation of a distribution system. In addition to demand, reactive power support is a common practice for voltage and power quality optimal operation;

$$\mathrm{NPV}_{\mathrm{Grid}}^{\mathrm{APower}} = \sum_{y\in\mathcal{Y}} \frac{\sum\limits_{d\in\mathcal{D}} \sum\limits_{h\in\mathcal{H}} \sum\limits_{i\in\mathcal{G}} P_{g\,(i,h,d,y)} \times C_{(i,h,d,y)}^{APower}}{(1+r)^y}; \tag{4.7}$$

$$\mathrm{NPV}_{\mathrm{Grid}}^{\mathrm{RPower}} = \sum_{y\in\mathcal{Y}} \frac{\sum\limits_{d\in\mathcal{D}} \sum\limits_{h\in\mathcal{H}} \sum\limits_{i\in\mathcal{G}} Q_{g\,(i,h,d,y)} \times C_{(i,h,d,y)}^{RPower}}{(1+r)^y}. \tag{4.8}$$

4.3.6 System Costs of Active and Reactive Power Losses

Minimizing system costs associated with losses (both active and reactive) is directly related to better performance. These costs, which can be relatively small, also directly affect system performance;

$$\mathrm{NPV}^{\mathrm{APower}}_{\mathrm{Loss}} = \sum_{y\in\mathcal{Y}} \frac{\sum\limits_{d\in\mathcal{D}}\sum\limits_{h\in\mathcal{H}}\sum\limits_{i\in\mathcal{I}} P_{(i,h,d,y)(loss)} \times C^{APower}_{(i,h,d,y)\ Loss}}{(1+r)^{y}}; \tag{4.9}$$

$$\mathrm{NPV}^{\mathrm{RPower}}_{\mathrm{Loss}} = \sum_{y\in\mathcal{Y}} \frac{\sum\limits_{d\in\mathcal{D}}\sum\limits_{h\in\mathcal{H}}\sum\limits_{i\in\mathcal{I}} Q_{(i,h,d,y)(loss)} \times C^{RPower}_{(i,h,d,y)\ Loss}}{(1+r)^{y}}. \tag{4.10}$$

4.3.7 Line Upgrade Cost

As part of the overall system cost problem, as seen in a system that considers all players' interests within the system, it is important to minimize the line upgrade cost;

$$\mathrm{NPV}^{\mathrm{Upgrade}}_{\mathrm{Lines}} = \sum_{l\in\mathcal{L}} \frac{C_{\mathrm{UP}_{(l)}}}{(1+r)^{y\left(\mathrm{UP}_{(l)}\right)}}; \tag{4.11}$$

$$C_{\mathrm{UP}_{(l)}} = \mathrm{UP}_{(l)} \times A_{(l)} \times LH_{(l)} \times C^{\mathrm{Unit}}_{(base)}; \tag{4.12}$$

4.4 Problem Formulation

This section mathematically formulates the problem. It begins with the objective, and the constraints to which the formulated objective is subject are subsequently developed.

4.4.1 Objective Function

In trying to satisfy multiple player gains in a situation, social welfare maximization is generally preferred. However, the distribution system is inherently incapable of maximizing revenues since revenues are only derived from selling electric power to end consumers. Therefore, the best practice is to minimize costs, but for a regional planner, the interests of several stakeholders in a distribution system are at the core of any conducted study. For LDCs, minimizing system upgrade requirements that meet technical and environmental constraints are needed. Investors' interests, however, are mainly focused on absorbing their investments while foreseeing acceptable returns. To comply with system requirements and engage investors, additional (i.e., not needed from an LDC viewpoint) upgrades may be required. Therefore, the overall objective function for any regional planner interested in satisfying both parties is described in Equations 4.13 to 4.15. This objective is subject to the constraints formulated in Equations 4.16 to 4.32.

$$Obj.: \quad \min\Big(\mathrm{NPV}^{\mathrm{System}}_{\mathrm{Cost}} + \mathrm{NPV}^{\mathrm{Investor}}_{\mathrm{Cost}}\Big); \tag{4.13}$$

where,

$$\begin{aligned}\mathrm{NPV}^{\mathrm{System}}_{\mathrm{Cost}} = \mathrm{NPV}^{\mathrm{Loss}}_{\mathrm{Energy}} &+ \mathrm{NPV}^{\mathrm{Unused}}_{\mathrm{Energy}} + \mathrm{NPV}^{\mathrm{APower}}_{\mathrm{DG}} \\ + \mathrm{NPV}^{\mathrm{Upgrade}}_{\mathrm{Lines}} &+ \mathrm{NPV}^{\mathrm{APower}}_{\mathrm{Grid}} + \mathrm{NPV}^{\mathrm{RPower}}_{\mathrm{DG}}, \\ + \mathrm{NPV}^{\mathrm{RPower}}_{\mathrm{Grid}} &\end{aligned} \tag{4.14}$$

and,

$$\mathrm{NPV}^{\mathrm{Investor}}_{\mathrm{Cost}} = \mathrm{NPV}^{\mathrm{Capital}}_{\mathrm{DG}} + \mathrm{NPV}^{\mathrm{OM}}_{\mathrm{DG}} + \mathrm{NPV}^{\mathrm{Fuel}}_{\mathrm{DG}}. \tag{4.15}$$

One can notice that to minimize overall costs, some system or investor costs may be increased compared to the case in which one cost interest is the objective. Regional planners must carefully study and make comparisons to base cases to reflect proper cost associations for all parties when considering cost increases. For instance, in $\text{NPV}_{\text{Lines}}^{\text{Upgrade}}$, $\text{NPV}_{\text{DG}}^{\text{Capital}}$ is strongly coupled and can either ease or put pressure on this cost. Therefore, further analysis of the marginal contribution and benefit is required to assign the variation of costs. However, this formulation (i.e., considering both parties' interests) is considered successful only if the total cost compared to the case of a single interest is lowered. A clear distinction can be drawn between the interests of the planners depending on the ownership of the units to be placed. For instance, LDC ownership of a DG unit is allowed in some countries but not all. However, the difference in ownership only directly affects two costs: $\text{NPV}_{\text{DG}}^{\text{APower}}$ and $\text{NPV}_{\text{DG}}^{\text{RPower}}$. If the LDC owns the DG unit, it is counterintuitive to minimize such costs. Therefore, in this case, these two costs can be removed from Equation 4.14. However, it remains part of the overall cost incurred, as seen from the third-party planner viewpoint in other cases. The following Sections 4.4.2 to 4.4.6 describes the set of constraints.

4.4.2 Constraints on Distributed Generation Unit Sizes and Allocation

These constraints are satisfied in the first step of the algorithm (a genetic algorithm). They govern the placement and sizing of DG units:

$$S_{(i,dg,y)} = \varpi_{(i,dg,y)} \times \kappa_{(i,dg,y)} \qquad \forall i \in \mathcal{Q}_{dg}, y \in \mathcal{Y}. \tag{4.16}$$

$$S_{(i,dg,y)} \leq S_{dg}^{max} \qquad \forall i \in \mathcal{Q}_{dg}, y \in \mathcal{Y}. \tag{4.17}$$

$$\varpi_{(i,dg,y)} : \begin{cases} \text{Integer}: & dg \text{ only available in steps} \\ \text{Continuous}: & \text{otherwise} \end{cases}$$

$$\forall\ dg \in \mathcal{DG};$$

$$\sum_{y \in \mathcal{Y}} \sum_{dg \in \mathcal{DG}} S_{(i,dg,y)} \leq S_i^{max}. \tag{4.18}$$

4.4.3 Power Curtailment Constraints

With new technologies emerging and being introduced to power systems, new planning frameworks that take advantage of these technologies must be developed. For instance, wider communication capabilities allow for several components that traditionally could not communicate with each other freely and efficiently. Furthermore, smart inverters allow for greater control of a DG's output power. This additional formulation allows DGs to be allocated, and then power can be curtailed if this allocation minimizes the overall cost of the objective function. The following set of constraints utilizes these capabilities to better plan future SDSs.

$$\begin{aligned} &S^{inj}_{(i,dg,h,d,y)} = \Psi_{(i,dg,h,d,y)} \times AF_{(dg,h,d,y)} \times S_{(i,dg,y)} \\ &\qquad \forall\ i \in \mathcal{I}, dg \in \mathcal{DG}, h \in \mathcal{H}, d \in \mathcal{D}, y \in \mathcal{Y}. \end{aligned} \tag{4.19}$$

$S^{inj}_{(i,dg,h,d,y)}$ where is the injected total power after curtailment, power factor incorporation, and renewable availability; $AF_{(dg,h,d,y)}$ is the availability factor for DG of technology dg in bus i at hour h, day d, and year y;

$$\begin{aligned} &P_{(i,dg,h,d,y)} = PF_{(i,dg,h,d,y)} \times S^{inj}_{(i,dg,h,d,y)} \\ &\qquad \forall\ i \in \mathcal{I}, dg \in \mathcal{DG}, h \in \mathcal{H}, d \in \mathcal{D}, y \in \mathcal{Y}. \end{aligned} \tag{4.20}$$

$$\begin{aligned} &Q_{(i,dg,h,d,y)} = \sin\left[\cos^{-1}\left(PF_{(i,dg,h,d,y)}\right)\right] \times S^{inj}_{(i,dg,h,d,y)} \\ &\qquad \forall\ i \in \mathcal{I}, dg \in \mathcal{DG}, h \in \mathcal{H}, d \in \mathcal{D}, y \in \mathcal{Y}. \end{aligned} \tag{4.21}$$

$$S^{inj}_{(i,dg,h,d,y)} = \sqrt{\left(P_{(i,dg,h,d,y)}\right)^2 + \left(Q_{(i,dg,h,d,y)}\right)^2}$$
$$\forall\ i \in \mathcal{I}, dg \in \mathcal{DG}, h \in \mathcal{H}, d \in \mathcal{D}, y \in \mathcal{Y}. \tag{4.22}$$

4.4.4 Line Power Flow Constraints

Although they add to the complexity of the problem, power flow constraints are essential to any optimal planning or operation study.

$$P_{g(i,h,d,y)} + \sum_{dg \in \mathcal{DG}} P_{(i,dg,h,d,y)} - P_{D(i,h,d,y)} = \sum_{j \in \mathcal{J}} V_{(i,h,d,y)} V_{(j,h,d,y)} Y_{(i,j,y)}$$
$$\cos\left(\theta_{(i,j,y)} + \delta_{(j,h,d,y)} - \delta_{(i,h,d,y)}\right) \forall i, j \in \mathcal{I}\ (\mathcal{I} = \mathcal{J})\ i \neq j, h \in \mathcal{H}, d \in \mathcal{D}, y \in \mathcal{Y}, \tag{4.23}$$

$$P_{g(i,h,d,y)} = \begin{cases} P_{g(i,h,d,y)} : & i \in \mathcal{G} \\ 0 : & i \notin \mathcal{G} \end{cases}$$
$$\forall i \in \mathcal{I}, h \in \mathcal{H}, d \in \mathcal{D}, y \in \mathcal{Y}, \tag{4.24}$$

$$P_g^{Rev} \leq P_{g(i,h,d,y)} \leq P_g^{Max}\ \forall i \in \mathcal{G}, \tag{4.25}$$

$$Q_{g(i,h,d,y)} + \sum_{dg \in \mathcal{DG}} Q_{(i,dg,h,d,y)} - Q_{D(i,h,d,y)} = -\sum_{j \in \mathcal{J}} V_{(i,h,d,y)} V_{(j,h,d,y)} Y_{(i,j,y)}$$
$$\sin\left(\theta_{(i,j,y)} + \delta_{(j,h,d,y)} - \delta_{(i,h,d,y)}\right) \forall i, j \in \mathcal{I}\ (\mathcal{I} = \mathcal{J})\ i \neq j, h \in \mathcal{H}, d \in \mathcal{D}, y \in \mathcal{Y}, \tag{4.26}$$

$$Q_{g_{(i,h,d,y)}} = \begin{cases} Q_{g_{(i,h,d,y)}} : & i \in \mathcal{G} \\ 0 : & i \notin \mathcal{G} \end{cases} \tag{4.27}$$
$$\forall i \in \mathcal{I}, h \in \mathcal{H}, d \in \mathcal{D}, y \in \mathcal{Y},$$

$$Q_g^{Rev} \leq Q_{g_{(i,h,d,y)}} \leq Q_g^{Max} \; \forall i \in \mathcal{G}. \tag{4.28}$$

4.4.5 Voltage Limits Constraints

$$V_{min}^{\text{spec}} \leq V_{(i,h,d,y)} \leq V_{max}^{\text{spec}} \tag{4.29}$$
$$\forall i \in \mathcal{I}, h \in \mathcal{H}, d \in \mathcal{D}, y \in \mathcal{Y}.$$

4.4.6 Line Upgrades and Current Constraints

$$I_{(l,h,d,y)} \leq I_{(l,y)_{max}} \tag{4.30}$$
$$\forall l \in \mathcal{L}, h \in \mathcal{H}, d \in \mathcal{D}, y \in \mathcal{Y}.$$

$$\text{UP}_{(l)} = \begin{cases} 1 : & I_{(l,h,d,y)} \geq I_{(l,y)_{max}} \\ 0 : & I_{(l,h,d,y)} < I_{(l,y)_{max}} \end{cases} \tag{4.31}$$
$$\forall l \in \mathcal{L}, h \in \mathcal{H}, d \in \mathcal{D}, y \in \mathcal{Y}.$$

$$I_{(l,y)_{max}} = \begin{cases} I_{(l)}^{CAP} : & \forall \; y < y_{\left(\text{UP}_{(l)}\right)} \\ A_{(l)} \times I_{(l)}^{CAP} : & \forall \; y \geq y_{\left(\text{UP}_{(l)}\right)} \end{cases} \tag{4.32}$$
$$\forall l \in \mathcal{L}, y \in \mathcal{Y}.$$

4.5 Proposed Solution Algorithm

Most population-based techniques do not guarantee global optimality. However, it is very common to find numerous variations of the heuristic means used to solve long-term planning problems [106–109]. Figure 4.1 describes the flowchart of the proposed algorithm. It solves the first subproblem by means of a genetic algorithm. A typical gene would include the type, size, location, and year of placement of each DG. This generation is then passed to the OPF engine, which partially solves the second subproblem and stores the operational costs. This sequence is subject to several technical constraints, which are described in Section 4.4 and repeated until the exit criterion is met.

