Zone-Distributed Optimization System for Energy Management in Smart Grids

by

Jamal Busnaina

A thesis
presented to the University Of Waterloo
in fulfilment of the
thesis requirement for the degree of
Master of Applied Science
in
Electrical and Computer Engineering

Waterloo, Ontario, Canada, 2017

Author's 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

Energy management system (EMS) is an important component of smart grid operation. A proper EMS is the key to the integration of smart grid (SG) features, which include two-way communication, smart metering as well advanced control algorithms, in order to operate different components of SG efficiently and constructively.

EMSs are both applied on the entity's and the system's level. On the entity level, individual entities don't coordinate with the system operator to optimize the objectives globally which would lead to inefficient solutions. System level EMS is implemented using centralized and decentralized approaches. Some of crucial drawbacks of the centralized EMS approach are that it's incapable of considering customer preferences while optimizing the operation of the networks, in addition to the lack of flexibility and scalability. Nevertheless, in the decentralized EMS approach, the customers and the system operator share information and interact constructively in optimizing their objectives. However, this approach still requires central coordination and long back-forth process to converge, as there is no shared background of mathematical foundation. In addition to that, most of the proposed decentralized techniques, do not consider network constraints, especially for unbalanced systems.

This thesis proposes a Zone-Distributed Optimization System (ZDOS) using distributed semi-definite programming for energy management of a SG. ZDOS divides distribution systems into numerous micro grid-like regions, or zones, to facilitate smart grid operation. The proposed ZDOS divides the grid into a number of Zone-Specific Optimization Subsystem (ZSOS), each responsible for controlling and managing the activities inside a zone. The ZDOS clusters the distribution system based on the customer-class (residential, commercial and industrial). Each class is controlled by ZSOS in order to optimize a certain objective function, as well as a set of constraints which are consistent with customer's nature, preferences, requirements and the applied Demand Response (DR) strategy. Furthermore, ZSOS's of connected zones exchange local information at the point of connectivity indicating the desired power exchange and voltage level until the iterative process of every ZSOS is satisfied.

Simulations and analysis are conducted on a modified 123-IEEE test system, which include diesel generators, renewable energy resources, and energy storage systems. The system is tested under different scenarios and demand response strategies. The analysis has shown that the results obtained by ZDOS are valid as the supply and demand are always balanced. Furthermore, the performance of ZDOS for minimizing operational costs has significantly improved when applying the DR, compared to ZDOS results without DR. The effectiveness of a multi-objective ZDOS when taking into consideration the preferences and requirements of different customers has been proven.

Acknowledgements

"And Allah has extracted you from the wombs of your mothers not knowing a thing, and He made for you hearing and vision and intellect that perhaps you would be grateful", (Quran 16:78). All thanks and praise are due to Allah alone, the Exalted, the most Merciful, and the most Giving for all His blessings that He bestowed upon me. May Allah accept my humble effort, and be pleased with me.

I would like to express my deepest gratitude and appreciation to my supervisor Professor Ramadan ElShatshat of the Department of Electrical and Computer Engineering at University of Waterloo. He has always been source of continuous guidance, support, patience, and encouragement throughout my Master's studies at University of Waterloo. It has been a great honor to complete my studies under his supervision.

I would also like to acknowledge Professor Ehab El-Saadany and Professor Khaled Shaaban of the Department of Electrical and Computer Engineering at University of Waterloo as the second reader of this thesis, and I am gratefully indebted to them for their very valuable comments on this thesis.

Finally, I must express my very profound gratitude to my father Husain, my mother Najwa, my wife Nawal and my sisters Huda, Fatihia and Hounida for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis. Also, I would like to thank my son Husain who has been source of happiness during times of difficult challenges. This accomplishment would not have been possible without them.

Special thanks are extended to my friends in Canada and Libya who make my life colorful and enjoyable.

Author

Jamal Busnaina

Dedication

I dedicate my dissertation work to the souls of my friends: Sanad and Seraj Al-Zawi, Abdo Ahlees, Khaled Al-Sheikhi, Mohammed Al-Fallah and Fathi Ghoneim, and to the souls of cousins: Osama Al-Sheikh and Ibrahim Busnaina.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

CEMS	Centralized Energy Management System
DEMS	Decentralized Energy Management System
DER	Distributed Energy Resources
DG	Diesel Generator
DLC	Direct Load Control
DSM	Demand Side Management
DR	Demand Response
EM	Energy Management
EMS	Energy Management System
SDP-OPF	Semi-Definite Programming base Optimal Power Flow
SG	Smart Grid
LOS	Local Operation System
MA	Multi Agent
MAS	Multi Agent System
MG	MicroGrid
OPF	Optimal Power Flow
PCC	Point to common coupling with the main grid
PSO	Particle Swarm Optimization
PV	PhotoVoltic panels
RER	Renewable Energy Resources
TOU	Time of Use prices
WT	Wind Turbine
ZDOS	Zone Distributed Optimization System
ZSOS	Zone-Specific Optimization Subsystem

Nomenclature

A. Indices and Sets

B	Set of buses in the system
$B^{(k)}$	Set of buses in zone k
E	Set of ESSs in the system
$E^{(k)}$	Set of ESSs in zone k
G	Set of DERs in zone k
$G^{(k)}$	Set of DERs in zone k
Hr	Hour
$N^{(K)}$	Set of neighbor zones to zone k
T	Total time intervals
$\mathcal{E}$	Set of edges in the system
$\mathcal{E}^{(k)}$	Set of edges in zone k

B. Parameters

$a_{p,i}$	cost coefficient for power generation to the power of p, at bus i, $/Kw
B_{ij}	Susceptance for line between bus i and j, Siemens
$c_{shft,i}^{t}$	Shifting cost of load at bus i and time t, $/Kw
$C_{em,i}$	Gas emission cost of generator at bus I, p.u. /Kw
$E_{Bat,i}^{max}$	Maximum charging capacity of ESS at bus i, Kw
G_{ij}	Conductance for line between bus i and j, Siemens
$P_{D,i}$	Active power demand of load at bus i, Kw
$P_{G,i}^{min}$	Minimum active power output of generator at bus i, Kw
$P_{G,i}^{max}$	Maximum active power output of generator at bus i, Kw
$P_{G,i}^{ramp}$	Maximum ramp rate of power output of generator at bus i, Kw/hr
$P_{shft,i}^{min.t}$	Minimum shifted load at bus i and time t, Kw

$P_{shft,i}^{max,t}$	Maximum shifted load at bus i and time t, Kw
$P_{Bat,i}^{ramp}$	Maximum ramp rate of power charge/discharge of ESS at bus i, Kw
$Q_{D,i}$	Reactive power demand of load at bus i, Kvar
$Q_{G,i}^{min}$	Minimum reactive power output of generator at bus i, Kvar
$Q_{G,i}^{max}$	Maximum reactive power output of generator at bus i, Kvar
V_j^{min}	Minimum magnitude of voltage at bus i, Kv
V_j^{max}	Maximum magnitude of voltage at bus i, Kv
$Z^{(k)}$	Zone k

C. Variables

C_i^{sdp}	Objective function i in SDP-OPF
$C_i^{sdp\ (k)}$	Objective function i for zone one in SDP-OPF
$E_{Bat,i}^{t}$	state of charge of ESS at bus i and time t , Kwh
$P_{G,i}$	Active power of generator at bus i, Kw
$P_{G,i}^{t}$	Active power of generator at bus i and time t, Kw
$P_{i\to j}$	Active power flow from bus i to bus j, Kw
$P_{shft,i}^{t}$	Shifted power demand of load at bus i and time t, Kw
$P_{Bat,i}^{t}$	Power charge/Discharge of ESS at bus i and time t, Kw
$Q_{G,i}$	Reactive power of generator at bus i, Kvar
$Q_{G,i}^{t}$	Reactive power of generator at bus i and time t, Kvar
v_j^{r}	Real part of voltage at bus i, Kv
v_j^{im}	Imaginary part of voltage at bus i, Kv
$V^{(k)}$	Voltage matrix of zone k, Kv
$V^{(k),t}$	Voltage matrix of zone k and time t, Kv

Chapter 1

Introduction

1.1 Motivation

Energy management is a conceptual framework that is implemented in the context of Smart Grid (SG). They are designed to coordinate all of SG's different components and network such as distributed energy resources including renewable energy resources, energy storage systems with DSM programs and network's equipment in order to improves efficiency, maintain reliability, sustain electric supply security, while minimizing a certain objective that is set by SG operator.

An enormous research have been conducted in investigating EM in SG at two main Levels: entity level and system level. Entity level EM controller monitors energy usage in a single entity and control its appliances in accordance with owner's preset preferences. In other words, it coordinates energy usage of different equipment of the entity by trading-off between cost minimization and owner's comfort level. However, the coordination between different entities in a network and the network operator, which is missing or highly limited on this level, is of crucial importance since that inappropriate coordination between a set of entities, which each one of them has specific objective and constraints, that are operating on the same network which in return has its own goals and operating limitations can result in defective or infeasible solutions.

Whereas, System level EM is to control the operation of the whole system and its different components such as network equipment, power generation units and loads in accordance to global objective function and a set of constraints that are designed by the system operator to optimize a certain goal and maintain operational standards. A broad categorization of existing architectures for System Level EMS is to divide them to Centralized EMS and Decentralized EMS. In

Centralized EMS, the system operator utilizes a central controlling approach that manages energy to maintain supply-demand and optimize operational costs, system efficiency, or to a combination of weighted sum of several objectives where utility is primarily responsible for decision making.

Nevertheless, Centralized EMS has many disadvantages, for instance, it operates from a single owner's prospective. Since it centrally optimizes the objective function which in its most flexible forms can be a number of weighted sum of objectives, it's incapable of reflecting the preferences of all customers in the system. Moreover, system level EMS lacks flexibility and scalability since it formulates the whole as a single problem considering an enormous number of requirements and constraints that increase as the system enlarges or as the level of details increases by incorporating customers' preferences.

In Decentralized EMS, different customers as well as the system operator share information and interact constructively to set a consistent feasible solution, from the networks prospective, that is supposedly optimized in accordance to individual customer's objective. However, existing distributed frameworks for DEMS, are incapable to target wide range of customer preferences and cope with highly random entities and require a central coordination and long back-forth process to converge. In addition to, network models adapted in most formulations do not consider network's constraints and losses, and they are trouble computational cumbersome when these constraints are included. Last but not least, some of drawback of decentralized approaches are voltage deviation due to droop based control schemes and failure to handle unbalanced systems.

In view of the above, there is a need for development of novel distributed control scheme with a comprehensive mathematical tool that is able to combine the operation of different system components taking into account the ultimate objective of system operator in addition to characteristics and preferences of customers. The developed scheme should be capable of flexibility and scalability, at the same time should include all of the aforementioned problem details, down to the level of network and customers constraints.

1.2 Literature Review

The concept of Energy Management has two different prospective: Entity level EM prospective and System level EM prospective.

The first prospective is entity level EM where control algorithms are designed to monitor and control entity's equipment such as air conditioning and home appliances in residential entities or plants and EESs in industrial entities. EM in the entity level utilizes power supply from network and any other internal resources in order to minimize electricity usage costs while maintaining entity's activates without undesirable effects.

In [1], proposed an algorithm for sparse load shifting for residential smart appliances to increase the comfort level of the customers. In the context of considering customer's comfort level, authors of [2] developed home EM controller that optimally operate to minimize demand, total cost of electricity and gas emissions, and peak load using energy prices, weather forecast, etc., while taking into account owner's preferences and comfort levels.

In [3] a three-layer EM algorithm is proposed. These three layers are: 1) Equipment layer with local and fast control mechanism, 2) anticipative layer which utilize forecasting tools to coordinate the system using average values of forecasted variables to cope up future scenarios, and 3) Reactive layer that adjust the system's setting after they are passed in from the anticipate layer to maintain energy balance. Furthermore, in [4]a Residential storage controller for storage system control is developed. The controller's algorithm is separated into two levels: The global control level which sets plans for discharging/charging schemes for a period of a month, and the local control level that refine the storage control policy to correct the errors caused by the prediction.

The authors of [5], developed residential energy consumption scheduling algorithm that trade-off between electricity costs and minimizing the waiting time of appliance operation in an environment of a real-time electricity rates. Using heuristic techniques, the authors of [6] proposes a methodology for making day-ahead scheduling for residential system equipped with DER to maximize owner's profit by scheduling DERs over a set of scenarios that expect a range of uncertainty. Also, the authors of [7] proposes a semi-centralized management system using Multi-Agent Decision-Making Control Methodology to improve energy efficiency and minimize the total electricity usage cost.

The Second perspective is the system level EMS. The purpose of EMS is to manage available DERs and loads in order to achieve a predetermined objective that is set by the system operator. A vast amount of research investigating different methodologies and techniques in implementing EMS in SG is conducted. Literature on the topic can be divided into two main approaches: 1) central EMS (CEMS) approach, and 2) distributed EMS (DEMS) approach.

In the Central approach, the utility implement a central operational system that manage energy supply-demand, and is responsible of final decision making. With an intelligent behavior considered to customers in the management of their own entities as a response to price incentives and direct load control agreements with the utility. An enormous number of proposed work have been built on the concept of CEMS approach. Starting from Single stage algorithms, Authors of [1 - 3], proposed a CEMS for MG that aims to minimize total operational costs.

Furthermore, rolling horizon strategy has been massively utilized to mitigate scheduling errors due to changes in customers' behavior and system's status[4 - 6]. An EMS for microgrid consisting of a RERs, DERs and ESSs employing real-time rolling horizon is proposed in [10]. A renewable-equipped MG with dispatchable DERs and ESS was studied in [12]. A rolling horizon strategy based EMS utilizing mixed integer programming was proposed.

Moreover, many researcher have proposed multistage CEMS approaches in order to tune the system at different time rates and resolution. Authors of [13] developed Multi-stage CEMS architecture for optimal energy management in MGs considering uncertainties in DERs. In [14], a three-layer operational structure was proposed to control future power generation, storage, and consumption in order to maximize system's efficiency. Nevertheless, the most popular central approaches are two-stage CEMS. An optimal scheduling algorithm is carried out in the first stage considering all the available DERs and power demand. Where the second stage readjust the operation set-points of DERs in accordance with real-time changes in the system [2 , 6, 9 - 11]

A two stage hierarchical control architecture using a number of time frames is proposed in [11] and [16]. Firstly, the dispatchable DERs, WT, biomass DGs and ESS are optimally scheduled in scheduling layer. Secondly during online operation, each generation unit is regulated dynamically to maintain real-time power balance in order to minimize system's operational costs. Utilizing AI and heuristic techniques, authors of [2, 9] proposed a two stage EMS that minimizes operational costs, taking into account a two-stage procedure using fuzzy-based supervisory control and PSO, respectively.

A key aspect of smart grid is RERs, therefore, it has attracted the attention of researchers who have studied EMS focusing on implementing RERs and their corresponding challenges [7, 11- 17]. A two-stage EMS framework using rolling horizon is proposed in [5, 11]. A daily scheduling algorithm of DERs is performed in the first stages, after that, scheduled operation pointes are regulated in real-time to take into consideration power mismatch and incoming data instantly in the second stage under uncertainty in MG's demand and generation.

EMS in the context of SG with high level integration of variable RERs and ESSs has been the subject of many studies. ESS has the potential to enhance the resiliency of MGs by providing a power reserve to the system to be exploited in peak-time periods, and to reduce the risk of renewable-energy forecasting errors. In [1, 3] Real-time EMS is proposed to minimize an economical cost function by controlling a set of DERs and ESSs. In [1, 13 and 14], optimal EMSs are proposed, which optimize charging/discharging cycles of ESS and system's operational cost. Authors of [14 - 16] proposed a number of techniques that aim to improve resiliency of MGs by minimizing load shedding in islanded mode. Novel power flow optimization strategy for a grid connected MG equipped with an ESS for increasing power stability, minimizing load shedding, optimizing energy trading, etc. is proposed in [20]. In [19 - 21], a control strategy to reduce power fluctuations which utilizes ESSs to smooth the output power of wind farm is proposed.

Load management is an adaptive feature that offer a fully integrated platform in which different participants in MS can collaboratively manage the network with all considerations of physical, financial, and environmental constrains [26]. Authors of [23 - 26] developed a novel EMS algorithm for MG with the integration of DERs and responsive load demand. In [27], the proposed EMS minimizes operational costs utilizing ESS and DR by basically exploiting high prices time to sell stored energy and load shedding during power demand peak times in MG. In [29], a multi-objective EMS that incorporate weighted sum of multi-objective function for reducing operational costs while minimizing customer's dissatisfaction associated with load shedding, shifting and other DR strategies.

Incorporating CEMS inherent the system a number of considerable disadvantages [30]:

1. It must be implemented on computationally powerful CPUs so as to process an enormous size of data and to produce appropriate decisions.
2. it suffers a single point failure so that any central unit fault will cause the shutdown of the entire MG [24, 25].
3. It lacks flexibility
4. EMS operational strategies are restricted to limited set of objectives.
5. Altering system configuration is very difficult.

In the distributed approach, both utility and participating entities have their individual intelligent management systems. They interact to agree on power exchange amount, schedule and prices. Distributed frameworks based on multi agent techniques have been known to be among the – most effective algorithms for energy management systems in MGs [33]. MAS-based energy management systems have proven to be powerful for the distribution systems which are designed to be robust, flexible, and extensible[32 - 34].