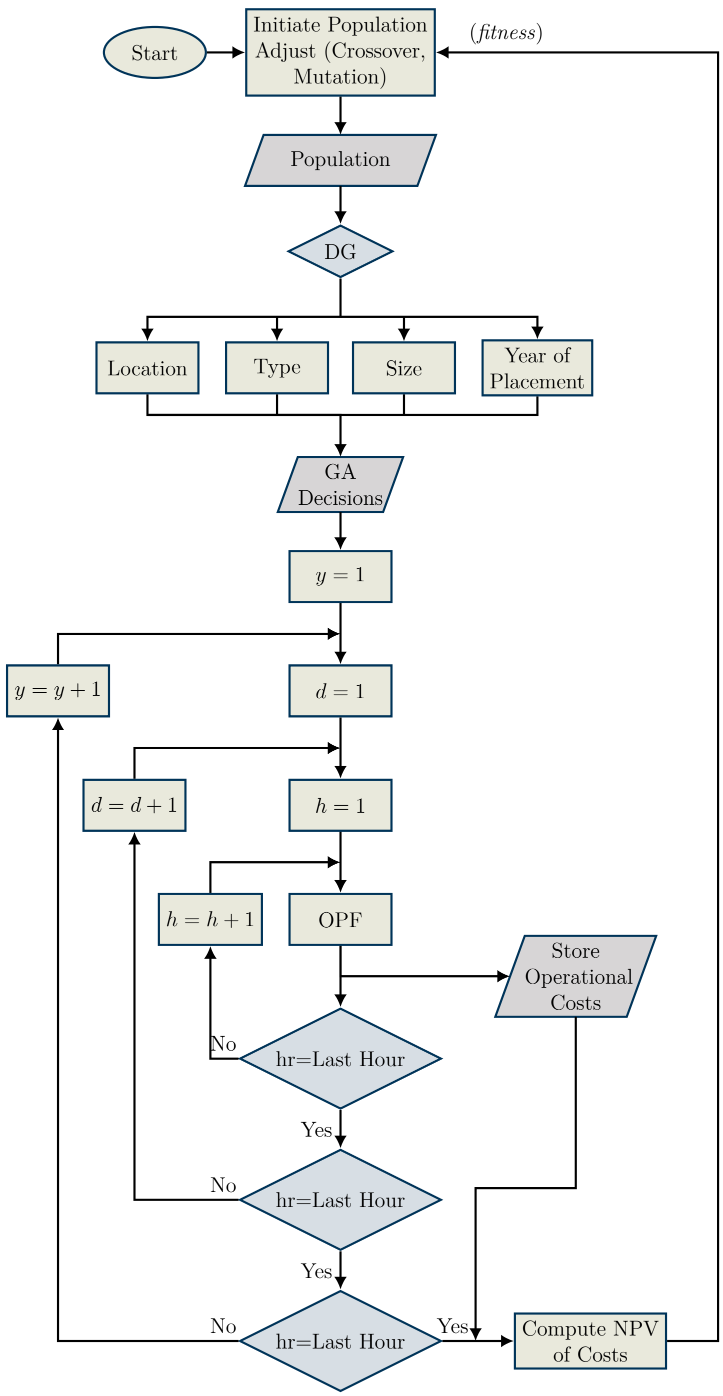

Figure 4.1: Proposed Algorithm Flowchart

4.6 Case Study

The power level's daily variation is taken for both non-dispatchable generation and loads. Moreover, the loads also differ in type: residential, commercial, and industrial. This work also considers eight days to reflect the season and day type (weekday or weekend). For each season, two days reflecting a weekday and a weekend are adapted from [110]. This representation allows the problem to be more dynamic. Therefore, the costs described in Section 4.3 are multiplied by $\frac{365}{8}$ to reflect the total days in a year. Figure 4.3 showcases an example of these days. Results are compared using a planning methodology without considering the daily optimal operations (i.e., Equations 4.19 to 4.22). Both are constrained according to the most recent regulations and technical parameters. Moreover, the results clearly indicate the superiority of the proposed methodology: lower costs, lower average voltage deviations, and higher DG hosting capacity. This case study is performed on a typical test system found in the literature [96]. The renewable data used are adapted from [111] and shown in Figure 4.4. The test system, shown in Figure 4.2, is composed of residential, commercial, and industrial loads with different loading levels. These levels are illustrated in Figure 4.3.

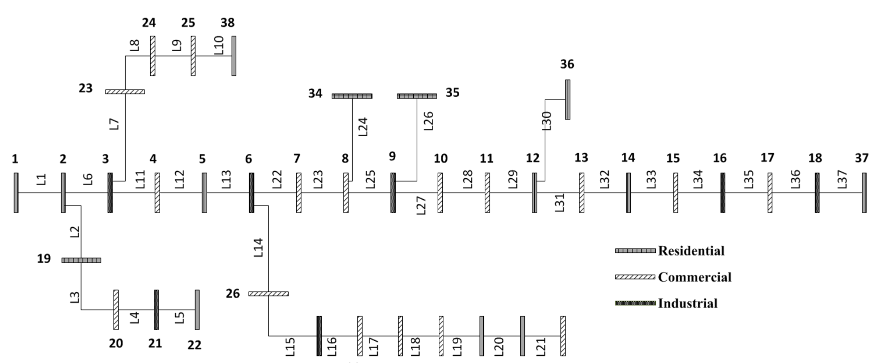

Figure 4.2: The 38-bus Test System Used in the Allocation of the DG Case Study

The objective to be minimized is shown in Equation 4.13. The costs are adapted from [97], and the energy prices are based on the average hourly prices in Ontario over the past four years and retrieved from [98]. For reactive power, average compensation for reactive power support paid by [112] in 2014 is used, which is similar to the typical ranges reported in [113].

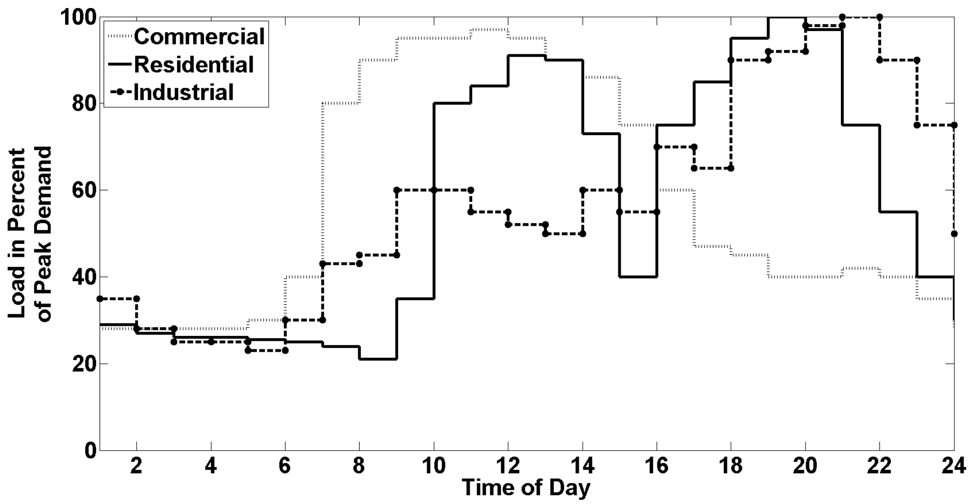

Figure 4.3: A Discretized Day Pattern of Hourly Loading Variation for Three Customer Types Over a 24-hour Span From 6 AM to 6 AM

The study is performed for a period of 20 years with a load increase of 10% per year. Three types of DGs are considered: wind, solar, and gas turbine. Hourly patterns of wind and solar power are illustrated in Figure 4.4.

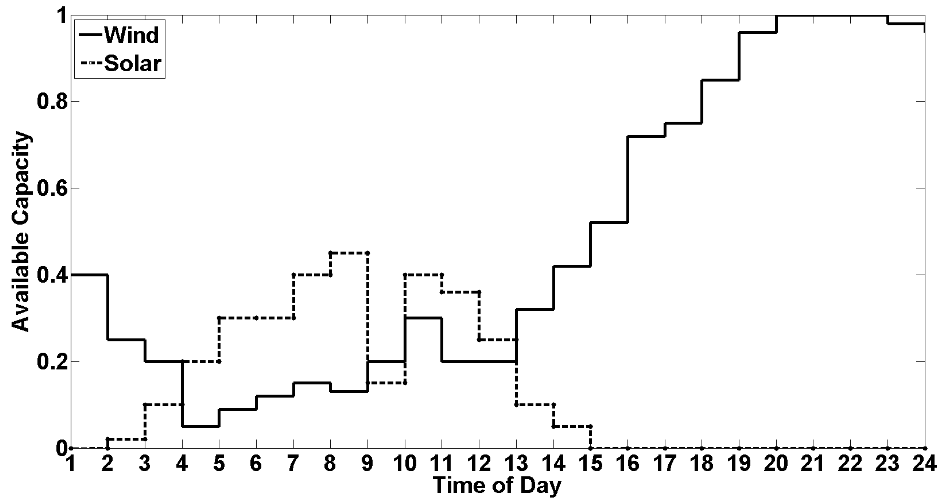

Figure 4.4: Discretized Hourly Available Capacity of Renewable Power Over a 24-hour Span From 6 AM to 6 AM

However, in this case study, the cost of purchased energy from a DG is not considered. The reason for excluding this cost is to mimic the behavior of utility-owned DG where the energy is virtually free. Nevertheless, the cost of curtailed (unused) energy is minimized by associating a cost with it. The cost used in this work for curtailed power (depending on the size and technology of the DG) is adapted from [105] (i.e., FIT and microFIT programs). Comparisons are made with base cases: a system with no DG allocation (line upgrades only) (i.e., Base 1) and a system with allocation of DG considering both parties' interests and neglecting power curtailment (i.e., Base 2). Specifically, Base 1 is the basic case that does not consider DGs at all, while Base 2 utilizes the formulated algorithm with the negation of one operational detail. A label 'Purposed' is given to the methodology that combines Base 2 with the power curtailment of DG units. It is assumed in this case study that fuel costs are time and location independent, and candidate buses are limited in the case of wind turbines (due to the physical and environmental constraints) and relaxed for the other two technologies considered (solar- and gas-based).

4.7 Results and Discussion

It is clear from Tables 4.3 and 4.4 that the proposed algorithm is superior to both Base 1 and Base 2 algorithms in total incurred costs. The comparison is conducted for different cases: Base 2 is compared with Base 1, and the proposed algorithm is compared to Base 1. It is noticeable that the proposed algorithm, as expected, incurs more capital costs overall for allocated DGs because more generation is used. It is important to mention that the total cost of active power loss is slightly higher (7.1%) in the proposed algorithm than in Base 2 due to time variation and the price of the incurred losses, yet the total active losses in the system are 17% lower in the proposed scheme. The lower active losses yield better voltage profiles as a by-product. In the case of Base 2, the average voltage deviation is lowered by 64.6% compared to Base 1. This improvement is very significant, and improving it without leading to additional costs is achieved by the proposed algorithm. An additional 71.5% reduction in the average voltage deviation from Base 2 is achieved by the proposed methodology. This enhancement is an almost 90% improvement compared to Base 1. In Figures 4.9 and 4.10, the frequency of occurrence of voltage magnitude over the study is illustrated in histograms of all three cases in both single and multiple ownership cases. Moreover, Figure 4.5 showcases the minimum voltage magnitude occurring in each case. It is clear, due to lower power losses, that the proposed algorithm yields better performance as a by-product. The substation voltage in this study was set to 1.05 pu, yielding an average voltage magnitude of 1.01389, 1.03115, and 1.04118 for Base 1, Base 2, and the proposed algorithms, respectively. Figure 4.6 summarizes the average voltage of each bus over the planning period in all three cases.

Tables 4.1 and 4.2 summarize the placement, size, and year of installation for all DG technologies used in the case study. A continuous size is used for the solar DG, and the discrete sizes are used for gas-based and wind DGs. Base 2 managed to allocate a total of 6.0403 MVA of DG capacity in the system, whereas the allocated capacity increased by 65.7% to a total of 10.0062 MVA in the proposed system.

Table 4.1: Technology, Size, Location, and Year of Installation of Allocated DGs Using the Proposed Algorithm

i/y	3	5	8	13	19	20	$\sum_{dg \in \mathcal{DG}}$
5						0.1	0.1
7				0.1			0.1
8			0.2				0.2
10		1.2348					1.2348
12			0.9				0.9
14						0.8123	0.8123
27						1.5	1.5
29			1.2421				1.2421
30					1.3	0.8	2.1
32						1.0842	1.0842
36	0.1532						0.1532
38						0.5796	0.5796
$\sum_{i \in \mathcal{I}}$	0.1532	1.2348	2.3421	0.1	1.3	4.8761	10.0062

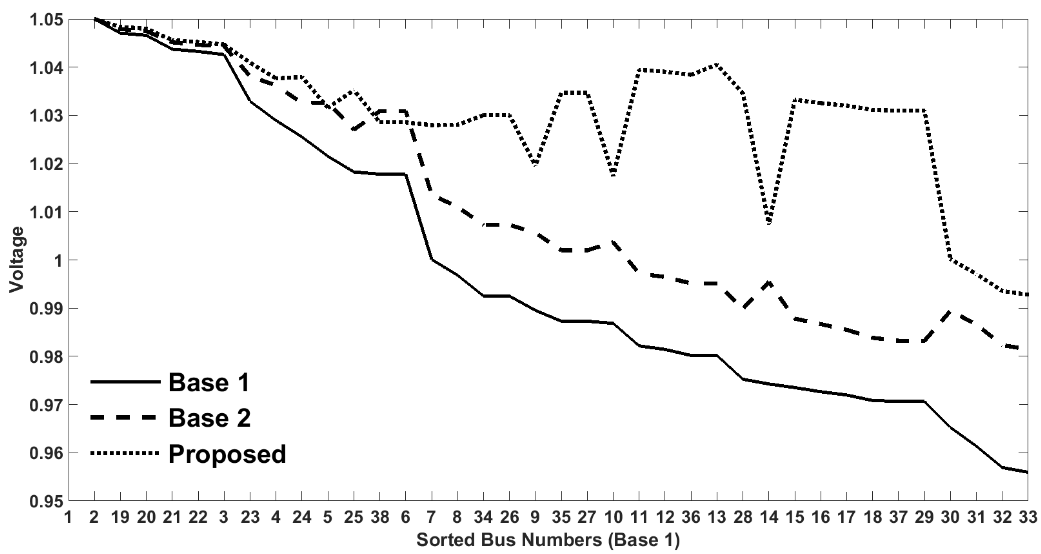

Figure 4.5: System Voltage Profile Containing the Minimum Voltage Occurrence for Each Case Over the Planning Period in the Single Ownership Case

Table 4.2: Technology, Size, Location, and Year of Installation of Allocated DG Using the Methodology of Base 2

i/y	4	5	6	8	9	12	16	17	18	19	20	$\sum_{dg\in\mathcal{DG}}$
4										0.2257		0.2257
12							0.3008					0.3008
13		0.1638										0.1638
14										0.2175	0.1	0.3175
15								0.1401				0.1401
16					0.5							0.5000
17			0.3125									0.3125
18	0.1916											0.1916
22				0.1								0.1000
23							0.6			0.1963		0.7963
27	1.4681											1.4681
29						0.3162						0.3162
32										0.2		0.2000
33								0.1				0.1000
35									0.2077			0.2077
38					0.7							0.7000
$\sum_{i\in\mathcal{I}}$	1.6597	0.1638	0.3125	0.1	1.2	0.3162	0.9008	0.2401	0.2077	0.8395	0.1	6.0403