In [34], Agent-based energy-management system for power trading among multiple MGs with demand response and distributed storage systems, is presented. The proposed approach divides the trading process into two process levels: 1) Local trading process that is performed in a local market within a microgrid, 2) Global trading process which is performed in a global market to facilitate energy trade between different MGs. In [36], a multi agent-based energy management system for power trading between MGs is proposed. In [37], an agent based market strategy for an operation a set of grid connected SGs is proposed. The customers are price responsive where demand side management strategies are utilized. In [33], authors designed a multi-agent based control framework to ensure the coordinated power management within the microgrids through effective utilization of EVs. Authors of [37] proposes a distributed energy management approach to operate networked microgrids in a distribution system. The approach applies a decentralized two stage algorithm; first stage allows negotiations among all MGs whereas the second stage updates the non-converging problems.

In [38], DEMS for optimal energy management in an environment comprising of RER, ESS and DERs is proposed. The problem formulation considers network's constraints and power losses in the lines, which is a formulation that is rarely considered in the problem of EMS. Authors of [39] and [40] propose an energy market based on trading agents for electrical entities utilizing price-based DR programs. In [41], an intelligent auction strategy using hybrid immune algorithm is implemented.

An MA-based management strategy for EV integrated MG is proposed in [42], that manage power sharing between DERs and does not rely on global information of MG. MA-based voltage and frequency control approaches are proposed in [36, 37], that is functional in communication constrained environment. An intelligent coordination system for both grid-connected and islanded microgrid using MA-based technique is presented in [38, 39].

A distributed MA-based control system utilizing non-cooperative game theory is designed in [47] and [48] to formulate a cooperative control scheme for energy management in islanded MG. In [49], mixed homogeneous and heterogeneous MA-based wolf pack hunting strategy is proposed to achieve faster power dispatch and control of an islanding smart distribution network. In [50 - 53], an MA-based supervisory control framework is proposed for energy management system in isolated ac/dc MGs.

Nevertheless, usually decentralized energy management schemes are incapable to cope with highly random loads because of their slow dynamic response [33]. Moreover, these techniques require a central coordination and long back-forth process to converge. Also, network models adapted in most formulations do not consider network's constraints and losses. The disadvantages of decentralized methods includes but not limited to: 1) deviational voltage/ frequency due to the utilization of droop based control schemes, 2) they fail to properly handle unbalanced systems and non-symmetrical loads which imbalances system's voltage.

1.3 Research Objectives

1. Develop a distributed optimization architecture that solves the optimization problem as a set of smaller optimization sub-problems, where each problem has its objective function and constraints. The aforementioned architecture has many advantages: 1) significantly reduces the size of the problem which is reflected on the computational time. 2) Enable the employment of advance parallel computing technologies.

2. Set up a framework that incorporate the distribution network, communication, forecasting, and optimization algorithms in order to establish the proposed intelligent operation system for scheduling and managing distribution system.

3. Investigate the performance of the proposed approach on a considerably large system that accommodate different participating entities such as DERs, RERs, ESSs and different type of loads with their respective characteristics and requirements including customized DR programs.

1.4 Thesis organization

The rest of this thesis is structured as follows; Chapter 2 presents a background of the concepts and the mathematical optimization tools utilized in this thesis. A brief overview of SG, DSM and DR programs. In addition to that, a detailed description to SDP-OPF that is used for distributed optimization is included. In Chapter 3, a detailed illustration on the frame work and mathematical formulation of the proposed ZDOS is provided. After that, a case study is investigated and accompanied with a comprehensive analysis of various sceneries in Chapter 4. Whereas, Chapter 5 summarizes the research work and presents suggestions for future work.

Chapter 2

Background

2.1 Introduction

Motivation of this work, research objectives and a detailed literature review pertaining to the research related to the proposed work are presented in chapter 1. Moving forward, this chapter provides a comprehensive background to the important concepts that are related to the subject as well as mathematical tools that are crucial to the foundation of the proposed work. Section 2.2 presents a brief overview on smart grid. Section 2.3 taps into energy management system. Followed in Section 2.4 by a brief discussion about demand side management and different demand response techniques. Section 2.5 presents a general description to optimal power flow problem in power systems, and provides an overview about Semi Definite programming. A thorough background about semi-definite programming based optimal power flow as well as detailed description of mathematical formulation of distributed semi-definite programming based optimal power flow are presented in this section.

2.2 Smart Grid

Nowadays, electricity is delivered to customers through traditional power systems that consist of three hieratical stages. First, electrical power is generated in large facilities located far from electricity end-users, then electric power is transmitted through a long system of transmission lines to supply a number of distribution systems which provide the end-users with electricity while maintain certain operating standards[54, 55]. Recently, power demand has tremendously increased rendering distribution systems operating close to their physical limits. Furthermore, governments and non-governmental organizations are enforcing laws aiming to reduce the effect of greenhouse emissions on climate change in the near future.

SM are high potential substitute to these traditional systems. A lot of new operational techniques are developed in this context in order to enhance the system's efficiency. These techniques utilize an integrated concept that utilize new technology, communication, smart metering and intelligent computing in order to optimize the operation of the network.

Smart grid is a distribution network that employ two way communication network, smart automation equipment, smart metering and advanced control algorithms in an integrated system that is capable to implement very intelligent and comprehensive techniques in order to enhance system's efficiency and minimize operational costs [54]. In particular, the US Department of Energy defines the smart grid as an automated bidirectional energy network that is capable of two way communication and monitoring participating entities in the network from power plants to individual customer's appliances [55].

There is no well-tailored definition of a smart grid that is global accepted across the academic community. However, a certain features are expected to be accommodated in a smart grid such as:

1. Intelligent: capability of sensing and automatically rerouting network's overloads.
2. Efficient: maintaining supply-demand balance in power demand increasing system without infrastructure upgrading.
3. Accommodating: bidirectional energy flow to/from any electrical entity in the system.
4. Real-time communication across the networks so electrical entities can control their energy consumption based and set their economical or environmental preferences.
5. Maintain high power quality.
6. Resistant to cyber-attack and natural crises as it characterized as a distributed network.

2.3 Energy Management System

Energy management system is a set of computer techniques and algorithms that are integrated to achieve a predefined goals by operating, controlling and optimizing the performance of the electrical power system. The EMS is responsible of maintaining the system's frequency and power exchange with main grid and adjacent microgrids in both grid-connected and islanded mode. This is achieved by coordinating the system based on the optimal unit commitment and dispatch of available DERs such as dispatchable generation units, renewable energy resources and ESS.

Some of the key techniques building blocks of the EMS are state system estimation, optimal power flow, voltage and reactive power control. Also, these techniques must be accompanies by number of important applications in order to carry out their task efficiently, applications such as Load forecasting, energy price forecasting , non-dispatchable generators output power forecasting, state of charge of ESS, Security and reliability assessment.

Objective functions of optimization that are set by the electrical power operators to satisfy system loadings under certain operational constrains and purse the performance required can be summarized on the following:

1. Minimize electrical system losses: for economic benefits and for higher capacity utilization.
2. Protect power distribution equipment: loading on all equipment must be within established manufacturer's operating specifications.
3. Sustain voltage within predefined acceptable limits at all times under all loading conditions.
4. Maintain acceptable level of services reliability in terms of number and durations of interruptions.

Energy management system has two different prospective. The first prospective is single entity level where the entity management system optimize the operation of the entity over the course of the day taking into account electricity prices, prediction of customer's electricity usage while considering the comfort level of the entity's owner. Entity management system has control over the entity's equipment in terms of operation settings such as reference temperature in air conditioners. Also, it can control the time and duration of operation in equipment such as washing machines and charging of electric vehicles.

The second prospective is whole system level where the system consist of a number of single entities, distribution network and components. The goal of energy management system in this level is to balance generation and consumption, maintain system stability and energy security taking into account the uncertainty of generation resources and randomness of customer's electricity consumption. Distribution energy management system has control over generation resources, energy storage systems, power exchange with main grid. Furthermore, these system level EMSs are the systems responsible in realizing demand side management and response by direct controlling of customers' some equipment and electricity exchange prices with generation entities and customers.

EMS will play an essential role in the control of SG to achieve desired operational performance by maximum utilization of all available resources. The energy management system will require new decision platform in order to exploit all capabilities of DERs and distribution system equipment in the decision making process such as taking full advantage of controllable generators, voltage regulators, reactive power devices, and system reconfiguration.

2.4 Demand Side Management and Demand Response

The programs and activates that are implemented by power utility in order to control customers' long term behavior of electricity consumption to change load shape to enhance and the performance and capacity of the distribution system [56].

Demand-side management encompasses a wide range of activities that can be classified into:

1. Load Management (Demand Response).
2. Energy conservations.
3. Energy Efficiency [57].

Demand Response is the customers' intentional reactions of electricity usage to the variation of electricity prices and their responses to the financial incentives offered by the utilities in order to shape and control the load profile of the distribution system to maintain the system's performance. [58]. Figure 1 shows a number of DSM activities and DR programs.

Demand response programs are implemented to change customer's load profile in three different aspects:

1. Peak clipping is to reduce energy consumption through load curtailment during peak consumption times to maintain the power supply within the permissible levels with respect to the distribution system's capacity and its physical equipment.

2. Valley filling is to motivate consumers to use electricity at off-peak energy consumption times by offering incentives and reduced electricity prices

3. Load shifting is to shift customer's energy consumption in some applications from peak to off-peak times, either by direct control of the electricity provider or by the customer's response to incentives and potential financial savings. This is without reduction of total energy consumption in a day.[61,62].

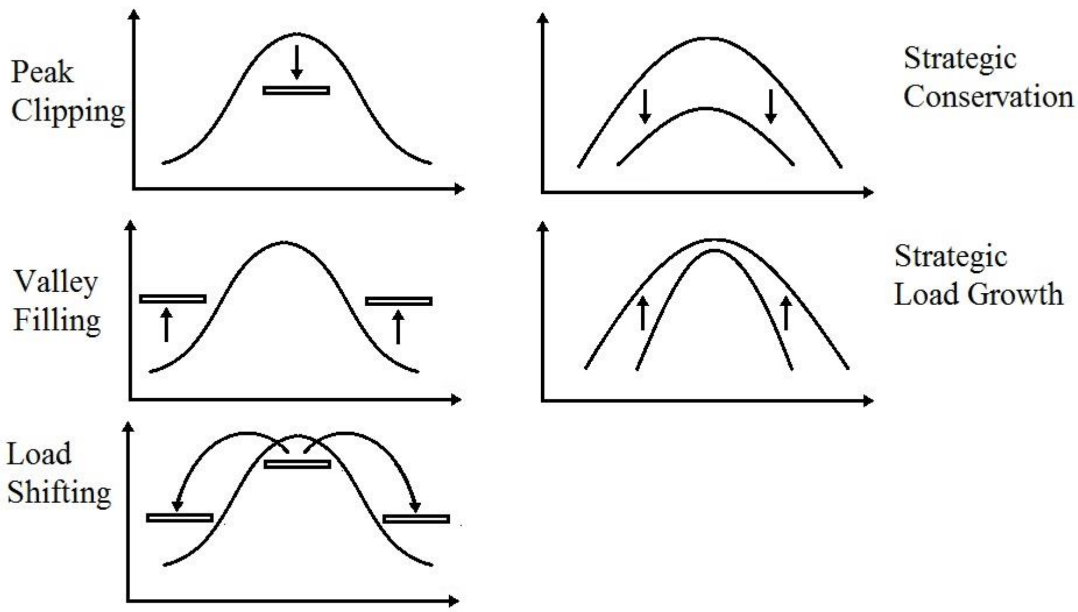

Figure 1: DSM activities and DR programs

Demand response programs can be realized by a number of different strategies and means that allow the utility to control, directly or indirectly, customers' electricity consumptions. These strategies are summarized as follow:

1. Price-based DR strategy: manage customer consumption indirectly by assigning different prices for each time interval. Prices can be determined day ahead or they can be streamed as real-time rate to customer's management systems. The electricity price should influence the customers to change their usage in a desirable pattern designed by the utility.

2. Incentive or event- based DR strategy: offer promotions and attractive reduced contract to the customers in return of a degree of controllability to the utility over some of the customer's appliances and equipment.

3. Demand reduction bids: utility initiate a request for a voluntarily demand reduction that customers bid on in return to some financial benefits [61].

2.5 Optimal Power Flow

The essential principle in the operation of SG is to supply demanded power in designated standards to consumers, while maintain minimum operational costs. These costs mainly stem from the generation expenses, and power losses in the network. The means of achieving this principle are energy resources management and optimal voltage control. As a further matter, energy resources management allocate power generation among available DERs over SG in order to attain minimum cost of generated power. Optimal voltage control aims to minimize voltage degradation on the network, while satisfying power demands[62]. Nevertheless, these means are conceptual framework that in need of powerful tools to be realized, this is where OPF comes into action.

OPF is an optimization problem that adjust control variables (voltages or powers) to optimize an objective function subject to network state and flow constraints to govern the operational decision in order to maintain pre-determined standards and physical limits of the network [63]. The objective function of OPF can be formulized to target different goals, depending on priorities of the operator. Usually, optimization goals are set to whether minimize energy generation costs or to minimize system power losses which in this case aims to operate the system in an efficient manner. Furthermore, the state of network constraints include standards that must be maintained during the operation such as buses voltages, and to balance customer demand and energy generation. Moreover, network flow constraints include physical limits of the network, for instance, maximum loadable current in distribution lines and equipment, and DERs limits.

Researcher over the past 50 years have established many formulations of OPF problem, especially mathematical representation of the network constraints [64]. One of the most well-known representations is the rectangular form representation, where voltage and power variables consist of separated real and imaginary terms. Together with generally considered constraints, form the following optimization problem:

Objective functions:

- Power losses

$$C_1(v) = \sum_{i \in G} P_{G,i} \tag{1}$$

- Power generation costs

$$C_2(v) = \sum_{i \in G} a_{0i} + a_{1i} P_{G,i} + a_{1i} P_{G,i}^2 \tag{2}$$

Power flow constraints for every $i \in N$:

$$P_{G,i} - P_{D,i} = \sum_{j|(i,j) \in \mathcal{E}} \left[v_i^r \left(v_j^r G_{ij} - v_j^{im} B_{ij} \right) + v_i^{im} \left(v_j^{im} G_{ij} + v_j^r B_{ij} \right) \right] \tag{3}$$

$$Q_{G,i} - Q_{D,i} = \sum_{j|(i,j) \in \mathcal{E}} \left[v_i^{im} \left(v_j^r G_{ij} - v_j^{im} B_{ij} \right) - v_i^r \left(v_j^{im} G_{ij} + v_j^r B_{ij} \right) \right] \tag{4}$$

DERs constraints:

$$P_{G,i}^{min} \leq P_{G,i} \leq P_{G,i}^{max} \tag{5}$$

$$Q_{G,i}^{min} \leq Q_{G,i} \leq Q_{G,i}^{max} \quad (6)$$

Bus voltage constraints:

$$(v_j^{min})^2 \leq (v_j^r + v_j^{im})^2 \leq (v_j^{max})^2 \quad (7)$$

The aforementioned equations are an arbitrary representation of OPF problem, the objective function can be as trivial as getting a feasible solution, or can be extended to be more complicated when, for instance, taps of transformers and capacitors are included. Furthermore, the number of constraints heavily depends on the network physical conditions and its operational standards.

The problem of OPF in distribution network is non-convex in its nature; due to nonlinear relationship between voltages and complex power, which makes it hard to solve resulting in rendering many techniques obsolete to approach acceptable results. The acceptable results for practical algorithm, is to obtain nearby global optima, while maintaining short computational time. The fact that the practical problem is large scale, and the fact that it's highly non-convex in nature have forced research studies to focus on tackling one aspect at a time [27][65]. [66].

Techniques such as sequential quadratic optimization, steepest descent-based methods[67], fuzzy dynamic programming [68], and particle swarm optimization [64] have been utilized to develop an OPF algorithm. Generally, these methods are faster, however, their convergence is not guaranteed and it's difficult to qualitative their attained solution in terms of its optimality. Nevertheless, SDP optimization techniques have proven to be successful in obtaining global optima while maintaining a reasonable computational time.

2.5.1 Semi-Definite Programming based Optimal Power Flow

SDP is an emerging subfield of optimization theory that focuses on optimizing rank one variable matrix over positive semi-definite cones in the context of affine space [69]. In other words, it's a generalization of linear programming where the vector of variables are replaced with rank one matrix of variables and the non-negative constraints with a positive semi-definite constraint. The superb proprieties of the semi-definite generalization are: (1) convert the optimization problem to be convex, and (2) has a rich duality theory and theoretically proved efficient solution procedures based on iterating interior points.

A SDP problem have different formulations, we mention below the standard form, the primal dual form

Primal SDP problem:

$$\min A_0 \cdot X \quad (8)$$

$$\text{s.t. } A_i \cdot X = b_i \quad i = 1,2,3 \ldots, n \quad (9)$$

$$X \succcurlyeq 0 \tag{10}$$

Dual SDP problem:

$$\max b^T y \tag{11}$$

$$\text{s.t.}\, A_0 - \sum_{i=1}^{m} y_i A_i \succcurlyeq 0 \tag{12}$$

To apply SDP on OPF, the following procedure has to be taken:

1. Convert the objective function and constraints to quadratic functions that are subject to vector of variable voltages v. After that, complex voltage variables are separated to vector of real parts and vector of imaginary parts, then the two vectors are orderly stacked in one vector.
2. Consider rank one matrix X that corresponds to the self-outer product of the vector of voltages $X = vv^H$.
3. Rearrange the quadratic function in order to form Linear Matrix inequalities of positive semi-definite cones and affine spaces.
4. Lastly, drop the rank one matrix constraint to relax the optimization problem and form a convex feasible region.

After solving the problem, if the optimization solution X is of rank one or two; then the optimal solution of the relaxed problem is indeed a global optima of the original OPF problem before the rank one constraint has been dropped. Furthermore, there are several techniques that can be used to readily obtain the vector of voltages from the optimal solution X. In the context of OPF, the SDP relaxation has been thoroughly investigated in recent studies to establish sufficient conditions at which rank one can be retrieved. These sufficient conditions are found to be substantially depending on the network topology and its physical parameters. Interestingly, many practical tree networks satisfy these conditions.

2.5.1.1 Mathematical formulation of SDP-OPF

Consider a distribution system with B nodes and Ɛ edges. Let v and Y represent complex voltages on the buses and system admittance matrix, respectively. To convert the problem to SDP, the nonlinear relationships in OPF problem: active and reactive injected power per bus, powers flow in the network, and voltages, must be formulated as linear functions of the outer-product matrix$V = vv^T$. To do so, we define the following matrices:

$$\varphi_{P,i} = \frac{1}{2}\left(Y_i + Y_i^H\right) = \begin{bmatrix} 0 & \dots & 0 \\ \vdots & \vdots & \vdots \\ g_{i1} & \dots & g_{in} \\ \vdots & \vdots & \vdots \\ 0 & \dots & 0 \end{bmatrix} \tag{13}$$

$$\varphi_{Q,i} = \frac{j}{2}\left(Y_i - Y_i^H\right) = \begin{bmatrix} 0 & \dots & 0 \\ \vdots & \vdots & \vdots \\ b_{i1} & \dots & b_{in} \\ \vdots & \vdots & \vdots \\ 0 & \dots & 0 \end{bmatrix} \tag{14}$$

$$\varphi_{v,i} = E_{ii} = \begin{bmatrix} 0 & \dots & 0 \\ \vdots & \vdots & \vdots \\ \vdots & 1_{ii} & \vdots \\ \vdots & \vdots & \vdots \\ 0 & \dots & 0 \end{bmatrix} \tag{15}$$

$$\varphi_{i\to j} = \frac{1}{2}\left[A_{ij}^H * e_i^T + e_i * A_{ij}\right] = \begin{bmatrix} 0 & \dots & \dots & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & (-g_{ij})_{ii} & \dots 0 \dots & (g_{ij} + jb_{ij})_{ij} \dots & \vdots \\ \vdots & 0 & \vdots & & \vdots \\ \vdots & (-jb_{ij})_{ji} & \vdots & 0 & \vdots \\ 0 & \dots & \dots & \dots & 0 \end{bmatrix} \tag{16}$$

Where,

$$e_i = [0, \dots, 1_i, \dots, 0] \tag{17}$$

$$E_{ij} = e_i e_j^T \tag{18}$$

$$Y_i = E_{ii} * Y = \begin{bmatrix} 0 & \dots & 0 \\ \vdots & \vdots & \vdots \\ y_{i1} & \dots & y_{in} \\ \vdots & \vdots & \vdots \\ 0 & \dots & 0 \end{bmatrix} \quad i \in B \tag{19}$$

$$A_{ij} = [\, 0_1, \dots\ , 0_{i-1}, -(y_{ij})_i, \dots, 0_{j-1}, (y_{ij})_j, \dots, 0_B] \tag{20}$$

The aforementioned matrices are then utilized to form the following linear relations:

$$\operatorname{tr}\left(\varphi_{v,i} V\right) = |V_i|^2 \tag{21}$$

$$\mathrm{tr}\left(\varphi_{P,i} V\right) = P_{inj,i} \tag{22}$$

$$\mathrm{tr}\left(\varphi_{Q,i} V\right) = Q_{inj,i} \tag{23}$$

$$\mathrm{tr}\left(\varphi_{i\to j} V\right) = P_{i\to j} \tag{24}$$

Finally, using these linear relations, one can convert the nonlinear OPF problem into a SDP- OPF as the following formulation:

Objective function:

- Power Losses

$$C_1^{sdp}(V) = \sum_{(i,j)\in\mathcal{E}} \mathrm{tr}\left(\varphi_{i\to j} V\right) + \mathrm{tr}\left(\varphi_{i\to j} V\right) \tag{25}$$

- Generation cost

$$C_2^{sdp}(V) = \sum_{i\in G} a_{0i} + a_{1i} P_{G,i} + a_{2i} P_{G,i}^2 \tag{26}$$

Power flow constraints

$$P_{G,i} - P_{D,i} = \mathrm{tr}\left(\varphi_{P,i} V\right) \tag{27}$$

$$Q_{G,i} - Q_{D,i} = \mathrm{tr}\left(\varphi_{Q,i} V\right) \tag{28}$$

Bus voltage constraints:

$$(V_i^{min})^2 \le \mathrm{tr}\left(\varphi_{v,i} V\right) \le (V_i^{max})^2 \tag{29}$$

Semi-definitive Constraint on V matrix:

$$V \succcurlyeq 0 \tag{30}$$

2.5.1.2 Distributed SDP-OPF

Suppose a distribution system is divided into a set of Z zones. Each zone is managed by a local operation system (LOS) where OPF is locally solved for the controlled zone. Define $N^{(k)}$ as the set of interlinked zones with the zone $z^{(k)}$. Also, let $\tilde{z}^{(k)}$ denotes the extended zone which includes all the buses of $z^{(k)}$ in addition to the interlinking buses with $z^{(k)}$that belong to $z^{(m)} \in N^{(K)}$. Finally, let $V^{(k)}$ denote the matrix of corresponding elements in V for the voltages on buses of the extended area$\tilde{z}^{(k)}$. Likewise, let $\varphi_{v,i}^{(k)}$,$\varphi_{P,i}^{(k)}$, $\varphi_{Q,i}^{(k)}$ and $\varphi_{i\rightarrow j}^{(k)}$ denote the voltage, active power , reactive power and power flow matrices required to formulate the linear relations in SDP-OPF for the extended zone $\tilde{z}^{(k)}$.

For every zone we formulate the local $\mathrm{OPF}^{(k)}$ for the zone $z^{(k)}$ as follow:

$$\text{minimize } C_i^{sdp\,(k)}(V^{(k)}) \tag{31}$$

Subject to the following constraints $\mathrm{const}^{(k)}$:

$$P_{G,i} - P_{D,i} = \mathrm{tr}\left(\varphi_{P,i}^{(k)} V^{(k)}\right) \;\forall\, i \in z^{(k)} \tag{32}$$

$$Q_{G,i} - Q_{D,i} = \mathrm{tr}\left(\varphi_{Q,i}^{(k)} V^{(k)}\right) \forall\, i \in z^{(k)} \tag{33}$$

Bus Voltage constraints:

$$(V_i^{min})^2 \le \mathrm{tr}\left(\varphi_{v,i} V^{(k)}\right) \le (V_i^{max})^2 \;\forall\, i \in z^{(k)} \tag{34}$$

Semi-definitive Constraint on V matrix:

$$V^{(k)} \succcurlyeq 0. \tag{35}$$

In addition to, interlinking constraints between zones that share connected buses are introduced for every $z^{(m)} \in N^{(K)}$:

$$\mathrm{real}([V^{(k)}]_m) = R_{(m)}^{(k)} \tag{36}$$

$$\mathrm{imag}([V^{(k)}]_m) = IM_{(m)}^{(k)} \tag{37}$$

$$R_{(m)}^{(k)} = R_{(k)}^{(m)} \tag{38}$$

$$IM_{(m)}^{(k)} = IM_{(k)}^{(m)} \tag{39}$$

Where, $R_{(m)}^{(k)}$ and $IM_{(m)}^{(k)}$ are auxiliary variables defined for each zone $z^{(k)}$ corresponding to every connection with a neighbor zone $z^{(m)} \in N^{(K)}$. These auxiliary variable are introduced to enable distributed optimization by exchanging this local information represented on the voltages across the shared buses and to ensure the consistency of the solution represented in$V^{(k)}$.

To apply alternating direction method of multipliers (ADMM) for distributed optimization solver, define the multipliers $T_{(m)}^{(k)}$ and $F_{(m)}^{(k)}$ associated with constraints in (36) and (37). Then, iteratively perform the following steps:

For each area $z^{(k)}$:

1) For iteration $i = 1$, initialize:

$$T_{(m)}^{(k)}(i) = 0 \tag{40}$$
$$F_{(m)}^{(k)}(i) = 0 \tag{41}$$

2) Update $V^{(k)}(i+1)$ by solving local $\mathrm{OPF}^{(K)}$:

$$\min_{V^{(k)} \succcurlyeq 0} C_i^{sdp\,(k)}\left(V^{(k)}\right) + \sum_{m \in N^{(k)}} \begin{array}{c} [\,(\,a_m + b_m) + tr(\,T_{(m)}^{(k)}\,(i) * real\left(\left[V^{(k)}\right]_m\right)\right) \\ + tr(\,F_{(m)}^{(k)}(i) *\ imag\left(\left[V^{(k)}\right]_m\right)\right)] \end{array} \tag{42}$$

$$V^{(k)} \in\ const^{(k)} \tag{43}$$

For every $z^{(m)} \in N^{(K)}$, subject to :

$$\begin{bmatrix} -\,a_m & rw_m \\ rw_m & -I \end{bmatrix} \preccurlyeq 0 \tag{44}$$

$$\begin{bmatrix} -\,b_m & iw_m \\ iw_m & -I \end{bmatrix} \preccurlyeq 0 \tag{45}$$

Where,

$$rw_m = real\ (\ vec\ (\ [V^{(k)}]_m - \frac{1}{2}(\left[V^{(k)}(i)\right]_m + \left[V^{(m)}(i)\right]_k))\right) \tag{46}$$

$$iw_m = imag(\ vec\ ([V^{(k)}]_m - \frac{1}{2}(\left[V^{(k)}(i)\right]_m + \left[V^{(m)}(i)\right]_k\ ))\right) \tag{47}$$

$$b_m \geq 0, \qquad a_m\ \geq 0 \tag{48}$$

3) Update multipliers $T_{(m)}^{(k)}(i+1)$, and $F_{(m)}^{(k)}(i+1)$ for every $z^{(m)} \in N^{(K)}$ such that:

$$T_{(m)}^{(k)}(i+1) = T_{(m)}^{(k)}(i) + \frac{r}{2} * \mathrm{real}([V^{(k)}(i+1)]_m - [V^{(m)}(i+1)]_k) \quad (49)$$

$$F_{(m)}^{(k)}(i+1) = F_{(m)}^{(k)}(i) + \frac{r}{2} * \mathrm{imag}([V^{(k)}(i+1)]_m - [V^{(m)}(i+1)]_k) \quad (50)$$

Where, r is constant > 0

After each iteration, LOS of zone $z^{(k)}$ exchange local information about the voltages on the interlinking buses with neighbor zone $z^{(m)}$ in the form of $[V^{(m)}]_k$ for all $z^{(m)} \in N^{(K)}$.

2.6 Summary

This chapter has summarized the background of smart grids and how they are operated using EMS. It has also discussed various types of DSM, in particular, DR and how they are implemented during the operational planning. Lastly, a brief overview OPF problem has been provided, followed by a detailed description of the mathematical optimization tool that is utilized in this work, DSDP.

Chapter 3

Proposed Zone-Distributed Optimization System

3.1 Introduction

As discussed in previous chapter, there is a need for a distributed control scheme that is founded on a comprehensive mathematical tool to enable flexibility and scalability. This chapter presents the methodology and the mathematical formulation for zone-distributed optimization system combining generation resources such as diesel generators and ESSs with DR programs taking into account different types of loads.

3.2 Methodology

Different zones in the distribution system have a diverse characteristics and requirements. Since every zone is usually accommodated by clusters of single type of customers such as clusters of industrial facilities, educational institutions, commercial and residential buildings. As a consequence, the requirements differ between every zone depending of customer type of cluster that inhabits the zone in terms of the amount of power consumption, power quality and the owner's objectives. Also, the dissimilarities in characteristics are reflected in the deterministic behavior of customer's consumption profile, availability of ESSs and DERs, as well as the degree of flexibility and response to the variation in electricity prices.

A Zone-Distributed Optimization System (ZDOS) is developed in this work, which control the network by a number of zone-specific optimization subsystems (ZSOS), where each subsystem take into consideration the nature and the requirements of the virtual zone such as demands response strategy and customers' preferences, which are then integrated through ZDOS. The implementation of ZDOS provides high flexibility to accommodate preferences of multiple participants, and split the huge network into small subnetworks so that each subnetwork is capable to take into account all the variables, constraints and zone-customized objective. Unlike microgrids, where physical boundaries are determined according to the power generation self-sufficiency and their ability to operate in both connected and disconnected modes [70]. In the proposed approach, zones are determined such that each zone accommodate homogenous type of customers that share common preferences and characteristics regardless of the power generation self-sufficiency.

Each ZSOS consist of peripherals and a set of multi multidisciplinary algorithms that works together to achieve single objective that is set by the utility or zone operator. To illustrate, ZSOS communicate with the zone customers, network's equipment and ZDOS. It exchange information with the customer in the zone to gather data as current demand, requirements, demand response signals and objectives.

After that, to produce proper decisions, ZSOS solve zone specific optimization problem that incorporate all the communicated information with the forecasted loads in order to optimize objective function set by the zone participants. The optimization algorithm is capable to exchange information with ZDOS during the optimization process in order to obtain global optimal solution in terms of power balance, state variables, and constraints satisfaction.

3.3 Mathematical formulation of ZDOS

3.3.1Objective function

Several objective functions are well known in the context of power network's operation. These objectives are subject to utilities strategies goals as well as participating customers' preferences.

a. Losses minimization:
   Minimizing the electric losses in the system is effective approach in increasing system efficiency, reducing emissions, and preventing line overloads.

$$J_{loss}^{(k)} = \sum_{t=1}^{T} \sum_{(i,j)\in \mathcal{E}} \mathrm{tr}\left(\varphi_{i\to j}^{(k)} V^{(k),t}\right) + \mathrm{tr}\left(\varphi_{i\to j}^{(k)} V^{(k),t}\right) \tag{51}$$

b. Minimization of operational cost:
Operational costs includes the cost of fuel consumption as well as cost of load shifting under the utilization of DR.

$$J^{(k)}_{operation} = \sum_{t=1}^{T} [\sum_{i \in G^{(k)}} a_{0i} + a_{1i} P^t_{G,i} + a_{2i} (P^t_{G,i})^2 + \sum_{i \in B^{(k)}} c^t_{shft,i} * P^t_{shft,i}] \tag{52}$$

c. Green emission.

$$J^{(k)}_{CO_2} = \sum_{t=1}^{T} \sum_{i \in G^{(k)}} C_{em,i} \, P^t_{G,i} \tag{53}$$

To this end, total objective function of DSDP for each zone is the following:

$$\begin{aligned} J^{(k)}(V^{(k)1,\ldots,t}) = {} & J^{(k)}_{Operation/Losses/CO_2} \\ & + \sum_{t=1}^{T} \sum_{m \in N^{(k)}} \begin{aligned}[t] & [(a^t_m + b^t_m) + tr(T^{(k),t}_{(m)} (i) * real \left([V^{(k),t}]_m \right)) \\ & + tr(F^{(k),t}_{(m)} (i) * \; imag \left([V^{(k),t}]_m \right))] \end{aligned} \end{aligned} \tag{54}$$

3.3.2 Operational Constraints

a. Generator Constraints:
The DGs' active and reactive power generation are constrained by the maximum and minimum limits, which are usually imposed by the DG's physical and control limitations.

$$P^{min}_{G,i} \le P^t_{G,i} \le P^{max}_{G,i} \quad \forall \, i \in \; G^{(k)} \tag{55}$$

Furthermore, DGs are constrained by maximum change rate of the output power:

$$|P^t_{G,i} - \; P^{t-1}_{G,i}| \le P^{ramp}_{G,i} \; \forall \, i \in \; G^{(k)} \tag{56}$$

b. ESS Constraints
They are limited by the change rate of charging /discharging process as follows:

$$|P^t_{Bat,i}| \le P^{ramp}_{Bat,i} \quad \forall \, i \in \; E^{(k)} \tag{57}$$

Moreover, the maximum ESS storage capacity is constrained by the following equation:

$$0 \leq P^{t}_{Bat,i}.\, t + E^{t}_{Bat,i} \leq E^{max}_{Bat,i} \tag{58}$$

c. DR Constraints:
Direct Load control is considered in the operation of the distribution. Therefore, load shifting is solely controlled by the ZDIOS. In this context, each customer has a predefined load control range per time interval within which, the ZDIOS can increase/ decrease power demand per time interval taking into account customer's preferences. Although the power demand is controlled by ZDIOS; it important to ensure that the total power demand in a day is maintained constant. In other words, a customer's daily activity can be shifted, but must be carried out in the same day.

$$\sum_{t=1}^{T} P^{t}_{shft,i} = 0 \;\; \forall\, i \in B^{(k)} \tag{59}$$

$$P^{min.t}_{shft,i} \leq P^{t}_{shft,i} \leq P^{max,t}_{shft,i} \;\; \forall\, i \in B^{(k)}, \forall t \in T \tag{60}$$

d. Power balance constraints:
These equations represent the mathematical description of power flow in the network. Also, they integrate the different components of the network as well as take into account the network's losses in order to maintain supply-demand balance.

$$\left[P^{t}_{G,i} + P^{t}_{Bat,i}\right] - \left[P^{t}_{D,i} - P^{t}_{shft,i}\right] = tr\left(\varphi^{(k)}_{P,i} V^{(k),t}\right) \;\; \forall\, i \in z^{(k)}, \forall\, t \in T \tag{61}$$

$$Q^{t}_{G,i} - Q^{t}_{D,i} = tr\left(\varphi^{(k)}_{Q,i} V^{(k),t}\right) \;\; \forall\, i \in z^{(k)}, \forall\, t \in T \tag{62}$$

e. Network's standard constraints:
The voltage level at each bus should be maintained within specified limits during every interval in the operation time.