Table 4.3: Results of the Case Study Comparing Two Base Cases with the Proposed Algorithm and Assuming DG Single Ownership

	Base 1	Base 2	B2 : B1	Proposed	Pr : B1
Total Cost	$369,969,184	$282,885,715	-23.5%	$258,507,940	-30.13%
Capital Cost of Gas DG	$0	$15,040,329	100.0%	$20,698,754	137.6%
Capital Cost of Solar DG	$0	$42,606,714	100.0%	$46,702,934	109.6%
Capital Cost of Wind DG	$0	$6,763,230	100.0%	$4,828,843	71.4%
Cost of Gas	$0	$1,732,701	100.0%	$1,958,564	113.0%
Cost of Surplus Power (DG)	$0	$8,609,528	100.0%	$8,252,252	95.9%
Cost of Operation and Maintenance	$0	$204,745	100.0%	$267,506	130.7%
Cost of Active Power (grid)	$281,706,124	$135,256,036	-52.0%	$108,116,957	-61.62%
Cost of Active Loss	$311,192	$122,402	-60.7%	$131,090	-57.88%
Cost of Line Upgrades	$1,611,523	$5,216,187	223.7%	$1,861,005	15.48%
Cost of Reactive Power (grid)	$86,252,801	$67,290,458	-22.0%	$65,654,565	-23.88%
Cost of Reactive Loss	$87,544	$43,386	-50.4%	$35,470	-59.48%
Total DG Capacity	0.0000	6.0403	100.0%	10.0062	165.7%
Average Voltage Deviation	0.187424697	0.066296069	-64.6%	0.018911835	-89.91%
Total Active Losses	3.2590	1.5398	-52.8%	1.2774	-60.81%
Total Reactive Losses	1.9999	0.9834	-50.8%	0.8024	-59.88%

Table 4.4: Results of the Case Study Comparing Two Base Cases with the Proposed Algorithm with DG Multiple Ownership

	Base 1	Base 2	B2 : B1	Proposed	Pr : B1
Total Cost	$369,969,184	$321,194,039	-13.2%	$310,510,006	-16.1%
Capital Cost of Gas DG	$0	$15,040,329	100.0%	$20,698,754	137.62%
Capital Cost of Solar DG	$0	$42,606,714	100.0%	$46,702,934	109.61%
Capital Cost of Wind DG	$0	$6,763,230	100.0%	$4,828,843	71.40%
Cost of Gas	$0	$1,507,778	100.0%	$924,848	61.34%
Cost of Operation and Maintenance	$0	$174,671	100.0%	$172,122	98.54%
Cost of Active Power (grid)	$281,706,124	$154,218,134	-45.3%	$139,889,484	-50.3%
Cost of Active Power (DG)	$0	$3,189,287	100.0%	$3,561,945	111.68%
Cost of Surplus Power (DG)	$0	$21,566,844	100.0%	$20,148,584	93.42%
Cost of Active Loss	$311,192	$145,532	-53.2%	$141,120	-54.7%
Cost of Line Upgrades	$1,611,523	$2,238,657	38.9%	$2,007,183	24.6%
Cost of Reactive Power (grid)	$86,252,801	$73,393,144	-14.9%	$71,030,658	-17.6%
Cost of Reactive Power (DG)	$0	$300,294	100.0%	$358,286	119.3%
Cost of Reactive Loss	$87,544	$49,425	-43.5%	$45,247	-48.3%
Total DG Capacity MVA	0.0000	6.0403	100.0%	10.0062	165.7%
Average Voltage Deviation	0.187424697	0.005298509	-97.2%	0.008777368	-95.3%
Total Active Losses MW	3.2590	1.7817	-45.3%	1.6413	-49.6%
Total Reactive Losses MVAR	1.9999	1.1217	-43.9%	1.0250	-48.7%

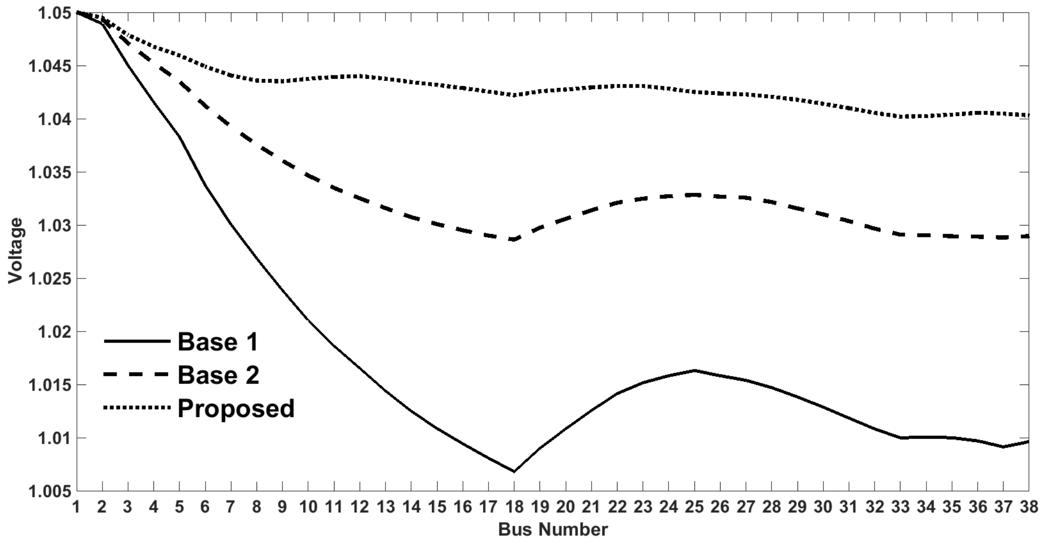

Figure 4.6: Average Voltage for Every Bus Over the Planning Period for all Three Cases in the Single Ownership Case

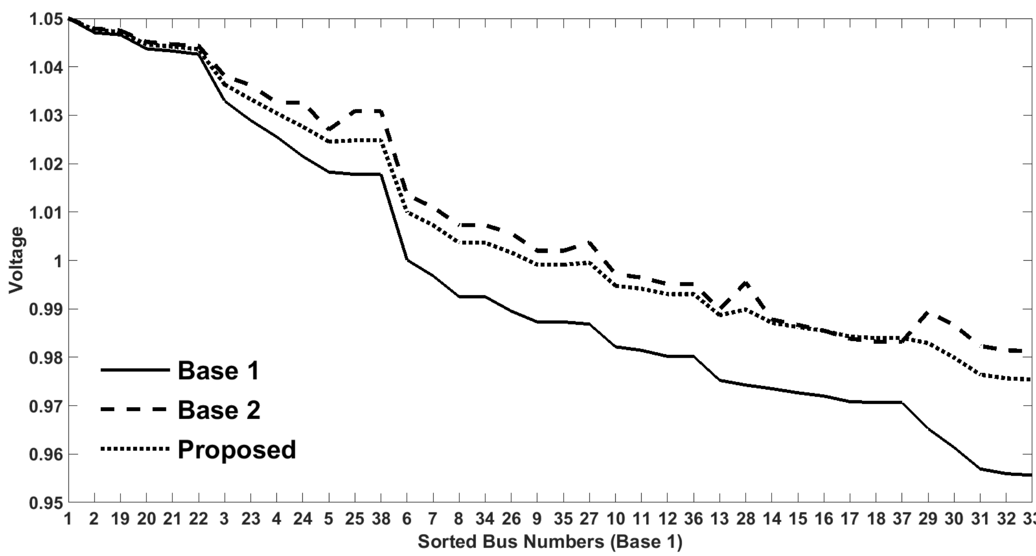

Figure 4.7: System Voltage Profile Containing the Minimum Voltage Occurrence for Each Case Over the Planning Period in the Multiple Ownership Case

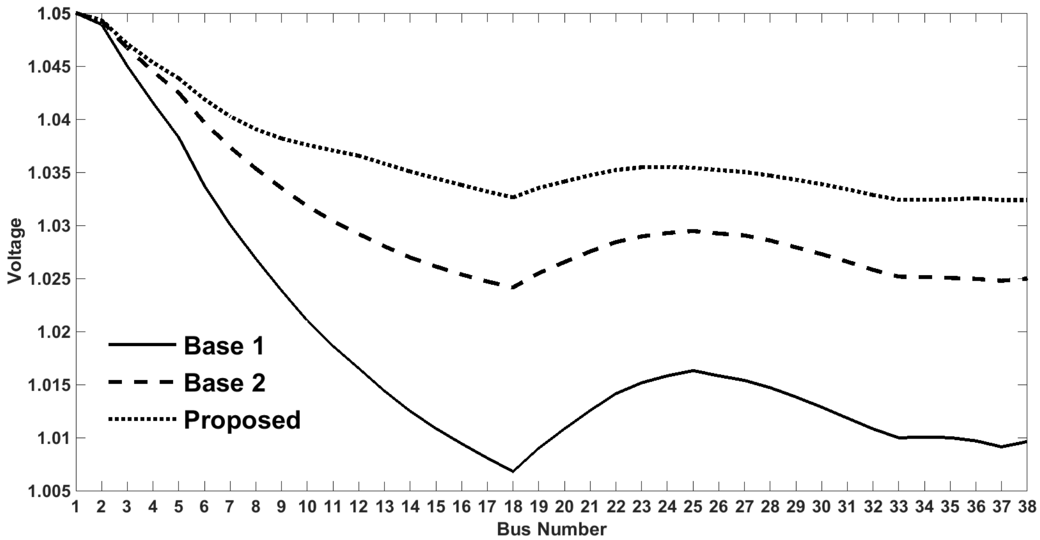

Figure 4.8: Average Voltage for Every Bus Over the Planning Period for All Three Cases in the Multiple Ownership Case

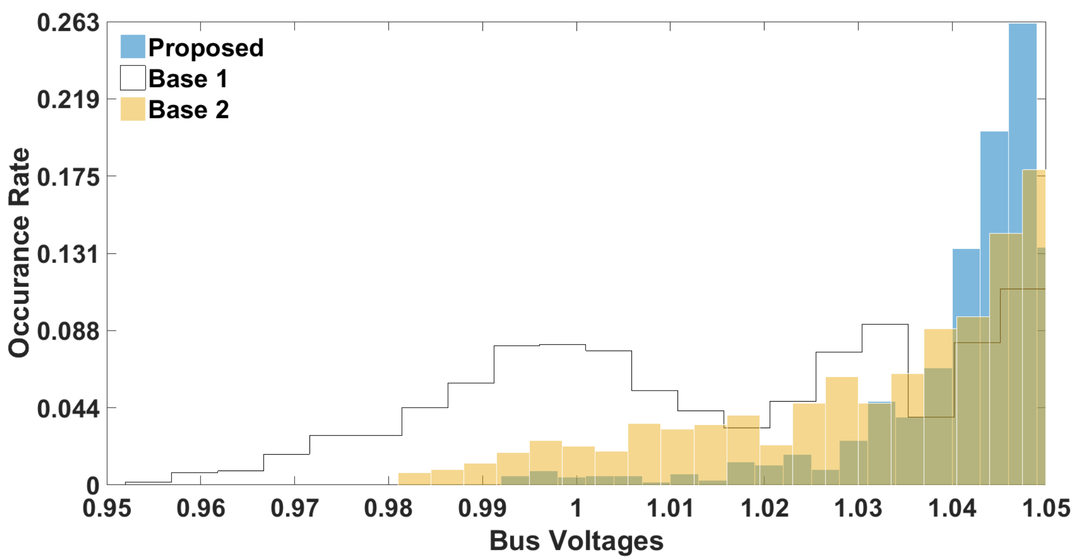

Figure 4.9: Voltage Magnitudes Occurrences Over the Planning Period for All Three Cases in Single Ownership

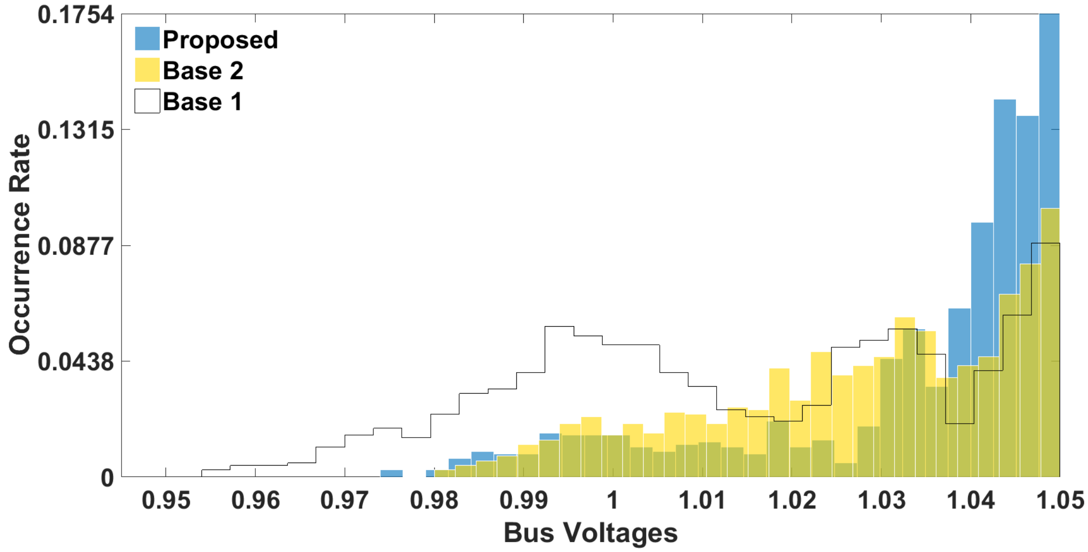

Figure 4.10: Voltage Magnitudes Occurrences Over the Planning Period for All Three Cases in Multiple Ownership

4.8 Chapter Summary

In this chapter, a long-term allocation planning framework for higher private investment absorption, hourly optimal operation, cost effective design, employment of different technologies, and feasible computational time (from a planning perspective), as well as the consideration of active network applications (i.e., an adaptive DG power factor and controllable DG output power) has been developed. This framework provides the backbone for future SDS asset and product integration. With overall objectives in mind for all stakeholders's interests, the developed framework allows for further enhancements and refinements to achieve higher accuracy and economic benefits. As a starting point, this work falls short of an absolute comprehensive adaptation of all possible practical constraints and representations. This drawback can be addressed in future studies. For instance, an optimal communication infrastructure between the newly formed (because of the generation units allocated) dynamic or static microgrids within the system is proposed for further study.

This communication infrastructure can allow for fair power sharing among prosumers or microgrids and better facilitates the cost/benefit allocation of each party within the planning problem. As suggested in this chapter, increasing the penetration level of DGs may, and probably will, increase costs on system operators (e.g., line reinforcements). These challenges and others will be tackled in future studies.

Chapter 5

Consensus-Based Algorithm for Cooperative Operation among Prosumers and the Realization of Market Clearance Alternatives[§]

"Nothing is more obstinate than a fashionable consensus."

— Margaret Thatcher

This chapter begins with an introduction in Section 5.1. It introduces the proposed cooperative algorithm and its realization in hybrid AC/DC systems. Section 5.2 formulate and verify the proposed cooperative algorithm. The realization of the proposed application in the AC/DC systems is showcased in Section 5.3. The chapter is then concluded with a summary in Section 5.4.

[§]Parts of this chapter are published in [114].

5.1 Introduction

For several important reasons, such as the move toward Active Network Management (ANM), electric systems and all of their players are moving toward smarter systems (i.e., smart grids). The concept of the smart grid has been the central interest of many researchers in several fields as well as in practice; power engineers are no exception. They are at the core of this interest, as they are responsible for implementing and integrating the new technologies posed in the literature. The understanding of the future grid is based on several stakeholders' changing roles or perhaps even new ones coming into existence. For instance, in the future, customers of a grid are seen as playing different roles as they change from a passive nature to a more active nature. Prosumers increase the complexity from both a technical and a market perspective [7]. In [9], the authors also suggest that the prosumer can be a collective or group of single physical entities (i.e., microgrids). Thus, their role can change from being a consumer to a producer within a short period of time, depending on their self-interests or preferences.

The role of customers/consumers has changed dramatically with the advent of SDSs. For instance, feed-in tariff (FIT) and micro feed-in tariff (microFIT) programs have engaged prosumers in the decision-making process. The ability to be self-sufficient and produce surplus energy is technically viable, although it is economically arguable. This new player (i.e., the prosumer) will inevitably be highly interested in a new framework that allows better integration and economic feasibility.

The main pillar of a smart-grid setup is the evolution from a vertically integrated, partially-automated and producer-controlled electric power network to a decentralized one that enables interactions among customers, network operators, and power producers. Accordingly, the existing and emerging stakeholders will change their roles. Furthermore, the smart networks are characterized by a paradigm shift from exclusively AC to DC and hybrid AC/DC networks.

The proposed algorithm utilizes the average consensus theory to stimulate prosumers to exchange and thus update their information synchronously. The simplicity of the new algorithm and the minimal associated implementation and communication requirements constitute essential positive features that will facilitate practical application.

In this work, the economic model of the producers/consumers (prosumers) in hybrid networks is developed based on a mathematical formulation of their interactions along with the network's technical aspects. The results demonstrate the effectiveness and validity of the proposed scheme in realizing possible buying/selling alternatives among the prosumers.

As systems develop and transform into a new futuristic paradigm, so does their technical and economic modeling. New emerging players and players that will change their roles in the new infrastructure complicate the situation. Authors in [90] concluded that even systems that are all AC in nature and connected to the main grid will suffer from contradictory goals in the new smart infrastructure, let alone the technical difficulties embedded in the successful operation of hybrid systems. Thus, a new economic model that can represent the stakeholders' interests in the new paradigm is needed. In this work, the economic model of prosumers is introduced. Accordingly, the gain scheduling of the DG units as well as the interlinking converter is addressed to realize a market clearing alternative in AC/DC hybrid microgrids.

5.1.1 Prosumer Definition

The expected increased numbers of customers opting to become more resilient and reliable service poses several operational and planning challenges. There are two main distinctive features of prosumers: several power level capabilities and preferences that don't necessarily depend on economic factors. Based on these features and the prosumers' interactions, the following definition is proposed.

Definition 1 *Let* $\mathcal{P} = \{p_1, p_2, \ldots, p_n\}$ *denote the set of all prosumers, where* $n \geq 2$*. For* $p_i \in \mathcal{P}$*, let* $\mathcal{Z}_{p_i} = \left\{z_1, z_2, \ldots, z_{m_{p_i}}\right\}$ *denote the set of* p_i*'s power levels, where* m_{p_i} *is the total* *number of power levels p_i has, and for every $p_i \in \mathcal{P}$, $m_{p_i} \geq 3$. Then, the Cartesian Products of all prosumers' power levels mathematically define the prosumers' market interaction, denoted as $\hat{\mathcal{Z}}$, as shown in Equation* 5.1.

$$\hat{\mathcal{Z}} = \bigtimes_{i=1}^{n} \mathcal{Z}_{p_i} \tag{5.1}$$

5.1.2 Prosumer Preferences

This section introduces the modeling of prosumers' interests. The method used is based on the attitude/preference matrix proposed in [115,116]. In Equation 5.2 and Figure 5.1, each prosumer chooses comfort/cost values, μ_k and ϕ_k, based on its own preference. Given its internal demand, generation, and associated costs (i.e., D_k, G_k, ρ_k, and υ_k), the preference value E_k is determined.

$$E_k = D_k \left[1 - \rho_k \mu_k \left(1 - \phi_k\right)\right] - G_k \left[1 - \upsilon_k \mu_k \left(1 - \phi_k\right)\right] \tag{5.2}$$

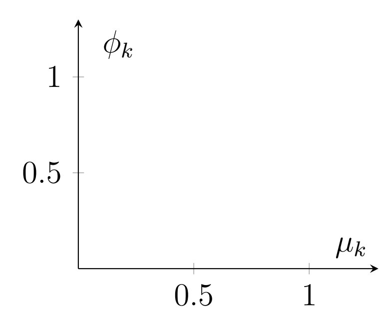

Figure 5.1: Attitude/Preference Matrix

5.2 Cooperative Decision Making for Prosumers

An average consensus algorithm is used for the proposed cooperative approach.Prosumers share the average values they have estimated for specific variables. It is based on a distributed control approach where prosumers are considered control agents that exchange information iteratively. A weighted graph among prosumers is modeled for exchanging data as follows:

$\mathcal{G} = \{\mathcal{V}, \mathcal{E}, \mathcal{A}\}$, in which $\mathcal{V} = \{1, 2, \ldots, n\}$ is a set of vertices (i.e. prosumers), where $\mathcal{G}$ is a set of grid connected busses ; $\mathcal{A} := \left[\mathcal{A}_i^j\right]$ is the adjacency matrix with $\mathcal{A}_i^j \geq 0$ representing a weight of edge (i, j); and $\mathcal{E} \in \mathcal{V} \times \mathcal{V}/diag(\mathcal{V})$ is a set of non-zero edges. In other words, $(i, j) \in \mathcal{E}$ if the weight $\mathcal{A}_i^j > 0$.

The neighbouring nodes of node i are ones that can send and receive information to or from node i, denoted $\mathcal{N}_i = \{j \in \mathcal{V} : (i, j) \in \mathcal{E}, \text{and} j \neq i\}$. Assumptions related to communication in the graph are derived from [117, 118].

1. A path that connects any two vertices Always exists. j,$i \in \mathcal{V}$, $j \neq i$.
2. A balanced communication defined by a doubly stochastic adjacency matrix as described in Equation 5.3.

$$\mathcal{A}_i^j = \begin{cases} \dfrac{1}{(\max(|\mathcal{N}_i|, |\mathcal{N}_j|) + 1)} & \text{if} \quad j \in \mathcal{N}_i \\ 1 - \sum\limits_{t \in \mathcal{N}_i} \mathcal{A}_i^j & \text{if} \quad j = i \\ 0 & \text{otherwise} \quad . \end{cases} \tag{5.3}$$

The primary objective of the average consensus theory is sharing an average value of a specific variable ξ among agents. For instance, ξ can represent the average preference mismatch. Each agent (i.e., prosumer) would have an initial value $\xi[0]$ that represents its own average estimation at the beginning of the data exchange. For an agent to update its estimation of the average value, it must exchange information about its estimated average value with its neighbours as shown in Equation 5.4.

$$\xi_i[1] = \sum_{j \in \{\mathcal{N}_i\} \cup \{i\}} \mathcal{A}_i^j \xi_j[0] \tag{5.4}$$

The vector $\overline{\xi}[k] = \left[\xi_1[k]\xi_2[k] \dots \xi_(N_g)[k]\right]^T$ collects the average values estimated by all of the prosumers. Equation 5.5 generalizes the process of any iteration $k+1$. Then, the relationship between $\overline{\xi}[0]$ and $\overline{\xi}[m]$ is formulated in Equation 5.6.

$$\overline{\xi}[k+1] = \mathcal{A}\overline{\xi}[k] \tag{5.5}$$

$$\overline{\xi}[m] = \mathcal{A}^m\overline{\xi}[0] \tag{5.6}$$

Since $\mathcal{A}$ is an irreducible and doubly stochastic matrix, $\lim_{(m\to\infty)} \mathcal{A}^m$ converges to a rank-one deterministic matrix. This means $|\sigma_2(\lim_{(m\to\infty)} \mathcal{A}^m)| \to 0$, where σ_2 is the second largest eigenvalue of a matrix. $\mathcal{A}^m$ also converges at a geometric rate subject to $\sigma_2(\mathcal{A})$ [119].

The more connected the graph, the smaller the $\sigma_2(\mathcal{A})$ value and the faster the convergence [120]. Figure 5.2 showcases arbitrary chosen modifications to a graph, which resulted in reduced average iterations. However, the original connectivity is used in the case study presented in Section 5.2.1. Figures 5.3 and 5.4 illustrate examples of a positive and a negative incremental cost/benefit. However, these examples involve unstable scenarios where market clearing alternatives are not possible (i.e. there is no Nash or Sequential stability in a market clearing situation).

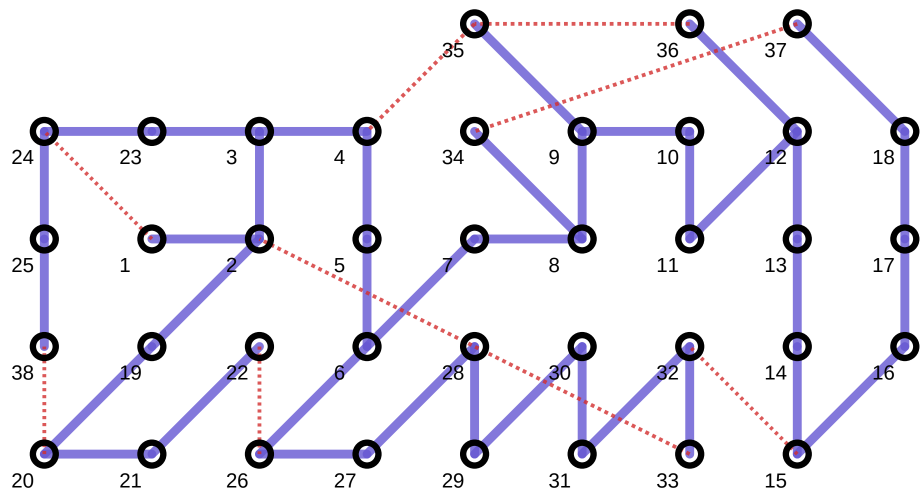

Figure 5.2: Modified 38 Prosumers Graph

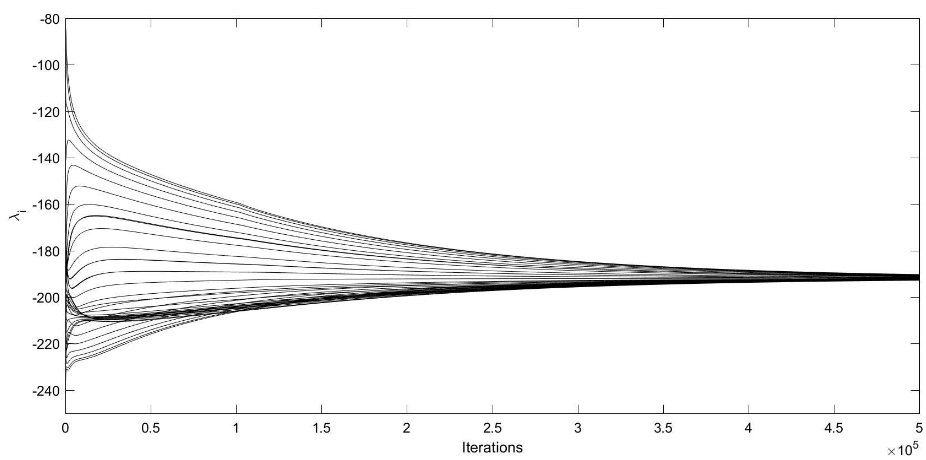

Figure 5.3: Negative Incremental Cost/Benefit

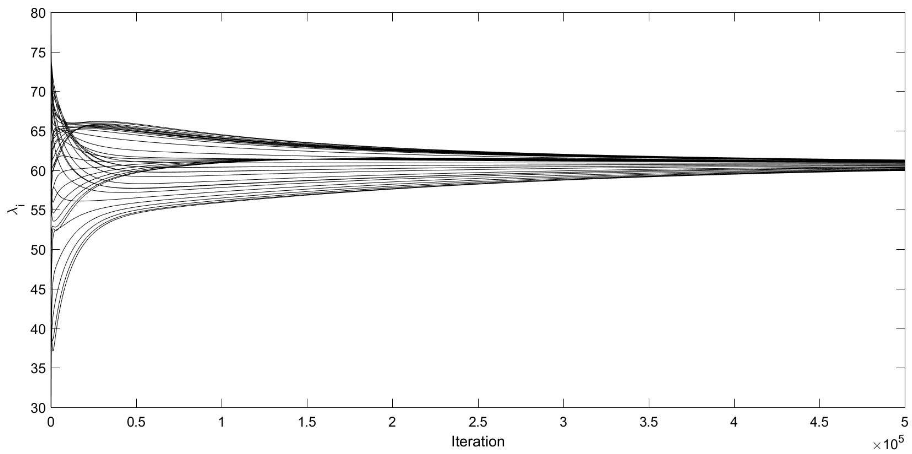

Figure 5.4: Positive Incremental Cost/Benefit

An economic dispatch problem can be formulated for each prosumer as in Equation 5.7 and subject to Equations 5.8 to 5.11.

$$min \sum_{(i \in G)} OC_i(p_i) \tag{5.7}$$

where each prosumer minimizes their own OC_i by adjusting their power level p_i;

$$\sum_{(i \in G)} p_i = \sum_{(i \in D)} p_d + P_{loss} \tag{5.8}$$

it is important to mention that the implementation of droop control, as described in Section 5.3, implies that losses are always shared and satisfied among the community;

$$p_i^{min} \leq p_i \leq p_i^{max} \quad \forall i \in G \tag{5.9}$$

upper and lower boundaries are only know for each prosumer and satisfied during the update algorithm described in Equation 5.12; proceeding from that, incremental cost/benefit for each prosumer can be rewritten as follows;

$$OC_i(p_i) = a_i + b_i p_i + c_i p_i^2 \tag{5.10}$$

$$\lambda_i = b_i + 2c_i p_i \tag{5.11}$$

then, the update algorithm becomes ready and can be summarized in Equation 5.12.

$$\begin{aligned}
&\lambda_i(k+1) = \mathcal{A}\lambda_i(k) + \epsilon y(k) \\
&p_i^{pref}(k+1) = \mathcal{A}p_i^{pref}(k) + \varepsilon y(k) \\
&p_i(k+1) = \min\left(\frac{\lambda_i(k+1) - b_i}{2 * a_i}, p_i^{max}\right) \\
&p_i(k+1) = \max\left(p_i, p_i^{min}\right) \\
&y(k+1) = \mathcal{A}\mathrm{y}(k) - \left(p_i(k+1) - p_i^{pref}(k+1)\right)
\end{aligned} \tag{5.12}$$

where p_i^{pref} is initially estimated using Equation 5.2.