$$(V^{min}_{i})^2 \leq tr\left(\varphi^{(k)}_{Q,i} V^{(k),t}\right) \leq (V^{max}_{i})^2 \;\forall\, i \in B^{(k)}, \forall\, t \in T \tag{63}$$

f. D-SDP constraints for every $z^{(m)} \in N^{(K)}$, $t \in T$:

$$V^{(k),t} \succcurlyeq 0 \tag{64}$$

$$\begin{bmatrix} -\,a^{t}_{m} & rw^{t}_{m} \\ rw^{t}_{m} & -I \end{bmatrix} \preccurlyeq 0 \tag{65}$$

$$\begin{bmatrix} -\,b_m^t & iw_m^t \\ iw_m^t & -I \end{bmatrix} \preccurlyeq 0 \tag{66}$$

Where,

$$rw_m^t = \mathrm{real}\left(\mathrm{vec}\left([V^{(k),t}]_m - \tfrac{1}{2}([V^{(k),t}(i)]_m + [V^{(m),t}(i)]_k\right)\right)) \tag{67}$$

$$iw_m^t = \mathrm{imag}\left(\mathrm{vec}\left([V^{(k),t}]_m - \tfrac{1}{2}([V^{(k),t}(i)]_m + [V^{(m),t}(i)]_k\right)\right)) \tag{68}$$

$$a_m^t \geq 0, \qquad b_m^t \geq 0 \tag{69}$$

Multipliers' updating every iteration for every $z^{(m)} \in N^{(K)},\ t \in T$

$$T_{(m)}^{(k),t}(i+1) = T_{(m)}^{(k),t}(i) + \frac{r}{2} * \mathrm{real}([V^{(k),t}(i+1)]_m - [V^{(m),t}(i+1)]_k) \tag{70}$$

$$F_{(m)}^{(k),t}(i+1) = F_{(m)}^{(k),t}(i) + \frac{r}{2} * \mathrm{imag}([V^{(k),t}(i+1)]_m - [V^{(m),t}(i+1)]_k) \tag{71}$$

Chapter 4

Simulation Results and Analysis

4.1 System Description.

The proposed ZDOS has been demonstrated on a modified 123-IEEE test feeder. The voltage regulators has been replaced with lines, and buses connected with a normally closed switches are merged into one bus. The 123-IEEE test feeder has been modified to be balance, Figure 2 shows a single-line diagram of the test feeder. Detailed information about the network's line parameters and loads are listed in Appendix A. The distribution system is divided into four zones:

1) Zone 1: it consists of 50 residential loads, and it's connected to zone 2 at bus 52. Moreover, the distribution system is connected to the main grid at bus 115 in the same zone. In total, it has four DERs: a DG, ESS as well as two RERs. Details of DERs parameters, generation costs and capacities are given in Table 1.

Type	Bus	Ramp rate	Capacity	base cost coefficients		
		KW/Hr	KW	a_2 $\$/KW^2$	a_1 $\$/KW$	a_0
PCC	115	800	1500	1.09	0.98	1.3
DG	44	300	420	1.102	0.97	1.2
ESS	40	150	450	N/A	N/A	N/A
PV	22	N/A	50	N/A	N/A	N/A
WT	33	N/A	100	N/A	N/A	N/A

Table 1: DERs parameters of zone 1

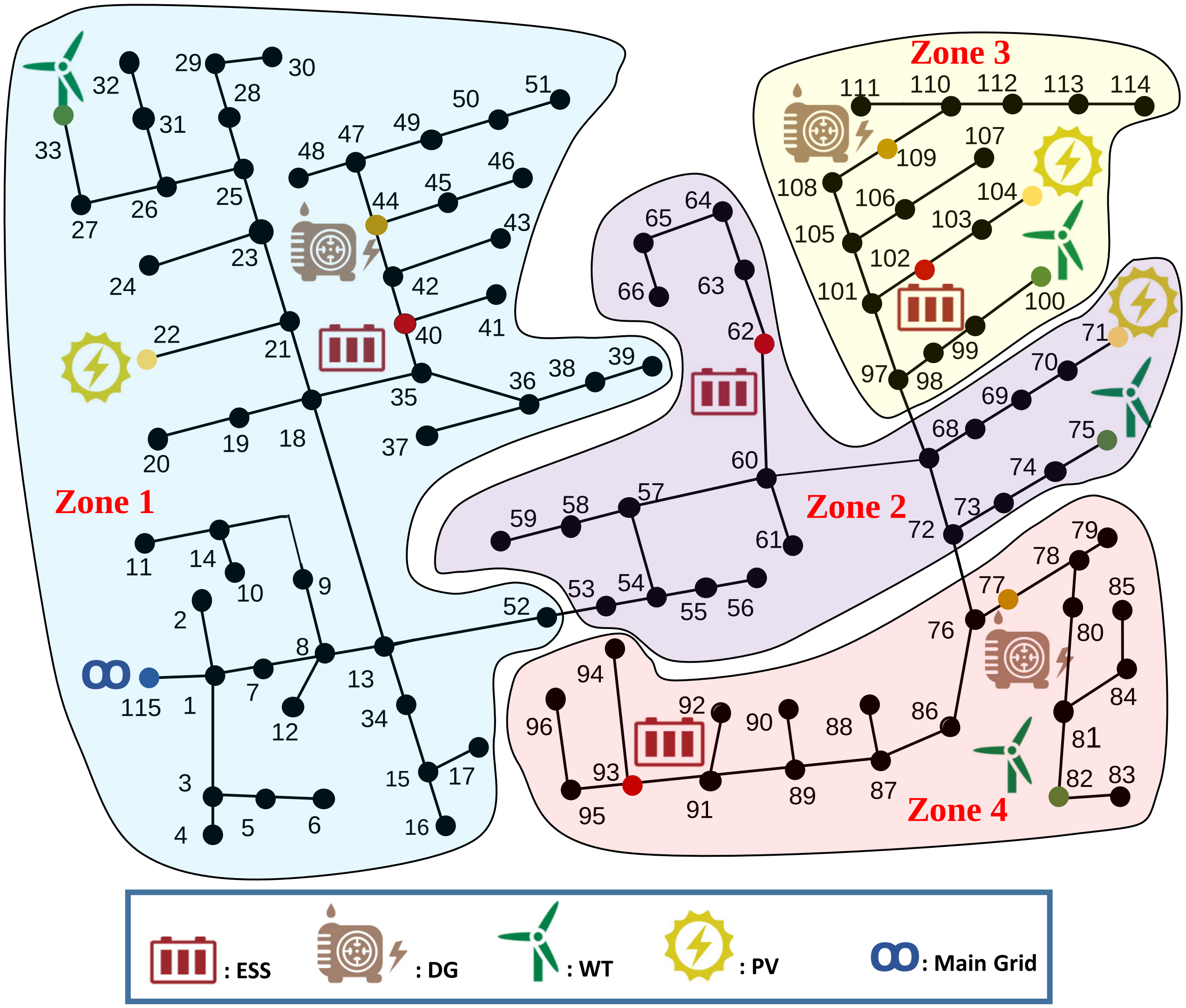

Figure 2: Modified 123-IEEE Test Feeder

2) Zone 2 is mainly a commercial zone, consists of 17 spot loads. This zone interconnects the whole distribution system. It's connected with zone 3 at bus 67, and connected with zone 4 at bus 72. The zone is supplies by one ESS and two RERs, Details are given in Table 2.

Type	Bus	Zone	Ramp rate	Capacity	base cost coefficients		
			KW/Hr	KW	a_2 $/KW^2	a_1 $/KW	a_0
ESS	62	2	100	350	N/A	N/A	N/A
PV	71	2	N/A	100	N/A	N/A	N/A
WT	75	2	N/A	50	N/A	N/A	N/A

Table 2: DERs parameters of zone 2

1) Zone 3 is an industrial zone that accommodate 13 loads and connected to zone 2 at bus 97. The zone has four DERs in total, one DG, an ESS as well as two RERs. Details of DERs parameters, generation costs and capacities are given in Table 3.

Type	Bus	Zone	Ramp rate	Capacity	base cost coefficients		
			KW/Hr	KW	a_2 $/KW^2	a_1 $/KW	a_0
DG	109	3	100	300	1.1032	0.89	1.24
ESS	102	3	50	150	N/A	N/A	N/A
PV	104	3	N/A	60	N/A	N/A	N/A
WT	100	3	N/A	70	N/A	N/A	N/A

Table 3: DERs parameters of zone 3

2) Zone 4 is small residential zone which supplies power to 16 loads and connected to zone 2 at bus 76. The zone is supplies by one DG and an ESS, Details are given in Table 4.

<table>
<tr><th rowspan="2">Type</th><th rowspan="2">Bus</th><th rowspan="2">Zone</th><th>Ramp rate</th><th>Capacity</th><th colspan="6">base cost coefficients</th></tr>
<tr><th>KW/Hr</th><th>KW</th><th colspan="2">a_2 $/KW^2</th><th colspan="2">a_1 $/KW</th><th colspan="2">$a_0$</th></tr>
<tr><td>DG</td><td>77</td><td>4</td><td>300</td><td>700</td><td colspan="2">1.1023</td><td colspan="2">0.98</td><td colspan="2">1.3</td></tr>
<tr><td>ESS</td><td>93</td><td>4</td><td>50</td><td>150</td><td colspan="2">N/A</td><td colspan="2">N/A</td><td colspan="2">N/A</td></tr>
<tr><td>PV</td><td>82</td><td>4</td><td>N/A</td><td>82</td><td>4</td><td>N/A</td><td>60</td><td>N/A</td><td>N/A</td><td>N/A</td></tr>
</table>

Table 4: DERs parameters of zone 4

4.1.1 Load profiles:

There are different types of loads that are supplied by the distribution system. Each type of customer has different behavior, characteristics and preferences. In this proposal, customers are classified into three main types of loads: residential, commercial and industrial.

1) Residential: these loads have the highest power consumption, since they represent the vast majority of customers. They are characterized by random behavior, and their preferences usually lay around lower power quality and minimum electricity cost. The considered load profile for this type of loads in the proposal is shown in Figure 3.

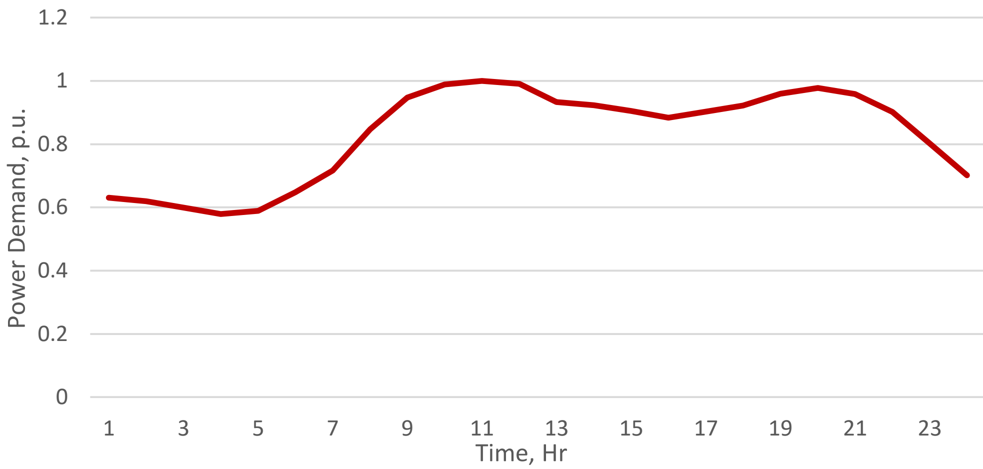

Figure 3: Residential load profile

2) Commercial: these loads are most often present in residential area, with relatively higher demands. Their load profile is deterministic, and they require a high power quality. The load profile taken into account for this type of loads is shown in Figure 4.

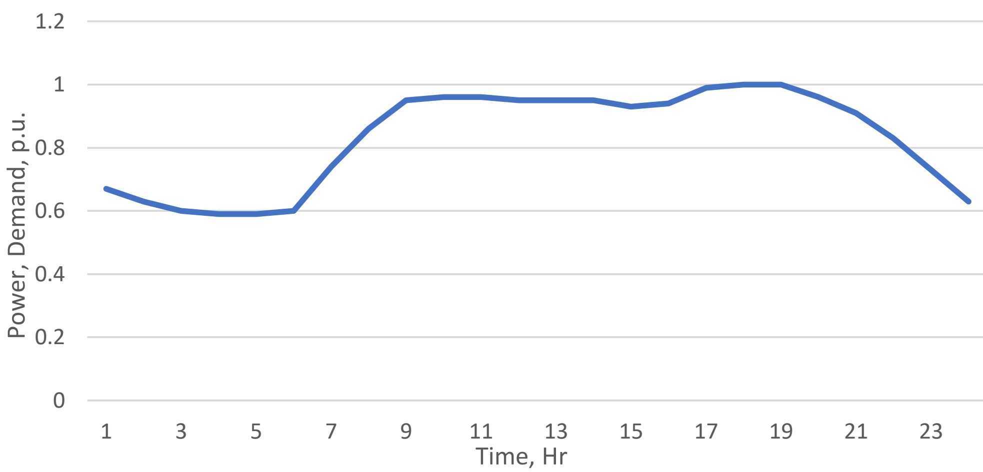

Figure 4: Commercial load profile

3) Industrial: They have a wide range of variations in their load magnitudes. Furthermore, their load profile is deterministic. Therefore, a very simple load profile has been considered for this type of load, as shown in Figure 5.

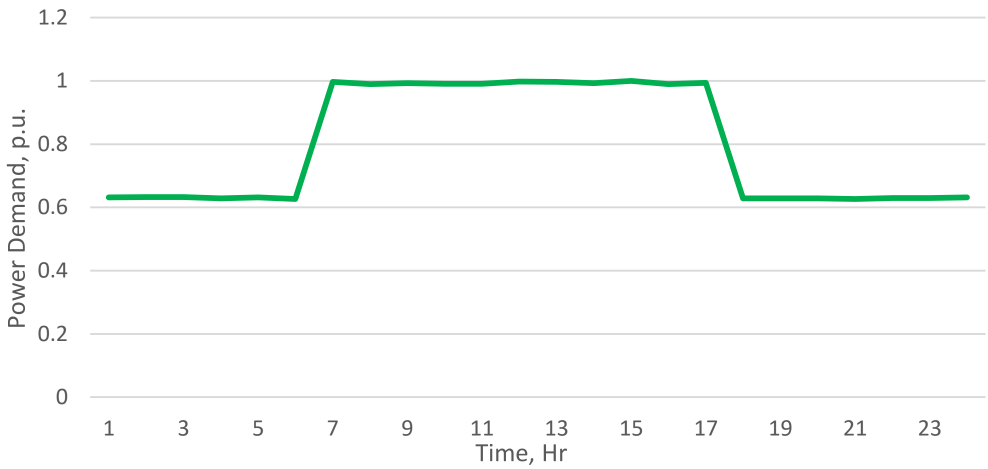

Figure 5: Industrial load profile

4.1.2 Demand Response:

The DR strategy applied in the proposal is DLC. It' assumed that utility has a predetermined agreement with the customers the allow ZDOS to shape and control the electricity consumption within a specified limits which are set according to customers' preferences in return to a predetermined day ahead price. The utility pays the customers proportional to the amount of load shifted.

Residential customers are flexible and willing to decrease their comfort level in return to payed incentives or reduction in electricity prices. Figure 6 shows that demand shifting for residential loads interval is ±5% of power demand at any time interval. Furthermore, commercial and industrial loads are agreed to shift power demand only during working hours with limited flexibility of ±4%. Figure 7 and Figure *8* show demand shifting interval for commercial and industrial loads, respectively.

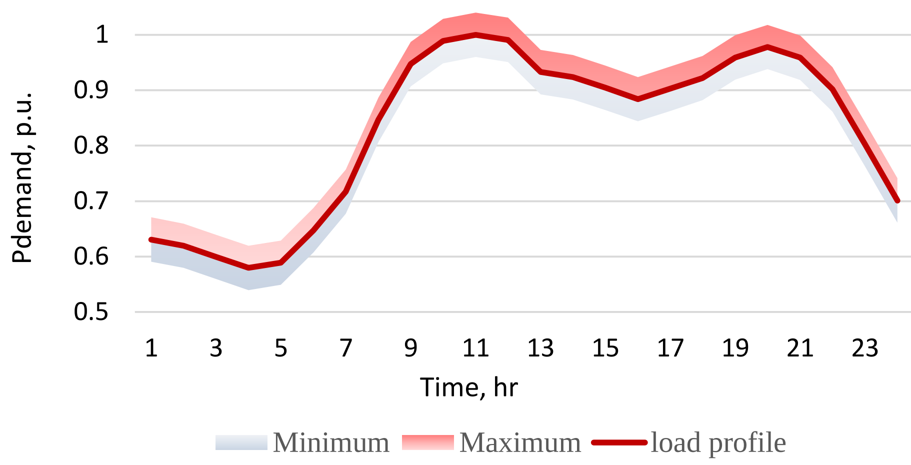

Figure 6: Demand shifting interval for Residential loads

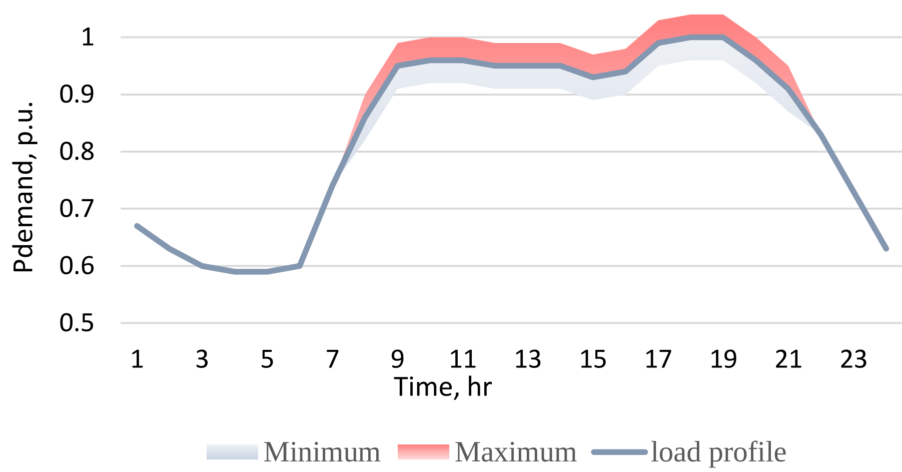

Figure 7: Demand shifting interval for Commercial loads

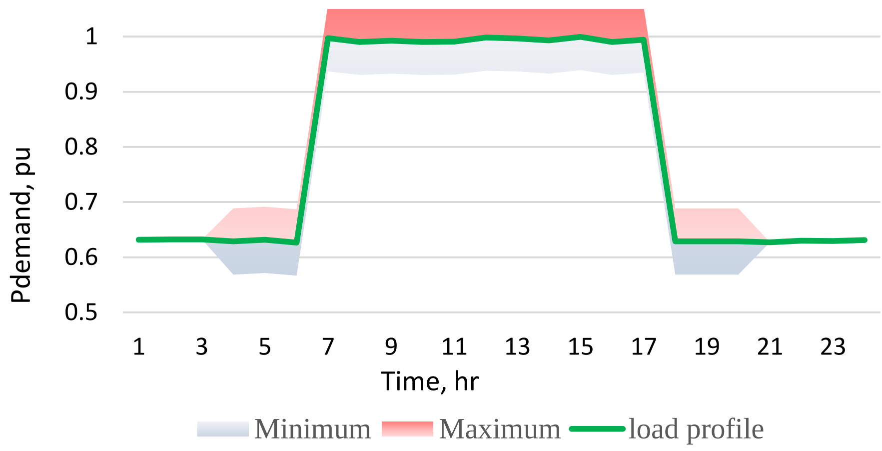

Figure 8: Demand shifting interval for Industrial loads

4.1.3 DR incentives

Three different incentive schemes have been considered in this proposal. Figure 9 shows these schemes which are designed for different types of loads.

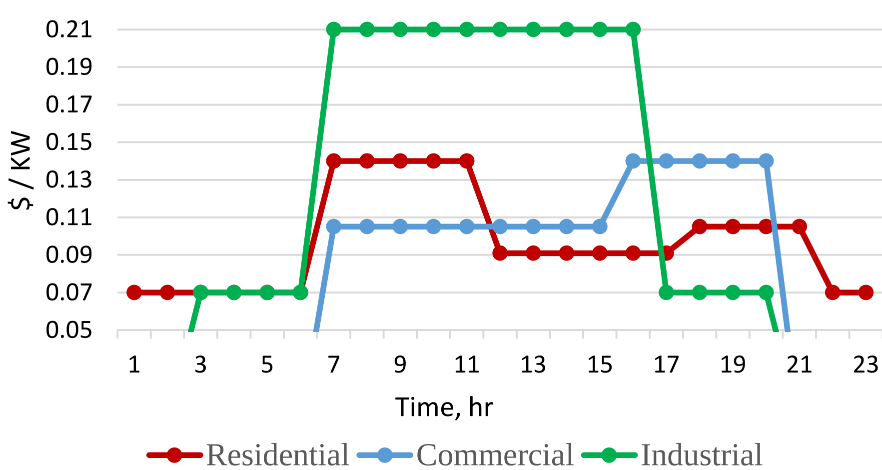

Figure 9: DR incentives

4.1.4 Time of Use Pricing

Essentially, the following pattern shown in Figure 10 will be multiplied by the base cost coefficients of the system's DERs to represent TOU pricing for each DER in the system.

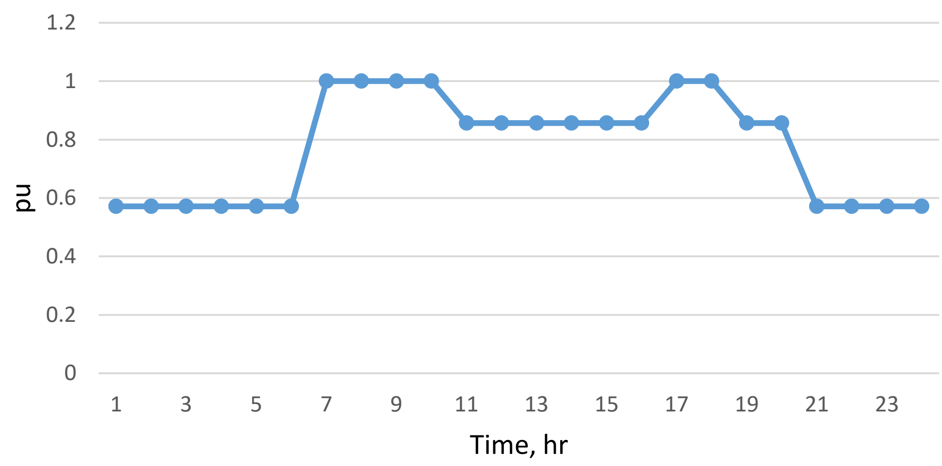

Figure 10: Time of Use Pricing

4.1.5 RER profiles:

Various factors affect the performance of PVs and WT such as temperature, wind speed, and solar radiation. In this work two different generation profiles are considered for both types of RER resources as shown in Figure 10 .

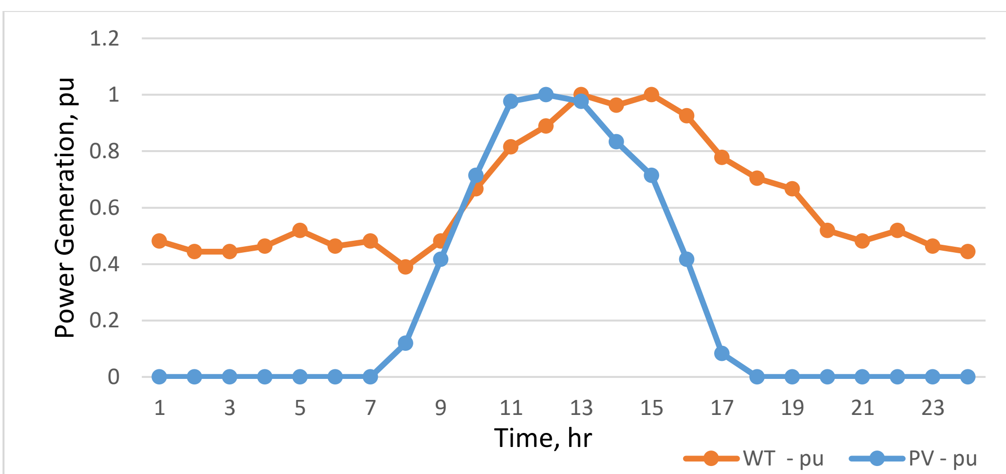

Figure 11: RERs power generation profile

4.2 Performance Evaluation

A number of different cases and scenarios have been simulated on IEEE-123 test feeder in order to evaluate the performance of the proposed ZDIOS and explore the potential benefits of applying the approach on smart environment that applies DR and DERs.

4.2.1 Case 1: Single objective ZDOS without taking into consideration DR programs

In this case, evaluation tests are performed to investigate the validity of the results obtained by the proposed ZDOS. To do so, the balance of power supply – demand of ZDOS results for each zone as well as for the whole system are checked. Furthermore, an analysis about power flow between different components and power exchange between zones is presented for the sake of comparison on further sections. Single objective ZDOS is utilized in this case for the purpose of minimizing operational costs of the whole system without taking into account DR programs.

The power demand and supply in zone 1 using ZDOS can be seen in Figure 12 and Figure *13*, respectively. As shown in Figure 13, power demand including losses in zone represented as blue line matches power supply during the whole at each time interval, therefore, the results of ZDOS has achieved a solution that balances supply-demand in the zone taking into account power transfer to other zone. Customers in the zone consumes a high portion of the power supplied in the zone. Also, it's noticed that ESS charges power during TOU mid peak times only, increasing the total power demand during these times of the day. Furthermore, the power transfer from zone 1 to zone 2 is consistently maintained during the whole day at a constant transfer rate. Since the objective function is to minimize operational costs ZDOS set PCC to supply 60% of total power supply to the zone as seen in Figure 13 due to its relatively low cost. Moreover, ZDOS utilizes ESS to discharge power during TOU peak times to supply cheaper power.

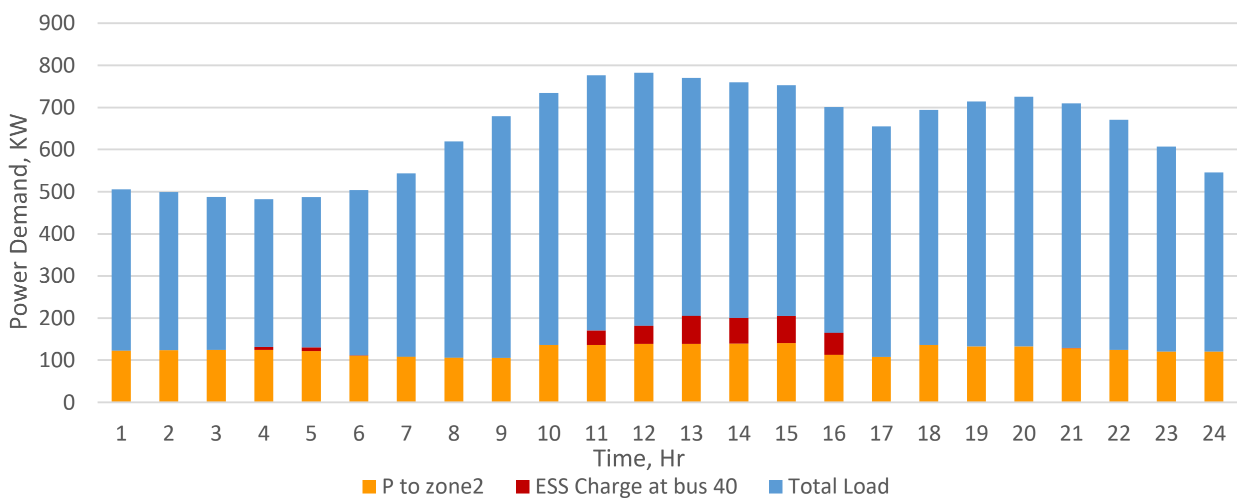

Figure 12: Power demand in zone 1 while minimizing operational costs without DR

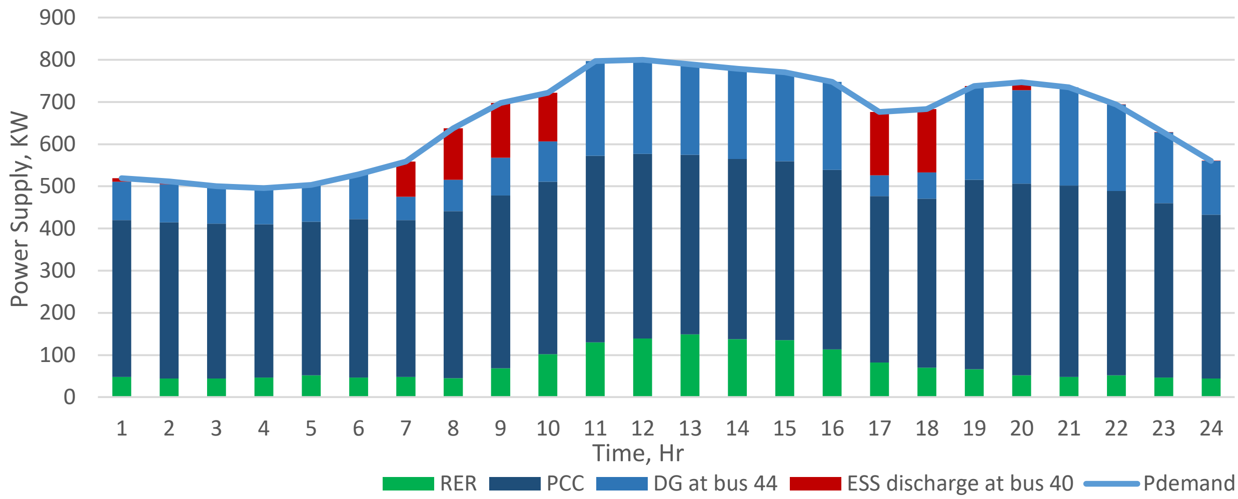

Figure 13: Power supply in zone 1 while minimizing operational costs without DR

Similar to the results of zone 1, the balance of power supply-demand is successfully maintained for every hour during the day as shown in Figure 15. Since zone 2 is connected to all other zones, it can been seen the power demand and supply is of higher complexity by including power transfer to and from other zones. In Figure 14, the power demand takes the shape of commercial customer load profile as expected, with an addition to few and small power transfer to other zones during TOU mid peak times. Furthermore, ESS charge/discharge pattern is unmistakably reasonable. First, ESS discharges power during TOU morning peak times, then after the stored power is entirely drained, ESS charges during TOU mid-peak times to store power in order to be utilized again during TOU evening peak times with the same manner, as result, ZDOS minimize the total operational costs for the day.

Power generation in zone 2 is limited to low power RERs which at maximum generation times can supply up to half the load. Therefore, most of the power supplied to zone 2 is coming from zone 1 since it has high power generation capacity as can be seen in Figure 15. Furthermore, zone 2 is supplied constantly from both zones 3 and 4 at different power transfer rates. Power exchange increases during TOU off-peak times and times of RER low level power generation. Similarly, ESS at bus 62 is exploited to store power at times where the generation is cheaper and supplies power back to the zone when the generation is at its peak prices.

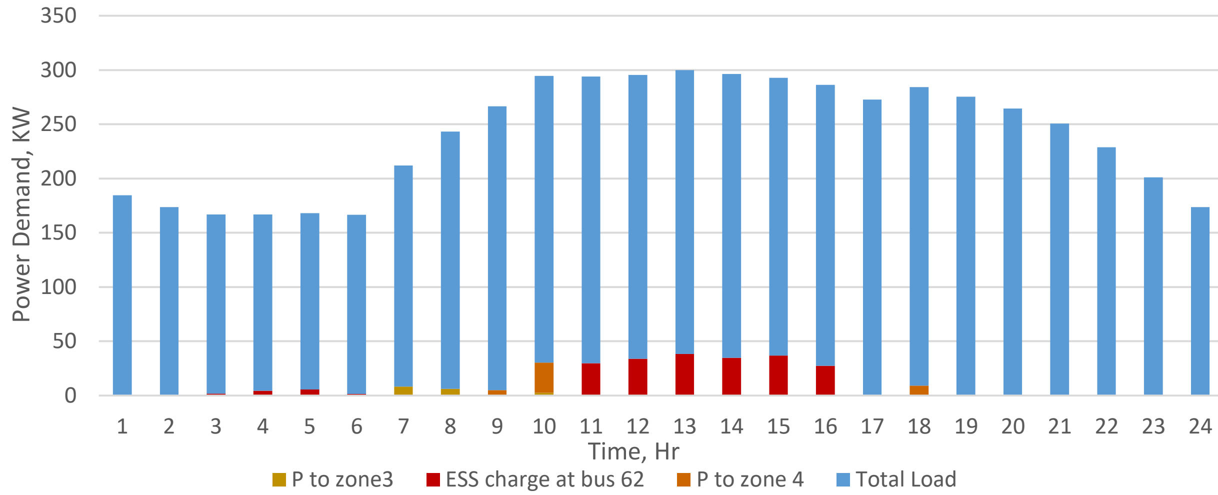

Figure 14: Power demand in zone 2 while minimizing operational costs without DR

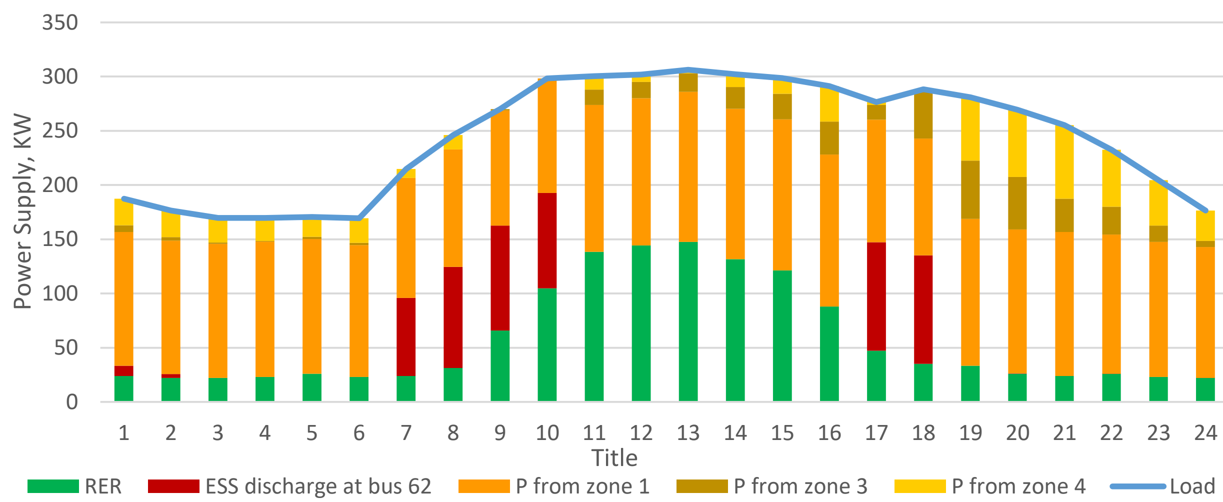

Figure 15: Power supply in zone 2 while minimizing operational costs without DR

For zone 3, power demand and supply using ZDOS are shown in Figure 16 and Figure *17* , respectively. As in Figure 16, power consumption in zone 3 consist of local customers in the zone which consume a large amount of power during TOU morning peak times and reduces it's consumption in night and early mornings. Since its peak time consumption occurs during TOU peak times. ZDOS sets ESS to be charged at times of TOU mid-peaks using the aforementioned analogy on managing ESS in zones 1 and 2. Furthermore, zone 3 start to supply zone 2 at 11:00 with low amount of power, and increases when local power demand and TOU prices decreases after 18:00.