Proceeding from the previous formulation and update algorithm, λ_i is given by Equation 5.13, where λ_i^* becomes the individual optimal incremental cost for each prosumer.

$$\begin{cases}
\lambda_i = \lambda_i^* & \text{if} \quad p_i^{min} < p_i < p_i^{max} \\
\lambda_i \geq \lambda_i^* & \text{if} \quad p_i = p_i^{min} \\
\lambda_i \leq \lambda_i^* & \text{if} \quad p_i = p_i^{max}
\end{cases} \tag{5.13}$$

5.2.1 Case Study

This section describes a test of the proposed algorithm on a 38-prosumer test system. Figure 5.5 presents the line diagram of the test system. Assuming that communication between prosumers is established in an existing physical connection, the system-directed graph is shown in Figure 5.6. Equation 5.14 presents the structure of the symmetrical adjacency matrix. Data used for maximum, minimum, and costs are based on uniformly-distributed random variables.

$$\mathcal{A}_i^j = \begin{bmatrix} a_{1,1} & \dots & a_{1,38} \\ \vdots & \ddots & \vdots \\ a_{38,1} & \dots & a_{38,38} \end{bmatrix} \tag{5.14}$$

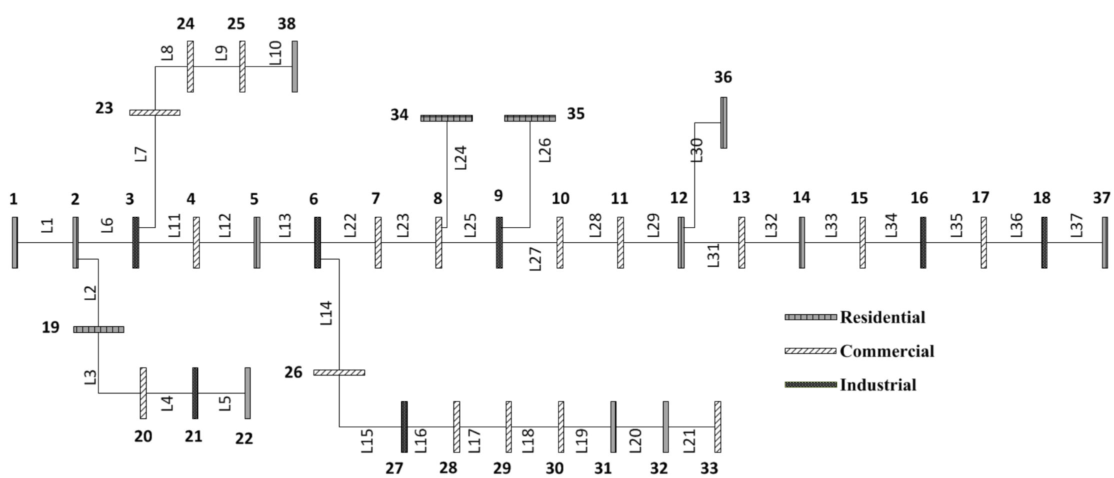

Figure 5.5: Test System of 38 Prosumers

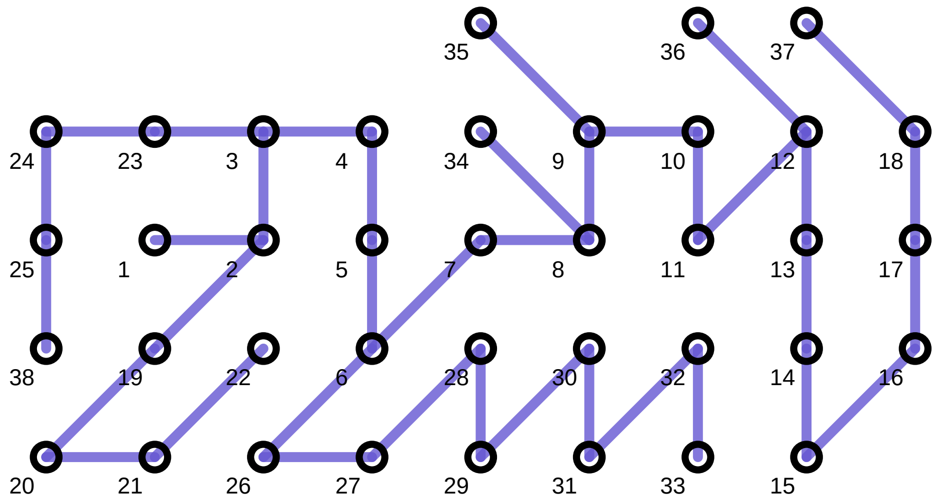

Figure 5.6: 38 Prosumers Graph

Figures 5.7 to 5.10 showcase four different preference scenarios for each of the 38 prosumers. It is important to mention that although iteration number differ in each scenario, mismatch zero is reached on average in less than 3000 iterations. Depending on each agent's hardware, iteration time ranges from 4 ms to approximately 120 ms. These numbers lead to communication being deployed for minute-based dispatching. The top figure in each scenario shows the individual power levels, while the middle figures show the power mismatch in the community, and the bottom figures show the different capabilities and preferences of each prosumer. In each scenario, the algorithm attempting to match power levels to the preference. However, this is not always 100% successful as can be seen in the different scenarios. While each prosumer starts with its preference in the beginning of the iterations, the cooperative consensus derives each one to global zero power mismatch.

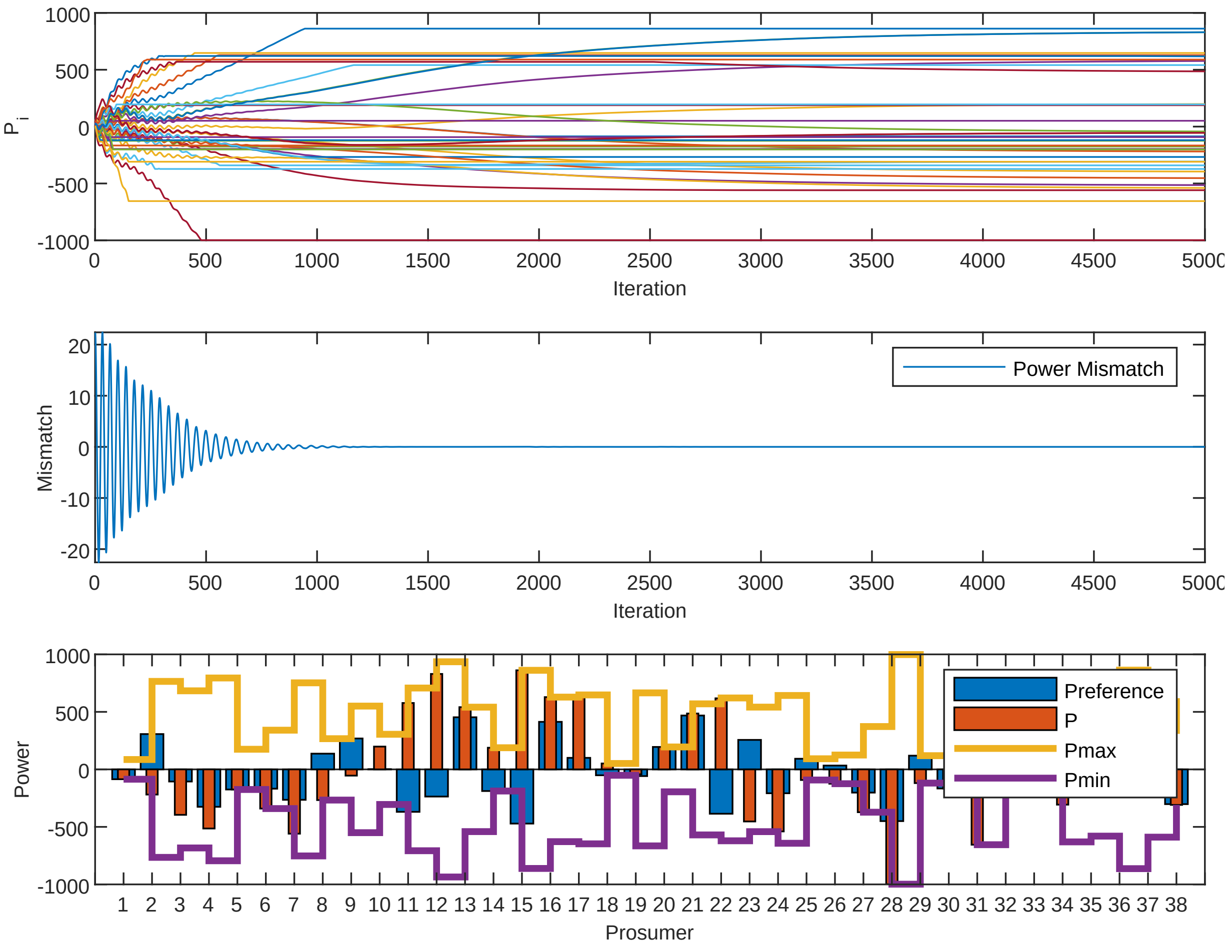

Figure 5.7: Preferences Scenario: 1

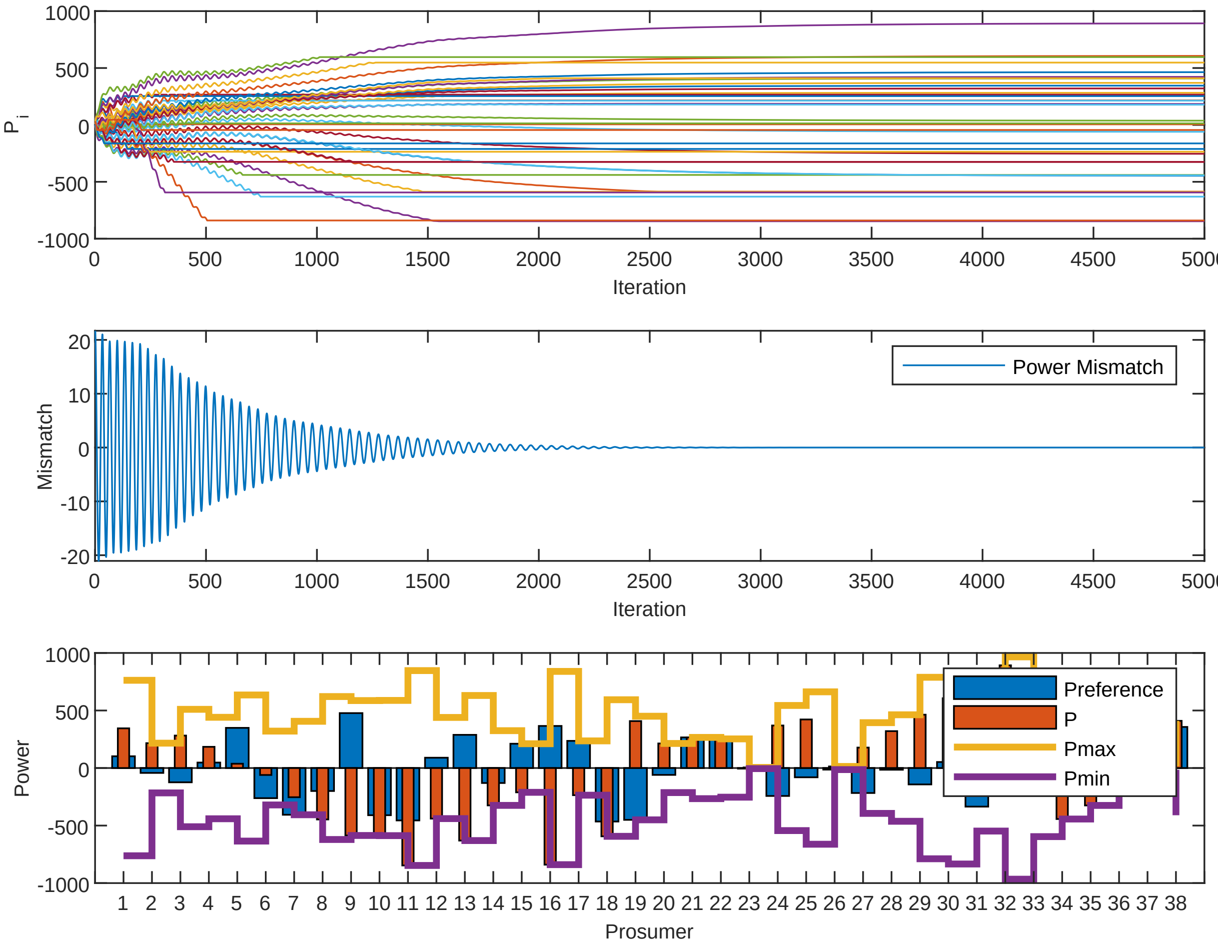

Figure 5.8: Preferences Scenario: 2

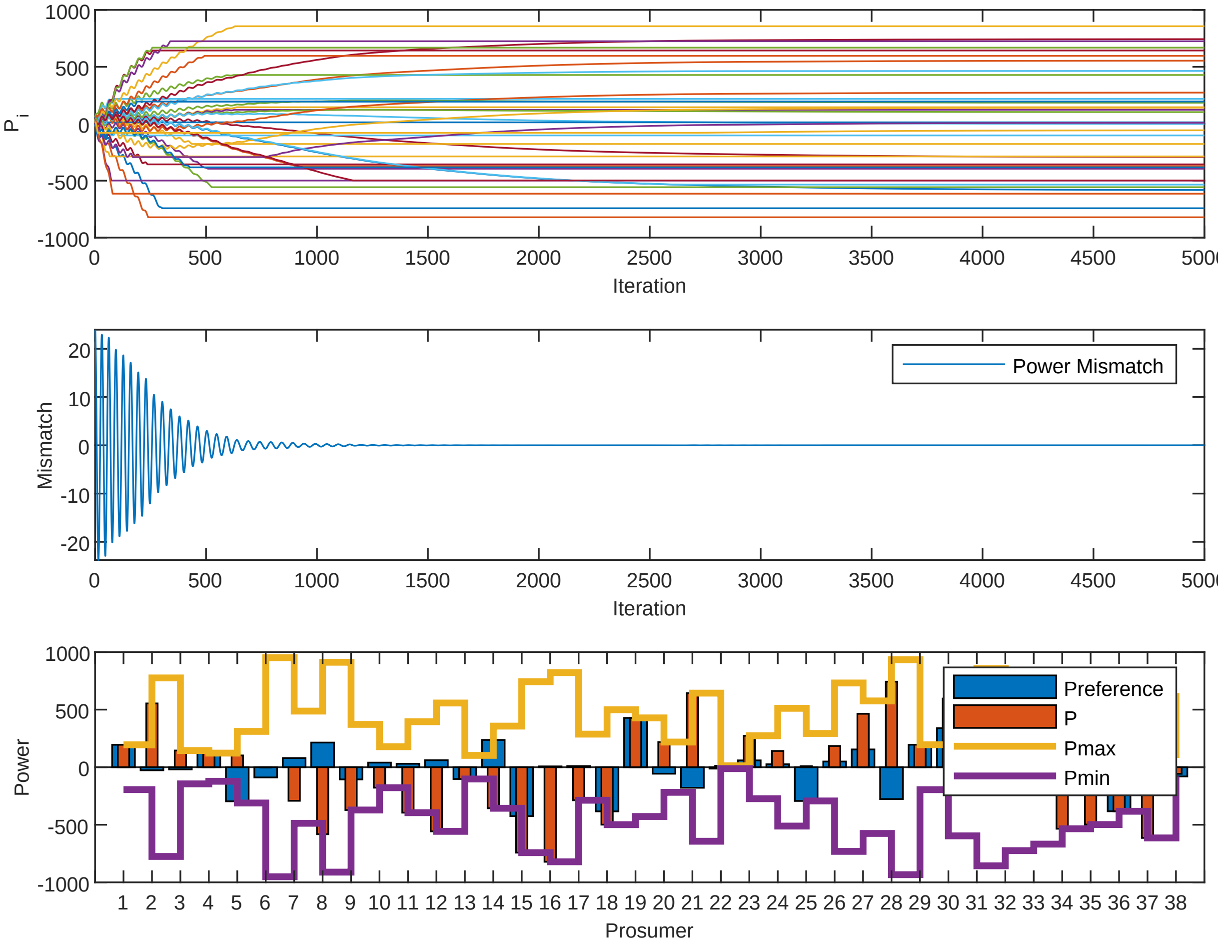

Figure 5.9: Preferences Scenario: 3

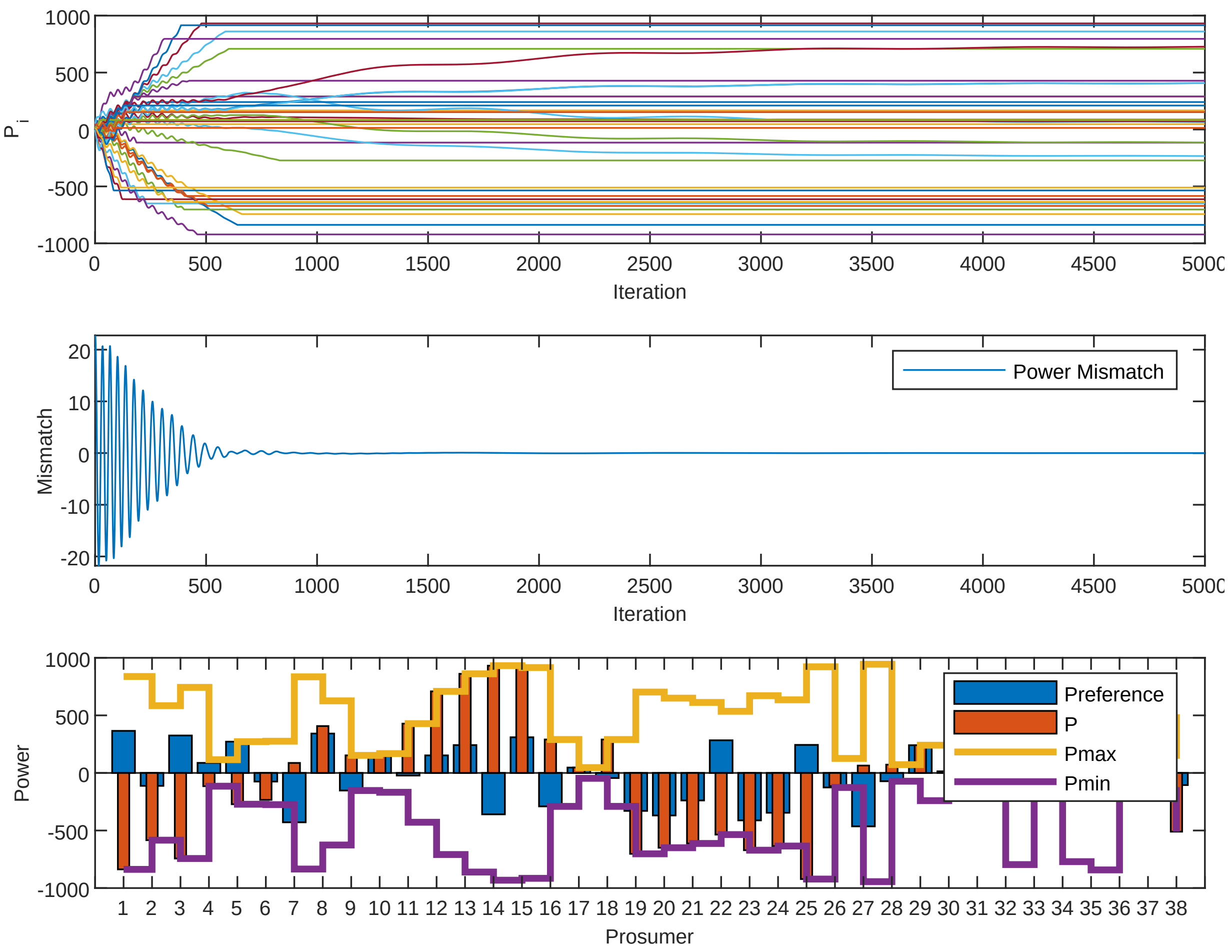

Figure 5.10: Preferences Scenario: 4

In the community, repeating the interaction over time will result in enhanced preference tracing. In Figure 5.11, two weeks of interactions is simulated. It is clear that with time, as each prosumer is locally minimizing the deviation from their preferences, the gap between realized cost/benefit and preference cost/benefit is decreasing. Figures 5.12 and 5.13 showcase two-week and one-week examples of stable and unstable preference relaxation. While the unstable realization provides minimum overall cost for preferences (i.e. equal incremental cost λ_i), they are not market clearing alternatives (power mismatch $\neq 0$). However, the proposed algorithm locally minimizes cost and preference deviation as it attempts to achieve a global community constraint. Although both operations can reach consensus, Figures 5.14 and 5.15 showcase scenarios where consensus is reached faster for the stable market clearance situation.

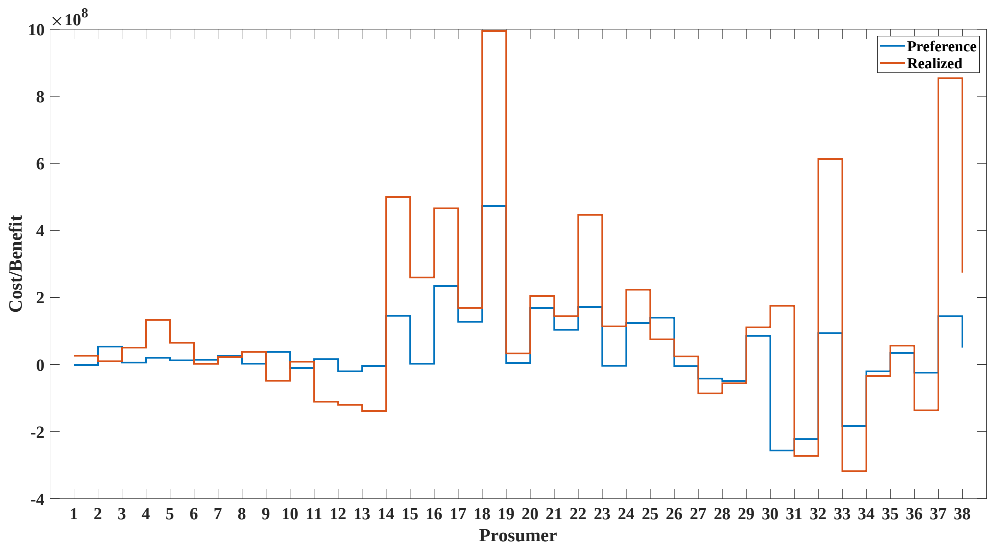

Figure 5.11: Realized Cost/Benefit for Each Prosumer after Two Weeks of Operation