Since dispatchable DERs, expect DG at bus 109, are located far from zone 3. The DG at bus 109 is highly utilized in supplying most of the power demand in the zone accounting for more than 70% at most of the time. The DG generation decreases during RER generation peak times during time from 10:00 to 16:00, as well as at specific times around highest TOU peak times when ESS are utilized to reduce operational costs.

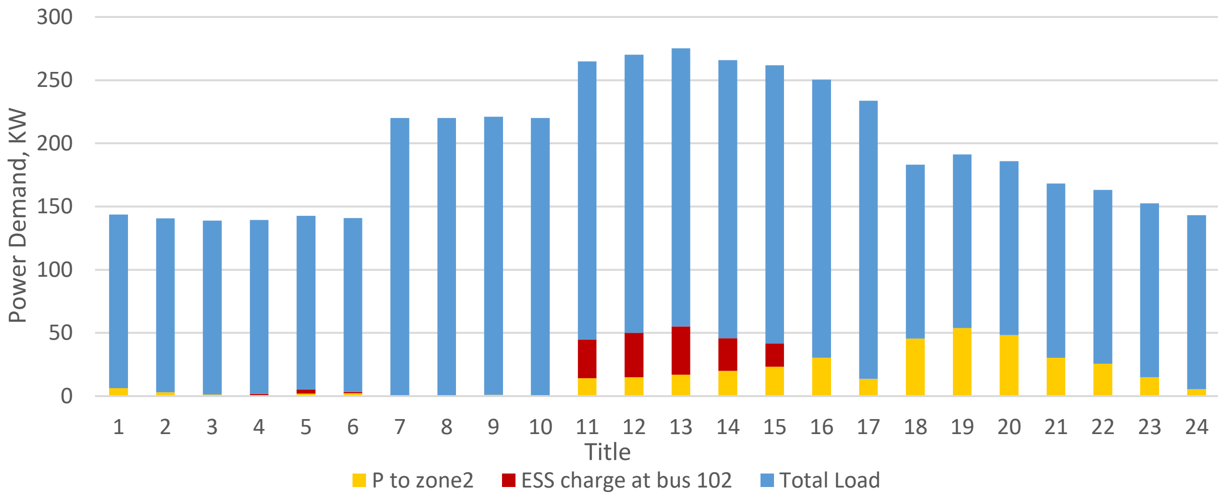

Figure 16: Power demand in zone 3 while minimizing operational costs without DR

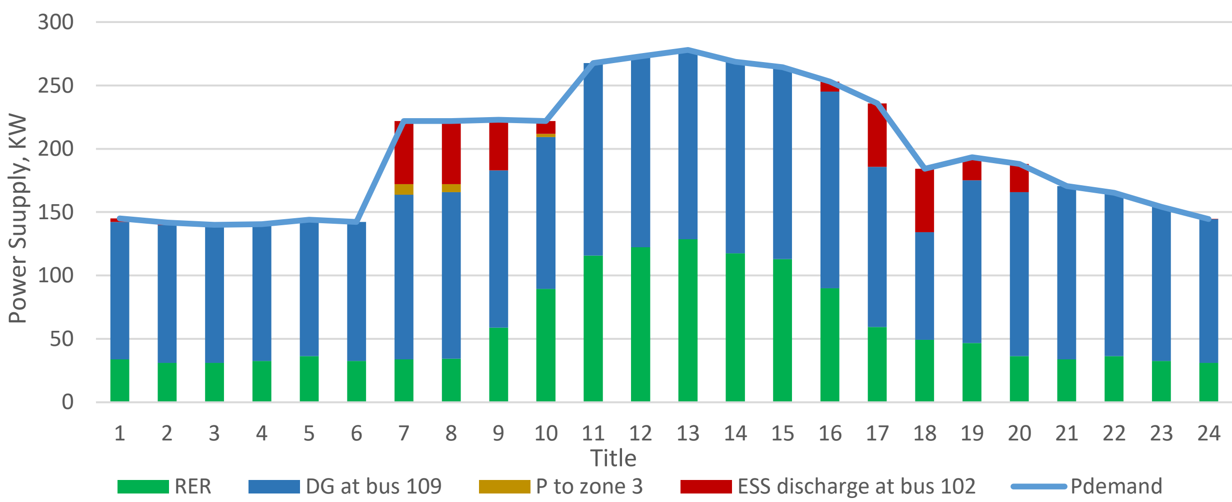

Figure 17: Power supply in zone 3 while minimizing operational costs without DR

In addition to power consumption by residential customers in the zone, zone 4 supplies zone 2 with a small amount of power during the course of the day except around TOU peak times where ZDOS aggressively utilizes PCC for its cheap power cost as can be seen in Figure 18.

As shown in Figure 19, most of supplied power to the zone is coming from the local DG due to the fact that RER are very limited. Moreover, since ESS stored power is utilized in the first TOU peak times, ZDOS set ESS to be recharged during mid-peak times to prepare for the second TOU peak time that starts around 17:00, similarly to results of all other zones in order to reduce operational costs.

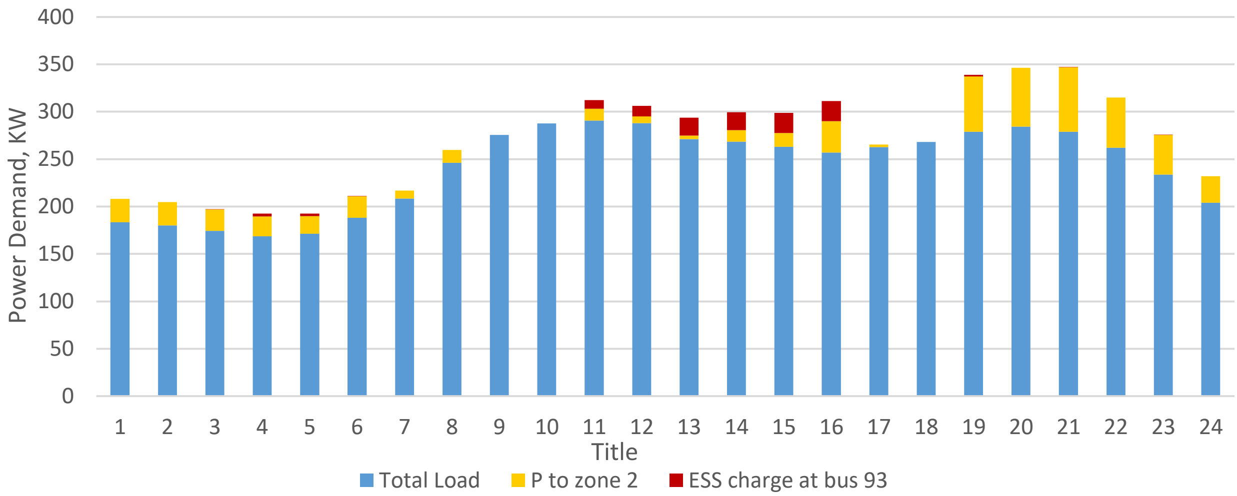

Figure 18: Power demand in zone 4 while minimizing operational costs without DR

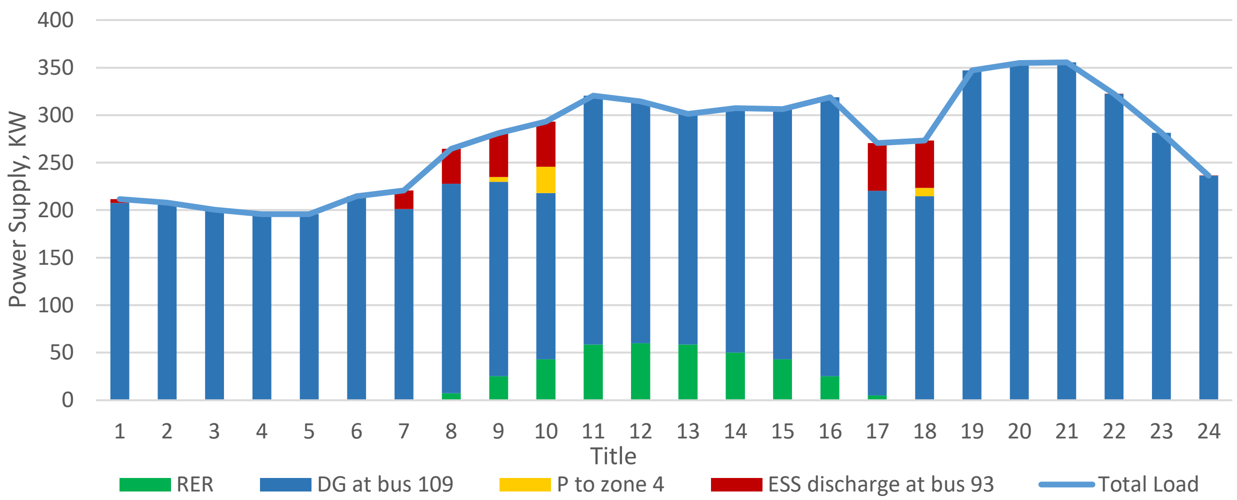

Figure 19: Power supply in zone 4 while minimizing operational costs without DR

In Figure 20 and Figure *21*, power demand and supply in the whole system is aggregated to investigate supply demand balance over the system for results of ZDOS, respectively. Indeed, the results of ZDOS have proven to be correct since supply-demand balance is preserved as can be readily observed. To summarize ZDOS operational strategy in minimizing operational costs:

power supply from DERs is reduced during RERs high level generation as well as during TOU peak times where ZDOS rely on PCC to obtain cheaper power. Furthermore, ESSs are utilized to supply power during TOU morning peak times, recharged again during midday before the TOU evening peak times in order to minimize power generation during these times.

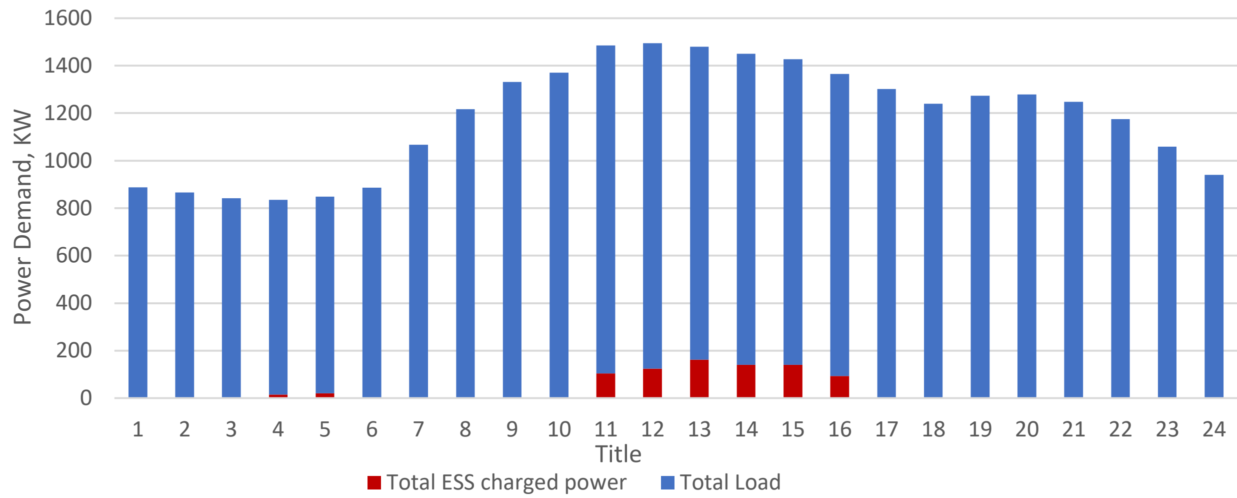

Figure 20: Power demand in the system while minimizing operational costs without DR

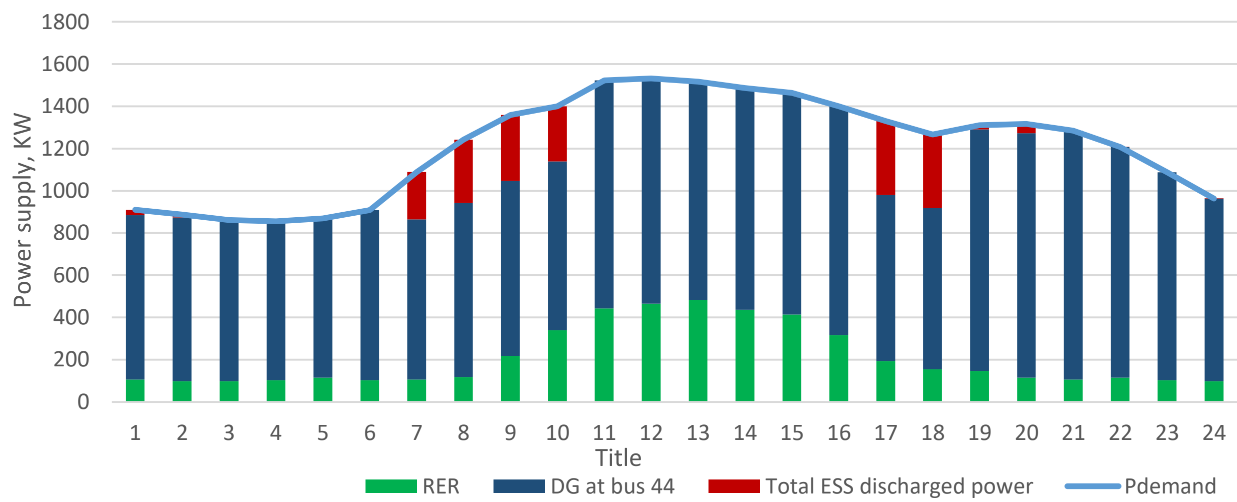

Figure 21: Power supply in the system while minimizing operational costs without DR

4.2.2 Case 2: Single Objective ZDOS taking into consideration DR programs.

Incorporation of DR programs into the task of energy management increase the complexity of the problem. In this case, the impact of including DR policies on the effectiveness of single objective ZDOS results is investigated.

4.2.2.1 Scenario 1: Minimizing Operational costs.

In this scenario, observations on how ZDOS strategies changes when applying DR policies compared to first case where the operational costs are minimized without considering DR policies will be made. Furthermore, comparison will be made between costs minimization for both cases in each zone as well in the system as a whole.

All of the customers in zone 1 are residential customers, since that, applied DR policies are highly flexible in terms of demand shifting as well as the prices for shifting the demand are relatively lower. Figure 22 shows power demand in zone 1, it's noticeable that a large proportion of power demand is reduced during TOU peak and mid-peak times and shifted to TOU off-peak times. Furthermore, ESS is charging during TOU mid-peak times and active power is consistently transferred to zone 2 at a constant rate that slightly increases at TOU mid-peak times.

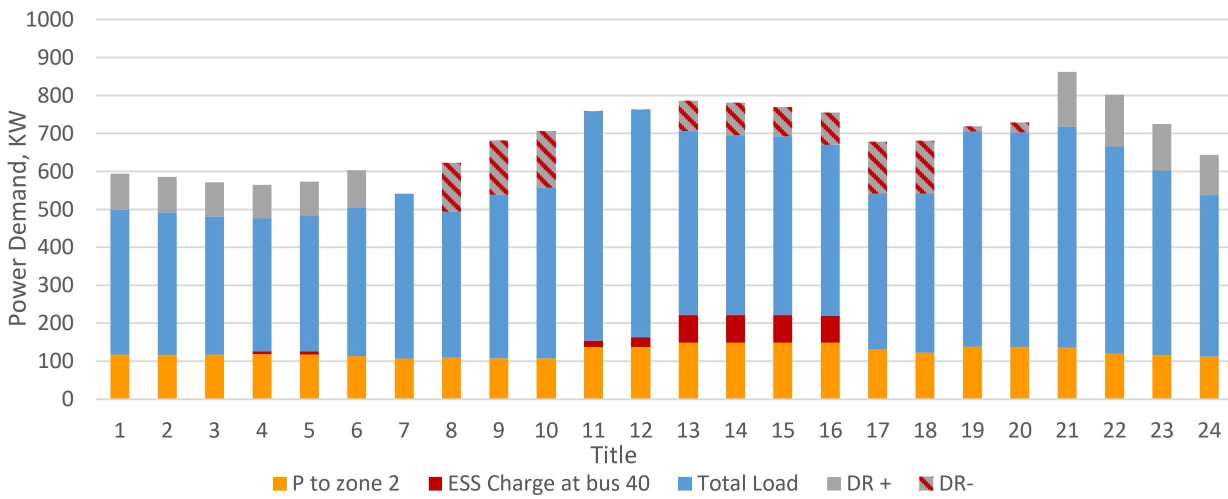

Figure 22: Power demand in zone 1 while minimizing operational costs with DR

Figure 23 shows power supply in zone 1, PCC supplies a considerable amount of power to the whole system, in particular, to zone 1 and zone 2 since zone 2 is consistently supplied at constant power rate through the day. In addition to that, it's noticed that DER at bus 44 is almost shutdown at TOU peak times, this is because the power generation from both RERs and ESS in addition to the supplied power from PCC at cheaper rate could meet the total power demand during these times. Furthermore, in similar manner to the previous case, when minimizing operational costs without DR, ESS is first utilized at TOU morning peak times. After that, they are recharged during TOU mid-peak times as noticed in power demand figure in order to use cheaper power at TOU evening peak times.

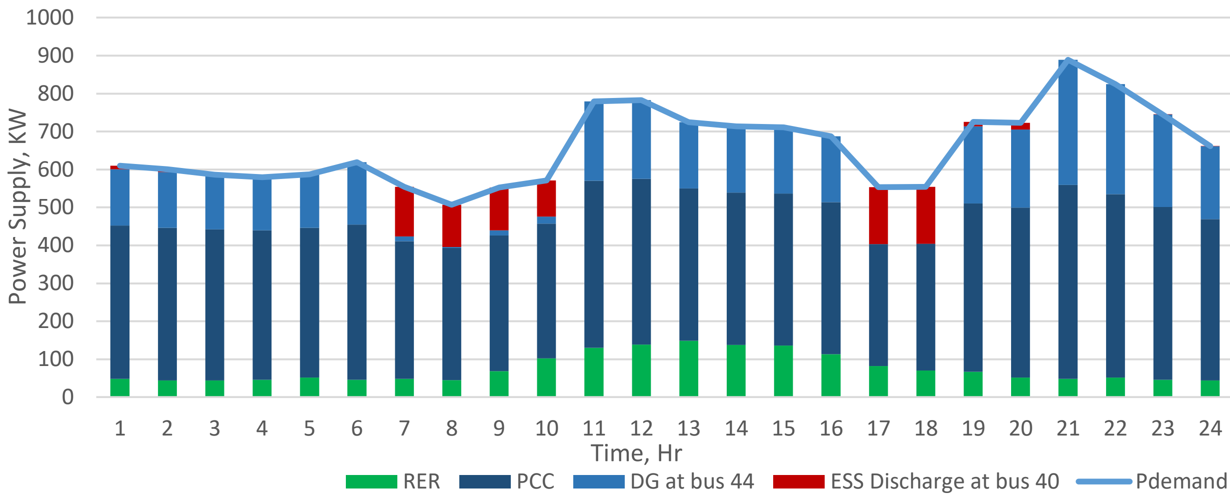

Figure 23: Power supply in zone 1 while minimizing operational costs with DR

Power demand and supply in zone 2 are shown in Figure 24 and Figure *25*, respectively. In the case of this zone, DR policies for commercial customers is applied since this type of customers represent all of the local demand in the zone. Therefore, demand shifting is relatively restricted compared to residential loads as can be seen in Figure 24. Furthermore, power transfer to zone 3 and zone 4 occurs during TOU peak times, this is because PCC is highly utilized during TOU peak times since that transferring power through long distances during peak times can be expensive, but cheaper than local DERs.

As can be seen in Figure 25, power transfer from zone 1 highly contributes to the total power supply in zone 2. In fact, it represent more than 60% of power supply to zone 1 during most of time intervals. Furthermore, RERs supplies large amount of power during TOU mid-peak and peak times which enormously decreases the total operational costs. Additionally, ESS generates around 30% of power supply during TOU peak times to reduce exporting power from DERs and PCC at higher costs.

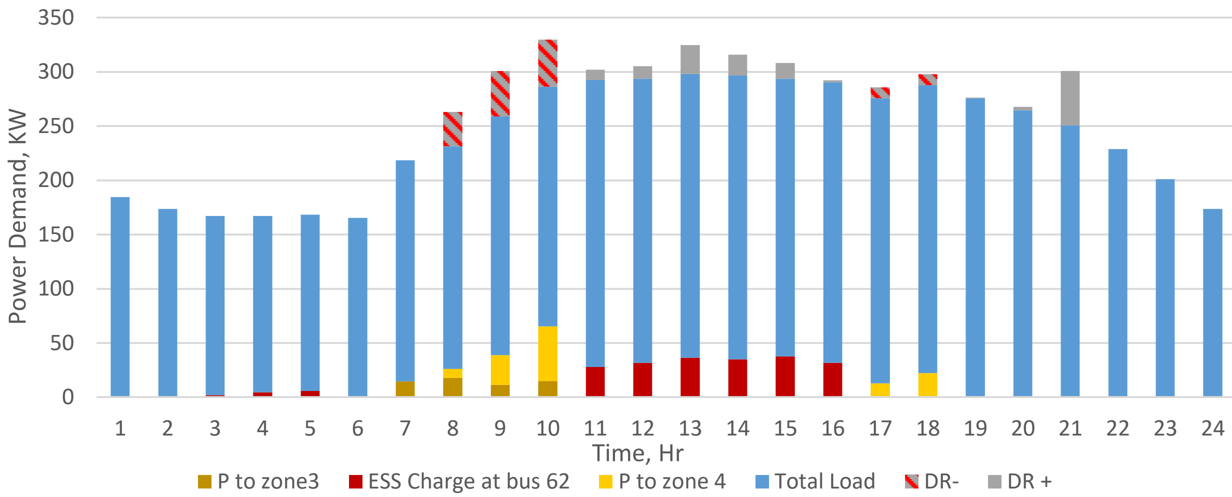

Figure 24: Power demand in zone 2 while minimizing operational costs with DR

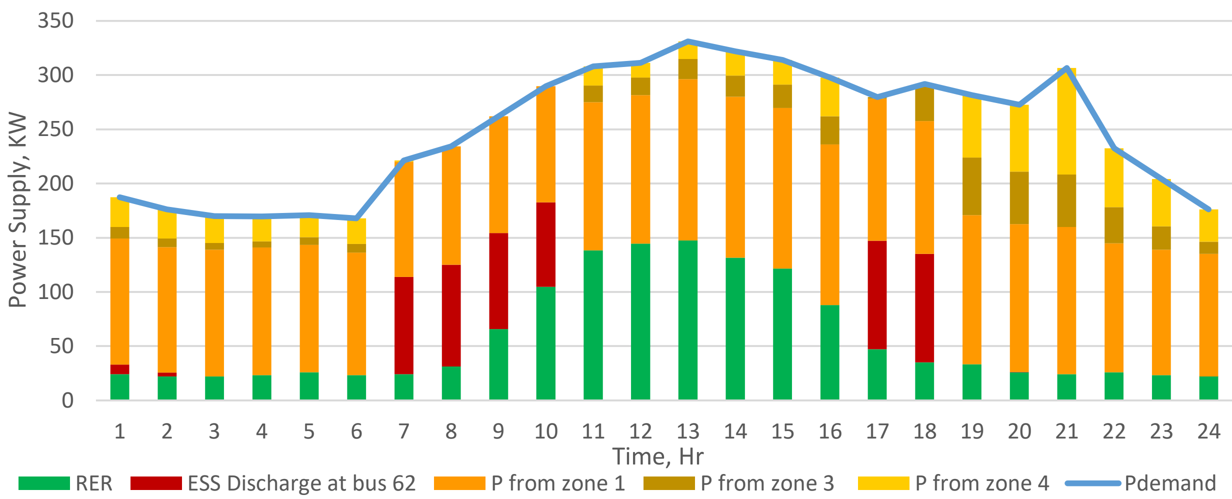

Figure 25: Power supply in zone 2 while minimizing operational costs with DR

The result of ZDIOS for power demand in zone 3 is shown in Figure 26. During TOU peak times only local customers of the zone are supplied, no power transfer to zone 2 nor ESS charging. Nevertheless, these activities are allowed during TOU mid-peak times for ESS charging, and off peak times for power transfer to zone 2. Furthermore, it's clear that no DR policies is applied during the management of this zone, and that's because customers set high cost on shifting their demands in order to maintain high level of power quality since the loads in this zone are mainly industrial.

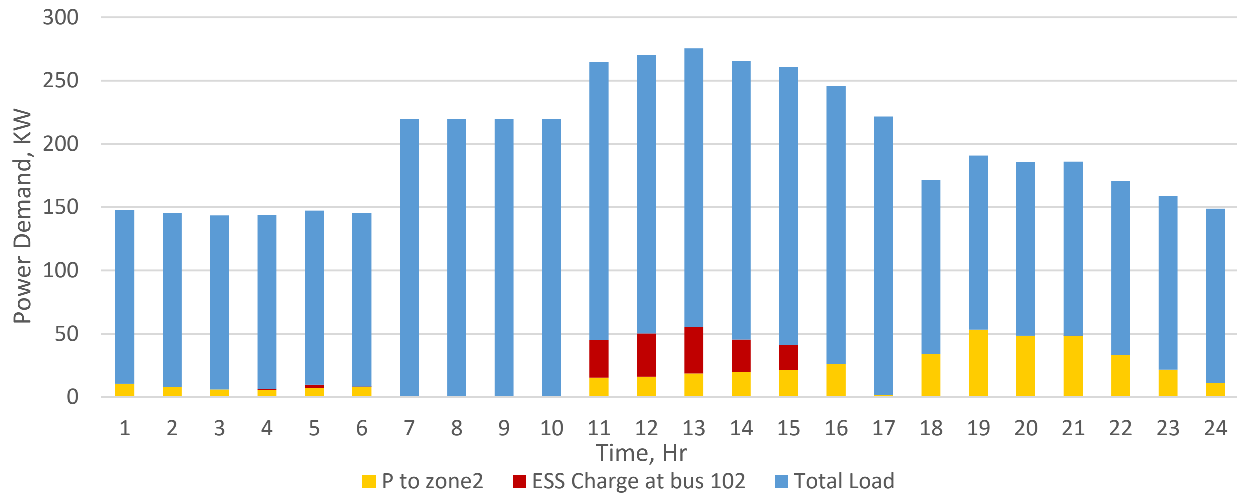

Figure 26: Power demand in zone 3 while minimizing operational costs with DR

Furthermore, comparing power supply in zone 3 before and after applying DR policies as in Figure 27, it's noticed that power supply settings are the same except that power transfer to zone 2 during the morning's TOU peak times slightly increases. That's due to the fact that industrial loads don't compromise power quality for small cost reduction.

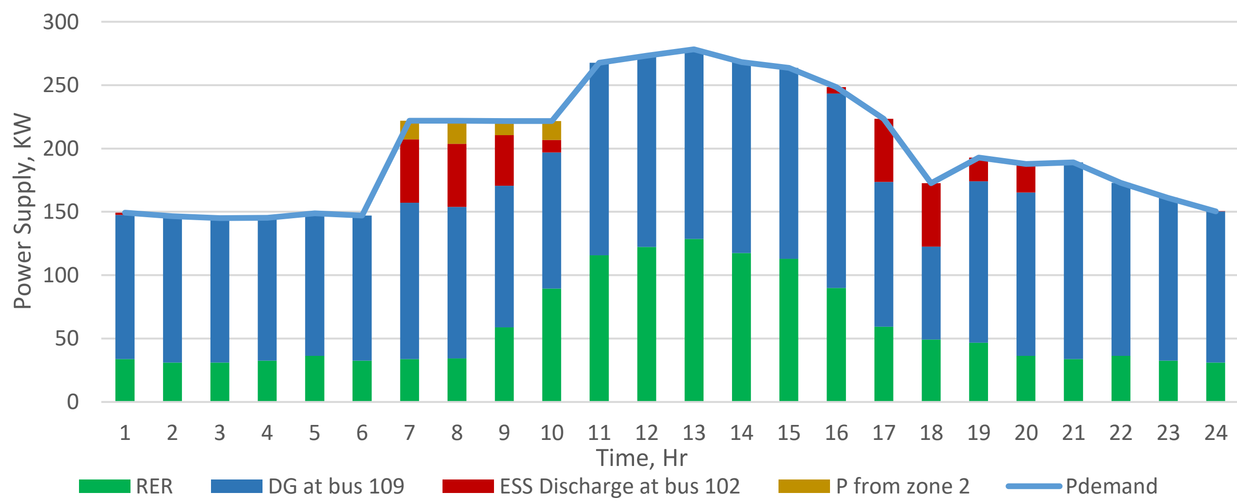

Figure 27: Power supply in zone 3 while minimizing operational costs with DR

Moving toward ZDIOS results for zone 4. Figure 28 shows power demand in zone 4 as it can be readily predicted. Since that customers in this zone are residential, DR policies are highly flexible and much cheaper than that of other type of customers. A considerable amount of power demand on TOU mid-peak and peak times are shifted to off-peak times for the purpose of reducing operational costs. Furthermore, power transfer to zone 2 is consistently maintained at constant rate except during TOU peak times when it's totally interrupted. Similarly, ESS is recharged after stored power was drained at TOU morning peak times.

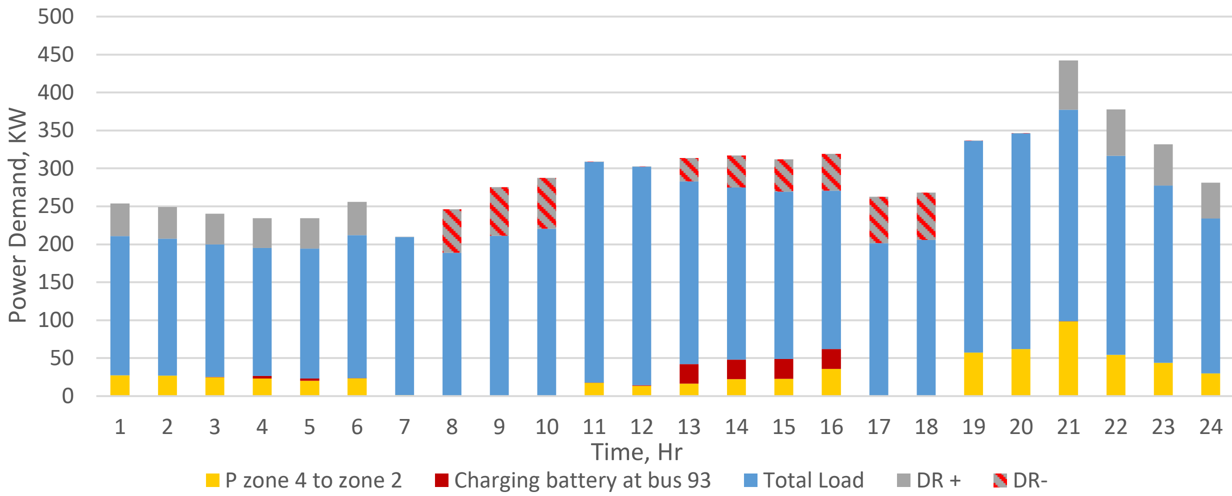

Figure 28: Power demand in zone 4 while minimizing operational costs with DR

Moreover, the pattern of power supply in zone 4 when applying DR policies as in Figure 29 is approximately the same as in Figure 19 without applying DR. A further advantage of DR is noticed in this figure, shifting power demand to TOU off peak times in order to supply it elsewhere at lower rates, not only reduce operational costs, but more importantly, reduce the network's loading as well as power generation of DERs during TOU peak time. By doing so, this strategy allows ZDIOS to transfer power through longer distances, so that it can utilize cheaper DERs that are located far in the system. And, that's what's happening on power supply in zone 4; the power transfer from zone 2 at TOU peak times is higher in the case of applying DR policies because zone 2 is supplied from zone 1 through PCC which is the cheapest power source available in the network.

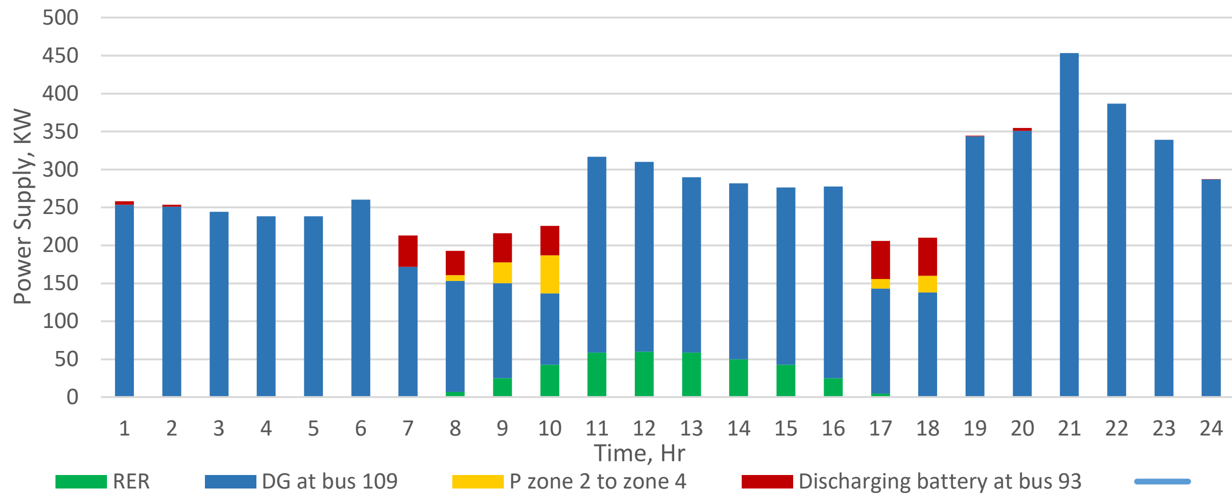

Figure 29: Power supply in zone 4 while minimizing operational costs with DR

To conclude, a comparison between the performance of ZDIOS in minimizing operational costs before and after applying DR policies is carried out. Figure 30 shows the reduction in operational costs for every zone as well as for the total system. On one hand, both zone 1 and zone 4 obtained the maximum reduction on operational costs since both of them consist of residential customers who allow for high controllability on the demand in order to minimize electricity bill. On the other hand, zone 2 didn't experience any operational cost reduction due to the fact that it has only RER resource, however, zone 2 has contributed to the operational cost reduction in zone 1 by shifting its load to TOU off peak times as been discussed in previous analysis. Furthermore, it's obvious that zone 3 has attained a much lower reduction percentage than zones 1 and 4, which was because of increasing power transfer from zone 2 during TOU peak time even though no DR policies has been applied to the zone.