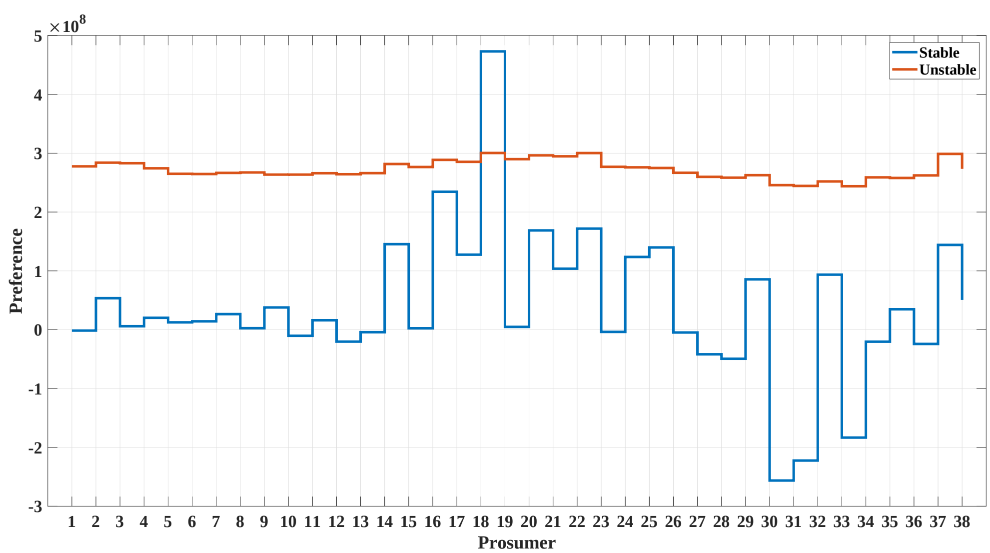

Figure 5.12: Stable and Unstable Operation over Two Weeks

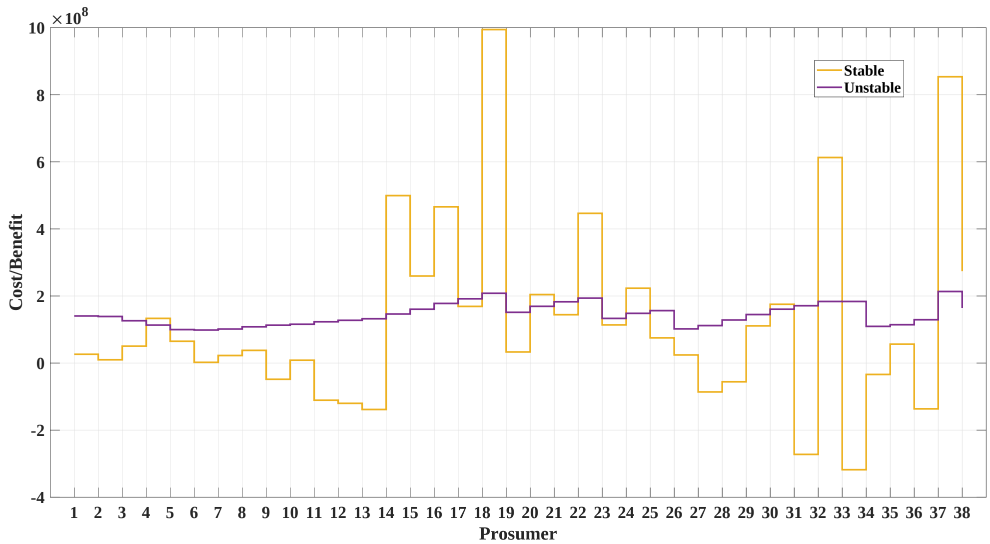

Figure 5.13: Stable and Unstable Operation over One Week

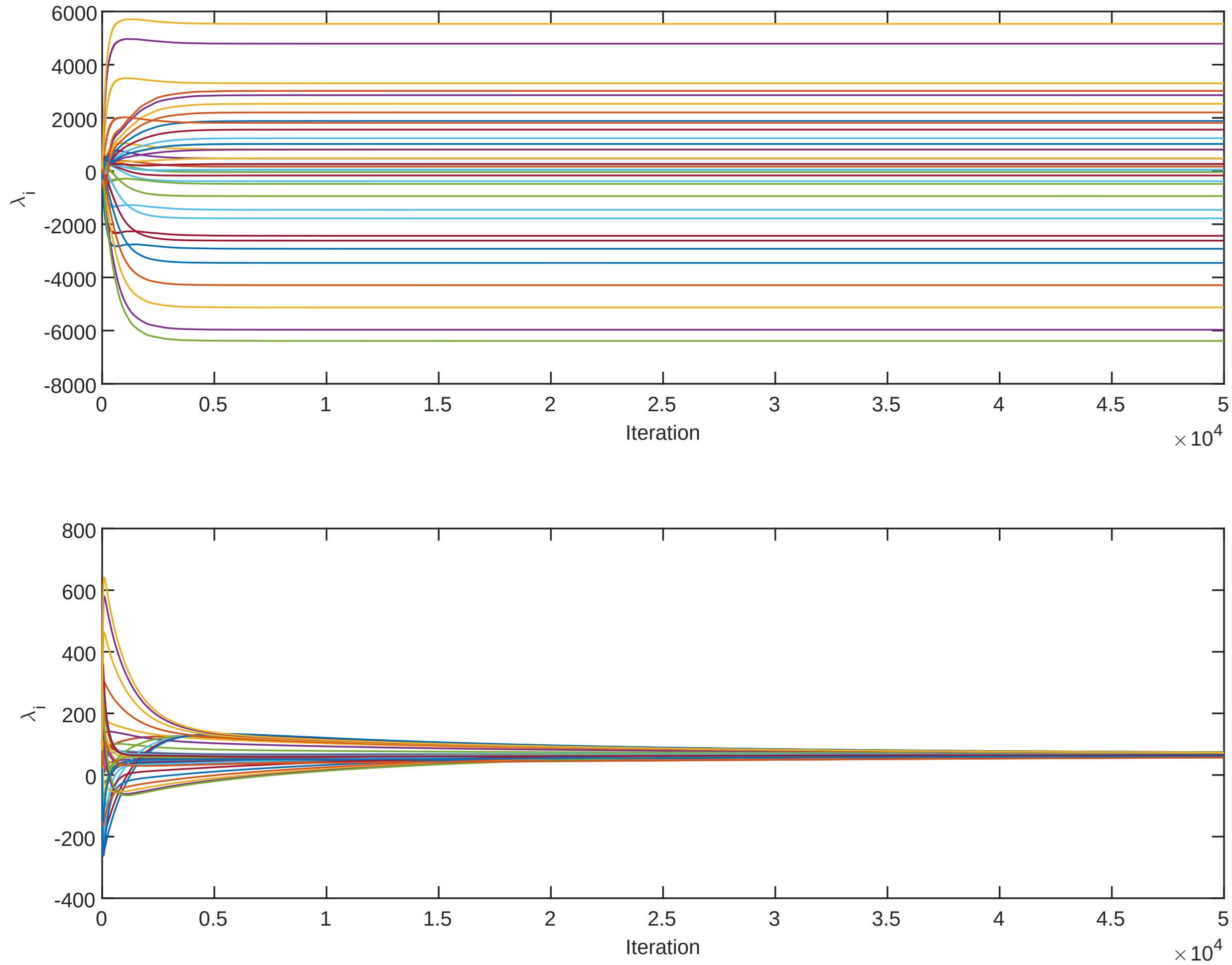

Figure 5.14: Stable and Unstable λ_i Realization

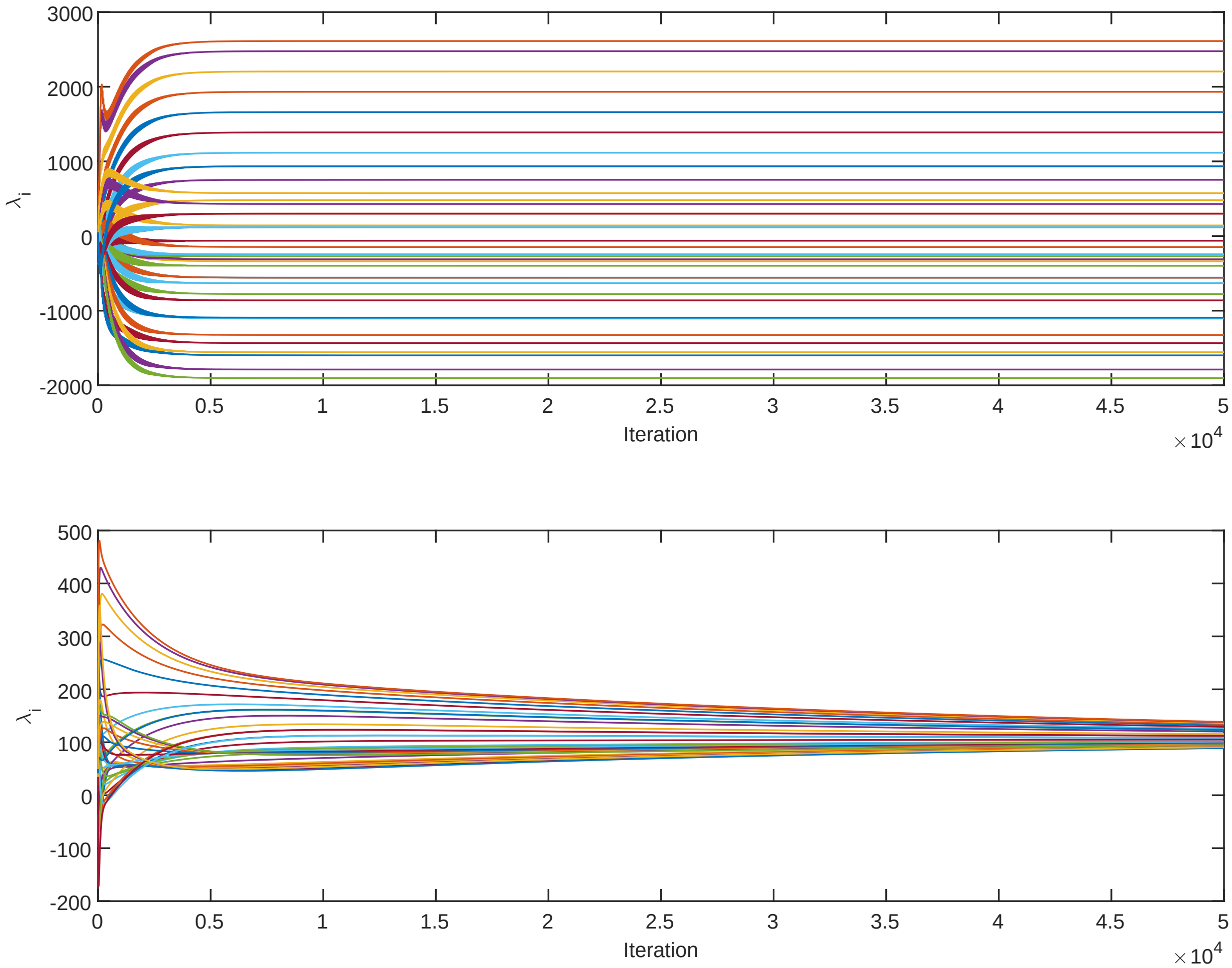

Figure 5.15: Stable and Unstable λ_i Realization

5.3 Realizing Market Clearance Alternatives in Hybrid AC/DC Systems

Proceeding from the previous sections, prosumers can agree on certain power levels to be either demanded or supplied into the community. Also, proceeding from the consistently increasing number of DC and AC/DC hybrid systems emerging, realizing interactions in a hybrid AC/DC system is studied in this section.

5.3.1 Hybrid AC/DC Modeling

Radical changes in the ratio of AC and DC loading and in the generation blend have promoted for power distribution in DC paradigms. Electronically-based DG units are more compatible with DC distribution than AC networks. Greater economies could be achieved if energy storage systems and renewable energy resources, such as wind and PV, were integrated into DC systems. However, major loads, such as modern elevators, operate based on variable speed drives [121]. PEV will be a crucial component in future electric distribution.

The evolving DC network will be integrable with the traditional AC network through interlinking converters, which will form a new hybrid distribution paradigm. If the connection with the main substation is lost, the hybrid distribution system forms an islanded microgrid that can partially or totally supply the local loads in the AC and DC subgrids. For higher system security, such islanded microgrids are characterized by droop control schemes that enable overall load sharing among the installed DGs [122]. For an AC subgrid, frequency and voltage are adapted to govern the output's active and reactive powers, respectively. Similarly, in a DC subgrid, the output power is controlled by adjusting the DG voltage. To maintain a power balance between the AC and DC subgrids, the interlinking converter adopts an operational criterion that relates the AC frequency to the DC voltage [123–125].

Modeling AC systems

Static AC load representation is one of the most commonly utilized models in AC analysis since it incorporates load behaviour with changes in the applied voltage and frequency. To capture the frequency dependency in load modeling, several factors can be added:

$$P_{ac,li} = P^o_{ac,i}\left(V_{ac,i}\right)^{\alpha}\left(1 + K_{pf,i}\Delta\omega\right) \tag{5.15}$$

$$Q_{Li} = Q_i^o \left(V_{ac,i}\right)^{\beta} \left(1 + K_{qf,i}\Delta\omega\right) \tag{5.16}$$

where $P_{ac,i}^o$ and Q_i^o are the nominal values for the active and reactive powers, respectively; α and β are the active and reactive power exponents. $\Delta\omega$ is the deviation of the frequency (i.e. $\Delta\omega = (\omega - \omega_0)$ and K_{pf}, and K_{qf} are two constants that range from 0 to 2 and from -2 to 0, respectively) [126]. As for the DG units, either PQ, PV, or droop characteristics are implemented to share the system loading. Both PV and PQ modes are frequency independent, and thus, their incorporation into the power flow formulation is straightforward. The steady-state model for the droop-based DG units, as depicted in Figure 5.16, can be given by

$$P_{ac,Gi} = \mu_i \left(\omega_i^* - \omega\right) \tag{5.17}$$

$$Q_{Gi} = \eta_i \left(V_{ac,i}^* - V_{ac,i}\right) \tag{5.18}$$

where $P_{ac,G}$ and Q_G are the DG output's active and reactive powers, ω^* and V_{ac}^* are the no-load reference values for the DG output frequency and voltage, μ and η are the reciprocals of the DG droop gains. The droop characteristic in Equation 5.17 implies an active power feedback that renders all DG units operating under a common frequency value, according to which, the fractional contributions of active power are achieved as intended. Likewise, Equation 5.18 suggests a reactive power feedback to assist reactive power sharing among the DGs.

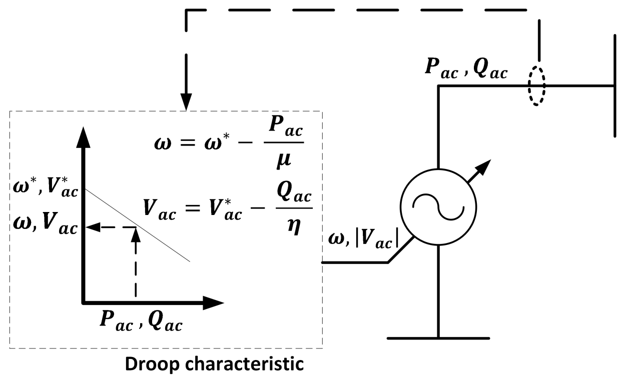

Figure 5.16: Steady-State Model for a Droop-Based DG Unit in the AC Subgrid

Modeling of DC systems

In general, constant power, constant current, and constant resistance loads are the main loading types in DC distribution systems [127–129]. Constant power loads are the most common since DC motors, variable speed drives, and DC-DC power supplies belong to this load category. However, some motors draw almost the same current for a wide range of input voltage; hence, the constant current model shows better fitting in this case. However, various types of lamps, heaters, and relays conform to constant resistance modeling. Only the constant resistance loads can be modeled implicitly within the system conductance matrix. Thus, $P_{dc,Li}$ an aggregated load connected at bus i can be generically modeled as

$$P_{dc,Li} = P^o_{dc,i} + V_{dc,i} I^o_{dc,i} \tag{5.19}$$

where $P^o_{dc,i}$ and $I^o_{dc,i}$ are the load constant power and constant current portions, respectively. Although constant resistance loads are considered in the conductance matrix ($G_{i,j}$ where $i = j$), the relative load size of constant resistance compared to constant power is low. The DG units follow either constant power or droop-based characteristics to share system loading in DC subgrids. The integration of constant power DGs in the system model formulation is similar to the constant power loads but with an opposite sign. The droop characteristics can be realized via a $P - V$ droop structure, as illustrated in Figure 5.17.

This operational characteristic could be modeled as follows:

$$P_{dc,Gi} = \vartheta_P \left(V^*_{dc,i} - V_{dc,i}\right) \tag{5.20}$$

where $P_{dc,Gi}$ is the DG out power, V^*_{dc} is the DG no-load reference voltage, and ϑ_P is the reciprocal of the droop gains for the DG output power.

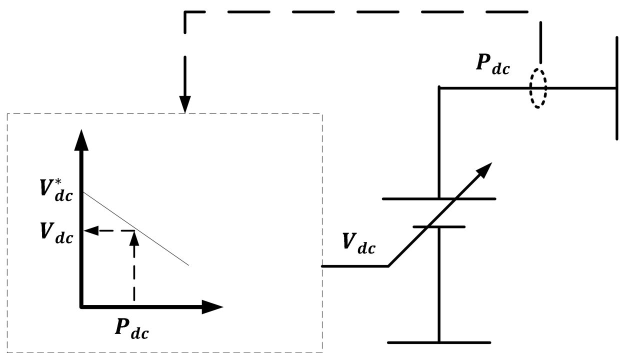

Figure 5.17: Steady-State Model for a Droop-Based DG Unit in the DC Subgrid

Modeling of AC/DC Interlinking Converter

If neither the AC nor DC subgrid has a relatively higher capacity, the main objective of the interlinking is to coordinate the AC and DC subgrids to achieve source power sharing. The interlinking converter realizes the source power sharing objectives by measuring and normalizing the frequency and DC voltage as loading indicators for the AC and DC subgrids, respectively. Then, the active power transfer between the two subgrids equalizes the normalized values of the frequency and DC voltage. This behavior could be modeled as

$$\omega_{pu} = V_{pu,i} \ \forall i \in \mathcal{I}_c \tag{5.21}$$

with,

$$\omega_{pu} = \frac{\omega - 0.5\left(\omega_{max} + \omega_{min}\right)}{0.5\left(\omega_{max} - \omega_{min}\right)} \tag{5.22}$$

$$V_{pu,i} = \frac{V_{dc,i} - 0.5\left(V_{dc,max} + V_{dc,min}\right)}{0.5\left(V_{dc,max} - V_{dc,min}\right)} \tag{5.23}$$

where $\mathcal{I}_c$ is the set of the interlinking converters within the hybrid microgrid. Substituting from Equation 5.22 and Equation 5.23 in Equation 5.21 yields

$$a_\omega \omega - a_V V_{dc,i} - a_{\omega V} = 0 \tag{5.24}$$

with,

$$a_\omega = \frac{2}{\left(\omega_{max} - \omega_{min}\right)} \tag{5.25}$$

$$a_V = \frac{2}{\left(V_{dc,max} - V_{dc,min}\right)} \tag{5.26}$$

$$a_{\omega V} = \frac{\left(\omega_{max} + \omega_{min}\right)}{\left(\omega_{max} - \omega_{min}\right)} - \frac{\left(V_{dc,max} + V_{dc,min}\right)}{\left(V_{dc,max} - V_{dc,min}\right)} \tag{5.27}$$

5.3.2 Solution Realization

To realize the market clearing price for the different alternatives, three main entities should be defined in this work: 1) the AC prosumer, 2) DC prosumer, and 3) the interlinking converter between the microgrids. Each prosumer should solely prepare the appropriate gain schedule of its own components to meet the different operational scenarios as follows:

AC Prosumer

The central controller in this prosumer is responsible for restoring the system frequency and voltage to their nominal values and achieving the generation requirements according to the power alternative. This can be realized by formulating a dispatch problem, according to which, the drop gains and no-load reference values could be adjusted. The objective function is defined as:

$$\min \sum_{u \in DG_{ac}} OC_u\left(p_u\right) \tag{5.28}$$

The main constraints are:

$$\sum_{u \in DG_{ac}} p_u - \sum_{d \in L_{ac}} p_d - P_{loss_{ac}} = P_{T_{ac}} \tag{5.29}$$

$$V^*_{ac_{lb}} \leq V^*_{ac,i} \leq V^*_{ac_{ub}} \tag{5.30}$$

OC_u is the operational cost of the DG, DG_{ac} is a set of the DG units in the AC system, $P_{loss_{ac}}$ is the AC system loss, and $P_{T_{ac}}$ the power exported from the AC system.

DC Prosumer

Similarly, this prosumer aims to maintain the microgrid voltage at the nominal value as well as achieve the power schedule through adjusting the DG droop gains and no-load voltages. Accordingly, a dispatch problem is formulated as

$$\min \sum_{u \in DG_{dc}} OC_u\left(p_u\right) \tag{5.31}$$

Given that:

$$\sum_{u \in DG_{dc}} p_u - \sum_{d \in L_{dc}} p_d - P_{loss_{dc}} = P_{T_{dc}} \tag{5.32}$$

$$V^*_{dc_{lb}} \leq V^*_{dc,i} \leq V^*_{dc_{ub}} \tag{5.33}$$

DG_{dc} is a set of DG units in the DC system, $P_{loss_{dc}}$ is the DC system loss, and $P_{T_{dc}}$ the power exported from the DC system.

Interlinking Converter Action

This element is not a prosumer but holds the coordination role between both AC and DC prosumers. Given that both AC and DC subsystems operate at their nominal frequency and voltage values, the interlinking converter could manipulate the power transfer between the two subgrids after agreement:

$$P_{T_{ac}} + P_{T_{dc}} = 0 \tag{5.34}$$

5.3.3 Case Study

This case study illustrates the interaction between AC and DC prosumers in a hybrid microgrid paradigm Figure 5.18 [130]. For simplicity, the DG units in the AC prosumers are assumed to be identical at 0.5 p.u. each. The system loading is 0.4 and 0.2 in the AC and the DC prosumers, respectively. The prosumers can change their role from power consumers to power producers in a very short period of time. Such a dramatic change in behavior has to be analyzed carefully from both technical and economic perspectives. From an economical perspective, these interacting parties have to reach a market clearing feasible situation for any successful operation. For instance, Table 5.1 demonstrates the list of power-level options a prosumer may have. Depending on the cost of production or the cost of load shedding, prosumers can change preference. Tables 5.2 and 5.3 summarize the DG parameter setting in the AC and DC subgrids, respectively, that realize the economic alternatives. Table 5.4 shows the possible interactions that can be technically realized for any successful agreement in the hybrid network via the interlinking converter setting ($a_\omega V$).

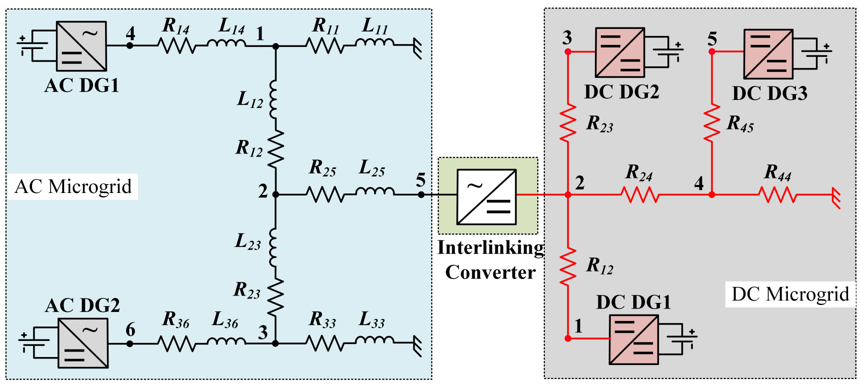

Figure 5.18: AC/DC Test System

Table 5.1: Prosumers Options for Power Levels

Prosumer	Options
AC prosumer, p_1	{sell,idle,buy}
DC prosumer, p_2	{sell,idle,buy}

Table 5.2: AC Prosumer p_1 Power Level Settings

Option	Power (p.u.)	Droop setting $\{\mu_i, \omega_i^*\}$
sell	0.2	{25,1.0080}
idle	0	{25,1.0053}
buy	0.2	{25,1.0027}

Table 5.3: DC Prosumer p_2 Power Level Settings

Option	Power (p.u.)	Droop setting $\{\eta_i, V_{ac,i}^*\}$
sell	0.2	{10,1.020}
idle	0	{10,1.010}
buy	0.2	{10,1.005}

Table 5.4: Possible Market Interaction

	Interaction Pairs	Interlinking converter parameters $\{a_\omega, a_V, a_{\omega V}\}$
	{sell,sell}	N/A
	{sell,idle}	N/A
	{idle,sell}	N/A
	{idle,idle}	{100,20,79.83}
$\hat{\mathcal{Z}}$	{idle,buy}	N/A
	{buy,sell}	{100,20,79.83}
	{buy,idle}	N/A
	{sell,buy}	{100,20,79.83}

5.4 Chapter Summary

In this work, a novel consensus-based algorithm is introduced as an economically efficient tool for coordinating prosumers interactions within the feasible solution region. Several objectives are targeted in this work; the global economic benefit maximization of all interacting prosumers is the most salient among them. This economic benefit comprises the total cooperative payoff of the interacting prosumers. Each prosumer has its own private bounds defining the range of power production and consumption. Furthermore, the total power transfer of all interacting prosumers are confined by the system infrastructure. Thus, the formulated problem is classified as convex with private and global constraints governing the interactions. The proposed algorithm can provide a global optimal solution for the aforementioned problem in a distributed manner. When compared to centralized communication, this distributed framework entails minimum communication requirements to provide reliable connections with higher data security among prosumers. The output results demonstrate key positive features for the proposed work's practical implementation.

A novel definition is proposed for prosumers' interactions in hybrid microgrids. The developed scheme stems from the dramatic change in the smart networks paradigms. Additionally, individual prosumers' preferences are recognized via the comprehensive mathematical modeling for the evolved AC/DC network. The results are provided for a basic two-prosumer scenario. However, these results highlight the potential of the proposed approach in a practical system setting.

Chapter 6

Conclusions and Future Research

"I've come to the conclusion that players want to be treated alike."

— Tom Landry

This chapter summarizes the work of this thesis and draws conclusions in Section 6.1. It also provides a list of major contributions this work has accomplished in Section 6.2. Finally, it proposes future paths for research in Section 6.3.

6.1 Thesis Summary and Conclusion

Chapter 1 introduced the work's motivations and objectives. It has established what the thesis will address in subsequent chapters and illustrated the structure of how the issues are addressed.

In Chapter 2, a background and literature survey about SDSs and what the term may entail has been conducted. The chapter began with an introduction to the topic and the general motives behind it. The topic required further background and an understanding of what is envisioned in the smart grid as well as the role of power system components in this smart paradigm. These notions needed further investigation and understanding of the stakeholders of this envisioned SDS to properly describe how a generalized planning framework may be developed. Moreover, an investigation of the current planning literature was needed and conducted. It is now clear that any long-term planning framework that facilitates a smooth transition to smart grids and utilizes a linearized OPF is considered to be a compromise in accuracy. Capitalizing on the capabilities of metaheuristic techniques and how NLP-based OPFs can enhance them are now of great interest to this work. With the ever-advancing commercial solvers created to address non-convex, nonlinear, and mixed-integer, as well as large numbers of constraints and variables-type problems, challenging these solvers with even greater objectives becomes a natural progression.

Several insights can be duly drawn from the strategic analysis in Chapter 3, which first identified, categorized, and assessed the relationship between stakeholders and the two anticipated conflicts: the long-term planning level and the operation level. Feedback systems between different stakeholder categories have been seen as advantageous, especially for groups with lower interest in an SDS. Moreover, it highlighted the importance of continuously keeping private investors informed about new developments that leans toward their interests (i.e., smarter systems). Direct engagements and monitoring of all customer types are essential to a successful transition. To conclude, contradictory goals can occur in a smart grid framework. These contradictions affect the planning process and should not be ignored [90]. As systems move toward multiple ownership and multiple stakeholders, planning entities must consider the goals of new stakeholders. Meeting conflicting objectives inherently involves compromises between parties; however, with smart grid technologies, ultra-fast communications and emerging markets and players make cooperation, coalition formation, and optimal operation of assets necessary in the planning of future SDSs.

In Chapter 4, a long-term allocation planning framework for greater private investment absorption, hourly optimal operation, cost effective design, employment of different technologies, feasible computational time (from a planning perspective), and consideration of active network applications (i.e., adaptive DG power factor and controllable DG output power) has been developed. This framework provides the backbone for asset and product integration in future SDSs. With overall objectives in mind, the developed framework allows for further enhancements and refinements to achieve greater accuracy and economic benefits. As a starting point, this work falls short of an absolute comprehensive adaptation of all possible practical constraints and representations. This drawback can be addressed in future studies. For instance, an optimal communication infrastructure between the newly-formed (because of generation units allocated) dynamic or static microgrids within the system is proposed for further study. This communication infrastructure can allow for fair power sharing among prosumers or microgrids and better facilitates the cost/benefit allocation of each party within the planning problem. As suggested in this chapter, increasing the penetration level of DG may, and probably will, increase costs on system operators (e.g., line reinforcements). These challenges and others will be tackled in future studies.

In Chapter 5, a novel consensus-based algorithm is introduced as an economically efficient tool for coordinating prosumers's interactions within the feasible solution region. Several objectives are targeted in this work, and global economic benefit maximization of all interacting prosumers is the most salient. This economic benefit comprises the total cooperative payoff of the interacting prosumers. Each prosumer has its own private bounds defining the range of power production and consumption. Additionally, the total power transfer of all interacting prosumers are confined by the system's infrastructure. Thus, the formulated problem is classified as convex with private and global constraints governing the interactions. The proposed algorithm can provide a global optimal solution for the aforementioned problem in a distributed manner. When compared to centralized communication, this distributed framework entails minimum communication requirements to provide reliable connections with higher data security among prosumers.

The output results demonstrate key positive features for the proposed work's practical implementation. Moreover, a novel definition is proposed for prosumers' interactions in the hybrid microgrids. The developed scheme gains its importance from the dramatic change in the smart networks paradigms. Furthermore, the individual prosumers' preferences are recognized via the comprehensive mathematical modeling of an evolved AC/DC network. The results are provided for a basic two-prosumer scenario. However, these results highlight the potential of the proposed approach in a practical system setting. More sophisticated case studies (i.e., multi-power levels, multi-prosumer, and different system topologies), could also be studied using the proposed work.

6.2 Contributions

Strategically analyzed stakeholders' interests and their interaction to highlight potential conflicts and understand the future of SDSs; this involved a detailed description and listing of the involved stakeholders based a conceptual NIST SDS. The strategic analysis of stakeholders yielded the development of interest-influence matrix categorizing stakeholders based on their keenness towards an SDS and how strong their decisions can affect the transition into the new system. Proceeding from the developed description and categorization, an actor-linkage matrix is developed using current and expected involvement reported in the literature and regulatory surveys. Conclusions were drawn that for the successful transition into an SDS, conflicts on two levels has to be addressed, namely; conflicts on the long-term planning level and conflicts on the operational levels.

Proceeding from previous findings, two conflicts were identified that require further study of their nature and how a resolution can be made. For that, a case study has been developed to highlight and showcase *long-term* planning studies' potential conflicts in the means of assessing two objectives using an NSGA-II optimization. The two objectives reflected two parties interests in a *long-term* planning study. The case study yielded evidence of a major conflict of interest between LDCs and investors. Conclusions were drawn that a multiobjective type of *long-term* planning has to be the new norm for regional planners by incorporating both parties interests. This framework can be achieved by lowering overall parties costs and increasing their participation to improve their revenues. Moreover, a second case study reflecting potential conflicts on the *operational* planning levels. It has shown their effects on daily operations of the involved players and the overall long-term planning consequences. The case study utilized graph theory for conflict resolution-based technique to assess states' stability. It concluded that, with BAU planning, independent and noncooperative interactions of parties would result in both market interactions infeasibility and conflict instability. Proceeding from these two conflicts and what overcoming them can achieve for transitioning to SDSs, two objectives were formulated and achieved in the subsequent chapters.

To overcome *long-term* planning conflicts, an algorithm to provide optimal *long-term* sizing and allocation planning of DGs that considered daily optimal operation, and considered electric utilities' and investors' interests to allow for the highest possible investment absorption has been developed. This algorithm divided the main problem into two subproblems: allocation and optimal operation. Although the operation studied in this part of the work does not reflect a proposed solution to overcome the conflicts on this level, it provided a solution for the *long-term* planning conflicts and a backbone that any developed future operation level conflicts solution technique can utilize. The developed algorithm solved the conflict via incorporation of two objectives that formulates costs and revenues associated with planning and operation. It introduced variables that expands the pareto front of such problems yielding results that overcome the conflicts and facilitates integration.

The operational level planning has shown potential conflicts in BAU-based transition. For that, this work designed and developed a consensus-based cooperation methodology to overcome these anticipated conflicts. This approach is cooperative to eliminate the contradictory nature of noncooperative schemes; it is also distributed to allow a more realistic approach to deal with isolated and grid-connected microgrids; and applicable to both AC and hybrid alternating current/direct current (AC/DC) systems for a smoother transition to future SDSs.

6.3 Directions for Future Work

The strategic analysis of stakeholders is an ongoing process. To ensure a successful and seamless transition to future smart grids, information regarding stakeholders, their nature, and their relationships have to be revisited on a regular basis. Further surveys of stakeholders's interests that help understand their positions is also highly encouraged. As stakeholders become more involved in the planning process, the complexity increases. This leads to a belief that the early adaptation of sophisticated planning tools at the industry level will provoke further research in the areas of deterministic operation and long-term planning. The naturally non-convex and np-hard problem requires further investigation on how operational-level planning can be reflected in the long-term planning framework in an entirely deterministic process. Furthermore, as smart grid technologies become more prominent, early inclusion in the planning process can dramatically increase the likelihood of successful integration.

Prospect theory and game theory need to be explored to better reflect human emotions and thinking to model what is typically a traditional optimization problem. Droop-based control in either AC or DC systems suffers from voltage magnitude measurements because it is a local rather than global variable. This inherently renders problems in DC active power sharing and reactive power sharing in the AC systems. Although this work is DC-based, DGs's droop characteristics work to keep the linking convertor bus voltage at a specific value; the problem of equal sharing while satisfying the consensus algorithm outcome still needs investigation. Moreover, reactive support is essential for the successful operation of islanded systems; thus, incorporating reactive power in the cooperative scheme is important. Further stability studies are also recommended to eliminate any possibility of hunting or degradation.

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Glossary

prosumer

Customer/consumer and producer of electric power. *pp:* viii, xx, xxii, xxiii, 25, 26, 33–35, 42–45, 48, 49, 76, 78–87, 91, 92, 95, 100–105, 109, 110

stakeholder

those who have a stake in the system. *pp:* vii, xix, xxi, 2–4, 6, 9, 14–22, 26, 31, 33–35, 49, 50, 52, 58, 75, 78, 79, 108, 110, 112