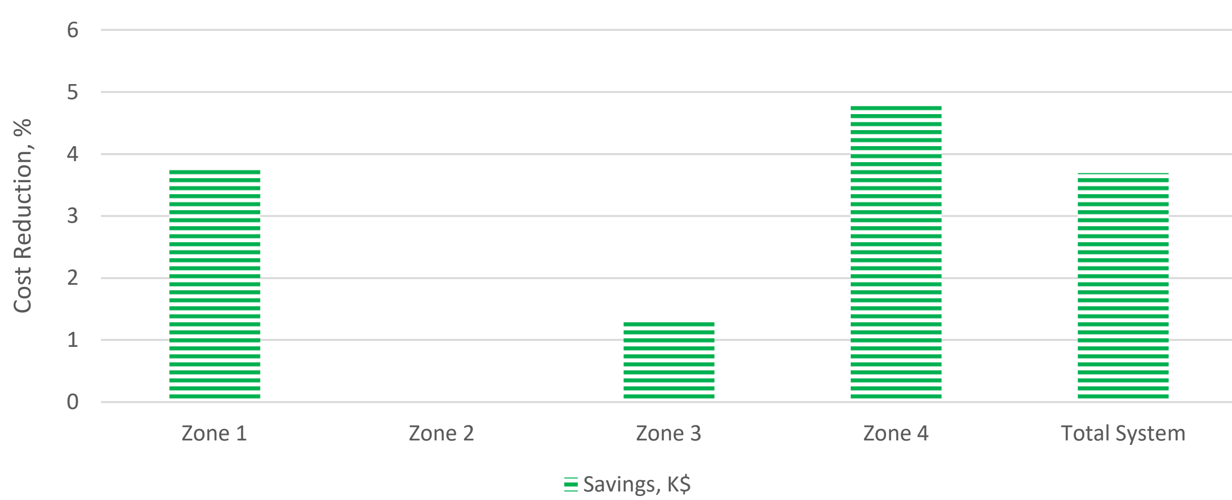

Figure 30: Operational costs reduction when applying DR

4.2.2.2 Scenario 2: Maximizing generation adequacy for each zone.

Network operators are responsible in front of customers for maintaining generation adequacy at a high level during the operation of the system. To assess the generation adequacy of a certain operational settings on the system, an investigation is performed on how well the system is able to satisfy loads using available generation units. It's important to assess the performance of ZDOS in applying this concept on the zone level. Therefore, in this scenario, a comparison is carried out between results of the first case and results of utilizing ZDOS to supply power demand in each zone using the available local DERs and DR policies, in other words, utilizing readjusted ZDOS in order to minimize power exchange with neighbor zones

Power demand and supply in zone 1 for minimizing power exchange can be seen in Figure 31 and Figure *32*, respectively. The results shows that DR policies were applied to uniformly distribute power demand over the course of the day. By doing so, local generation capacity can be further exploited at their maximum level at all times as well reducing power demand change rate can help to overcome the limitation of DERs generation ramp rate. Furthermore, ESS is charged during times of minimum loading conditions, Power transfer to zone 2 is regulated with the same analogy with consideration of loading conditions on other zones.

Moreover as shown in Figure 32, power supply in zone 1 follows the same pattern as power demand, however, differently than the case of minimizing operation costs; the power generation of local DER significantly increases in order to maintain high power adequacy in the zone. In addition to that, the main purpose of ESS is to be charged at low loading conditions and discharge power to the system during higher loading condition and TOU peak times.

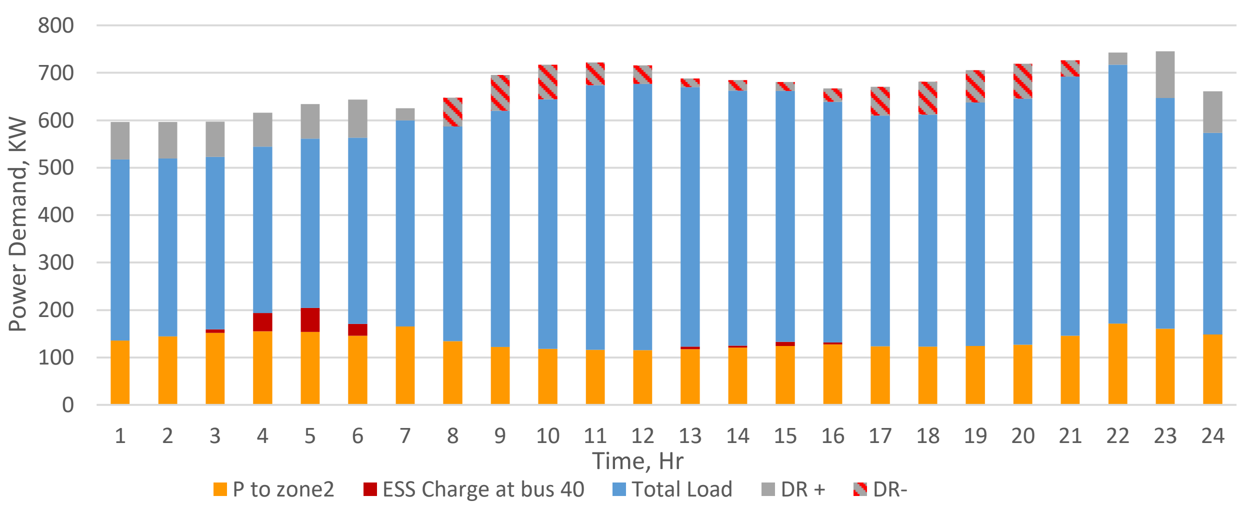

Figure 31: Power demand in zone 1 while maximizing zone generation adequacy

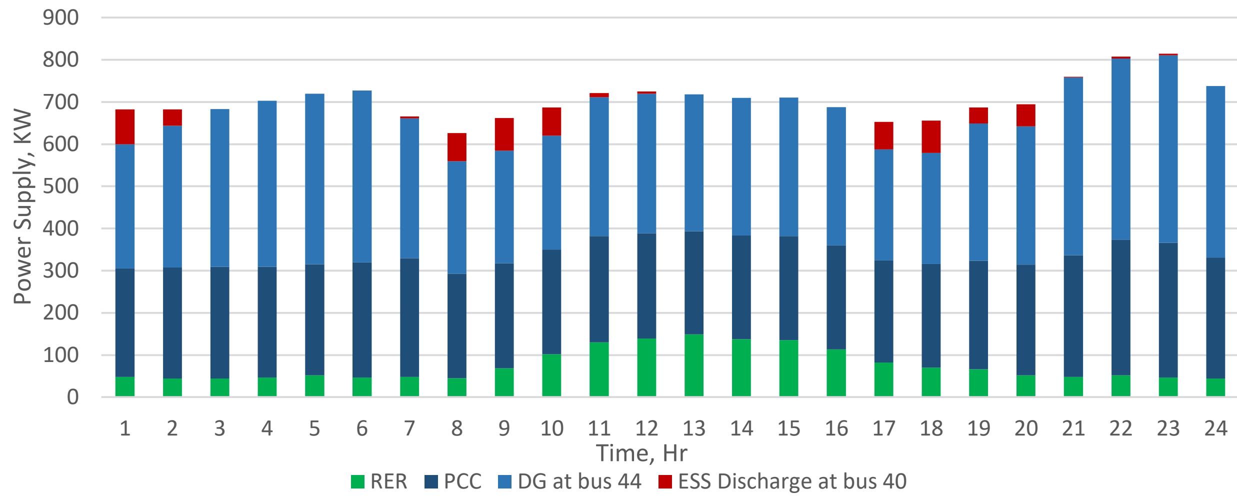

Figure 32: Power supply in zone 1 while maximizing zone generation adequacy

Figure 33 shows power demand in zone 2. Keeping in mind that load shifting can be performed around working hours of commercial customers as illustrated in previous sections, it can be noticed that loads are shifted, when possible, from regions around morning and late evening to midday between 11:00 and 16:00; this is due to the fact that RERs in the zone reach their maximum power generation outputs during midday as can be seen in Figure 34. Furthermore, the total power generation in zone 2 is always lower than power demand, since that, charging ESS is a useless procedure to be done. Charging ESS will increase power demand resulting in increase in power transfer to zone 2 which will defect ZDIOS performance in maximizing zone's power adequacy. Therefore, ZDIOS utilize the initial charge of ESS at the start of operation to supply power demand during times of low RERs power generation and high power demand without any recharging process.

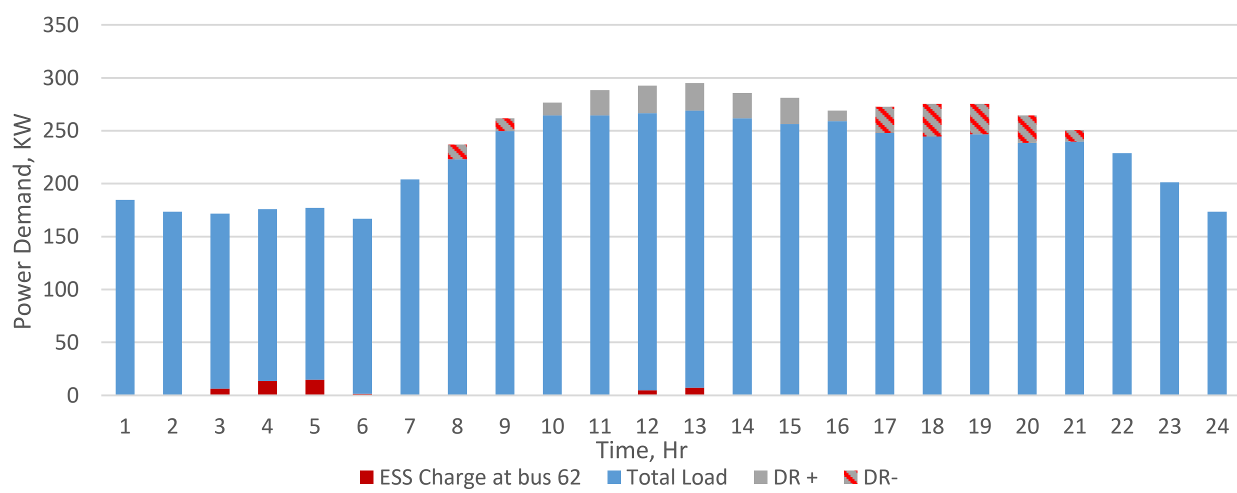

Figure 33: Power demand in zone 2 while maximizing zone generation adequacy

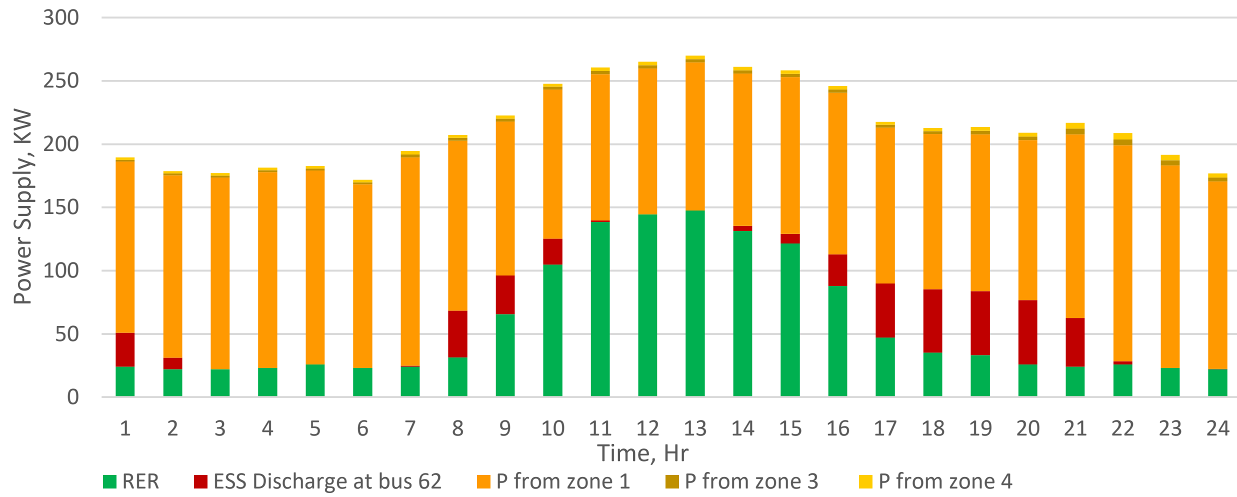

Figure 34: Power supply in zone 2 while maximizing zone generation adequacy

Moving toward ZDIOS results for maximizing generation adequacy of zone 3. Power demand in zone 3 accounts for local customers in zone 2 as well as for ESS charging during high level of power generation coming from RERs around midday and during low power demand as can be seen in Figure 35 and Figure *36*. In contrast to the case of minimizing operational costs, power transfer to zone 2 is almost zero. Furthermore, it can be readily observed that zone 3 depend entirely on local resources of RERs and DER to supply its power demand. Also, the assigned purpose of ESS by ZDIOS is to supply power during times of low RER power generation and high power demand.

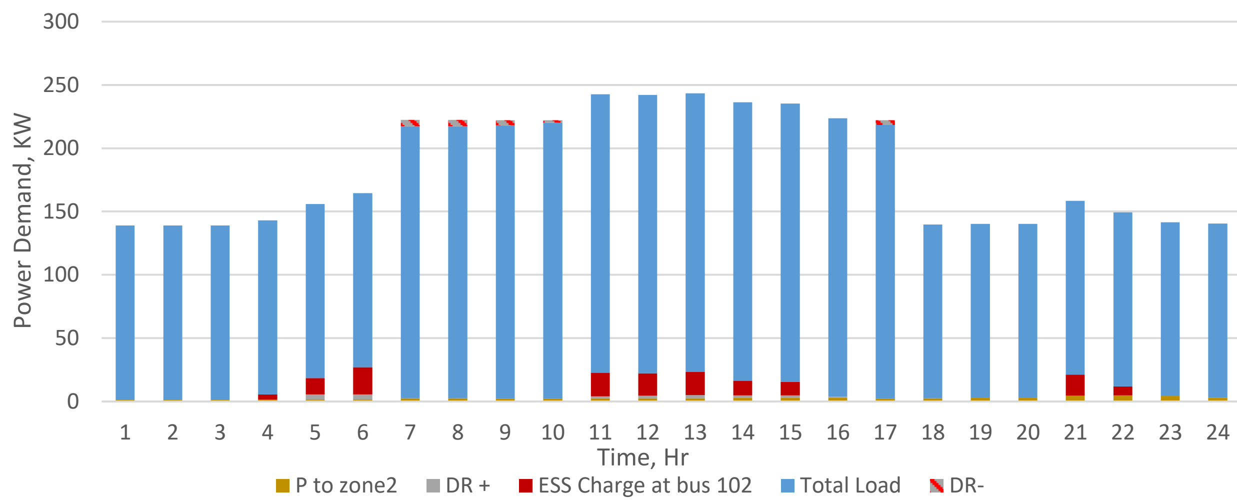

Figure 35: Power demand in zone 3 while maximizing zone generation adequacy

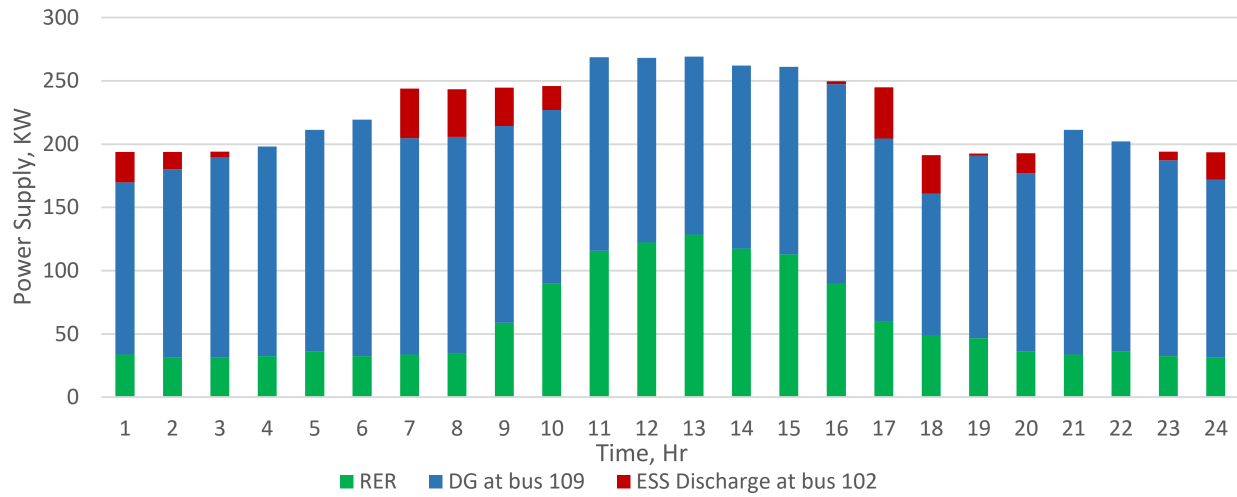

Figure 36: Power supply in zone 3 while maximizing zone generation adequacy

Power demand and supply in zone 4 are shown in Figure 37 and Figure *38*, respectively. With the same analogy of power management on other zones, it's clearly obvious that there is no aggressive demand shifting during TOU peak times as in the case of minimizing operational costs, in contrast, power shifting is performed in order to uniformly distribute the demand over the course of the day. Similarly to ZDOS strategy of managing ESS in other zones, ESS is charged during high level of RER power generation and discharge it back to the system when RER power generation decreases.

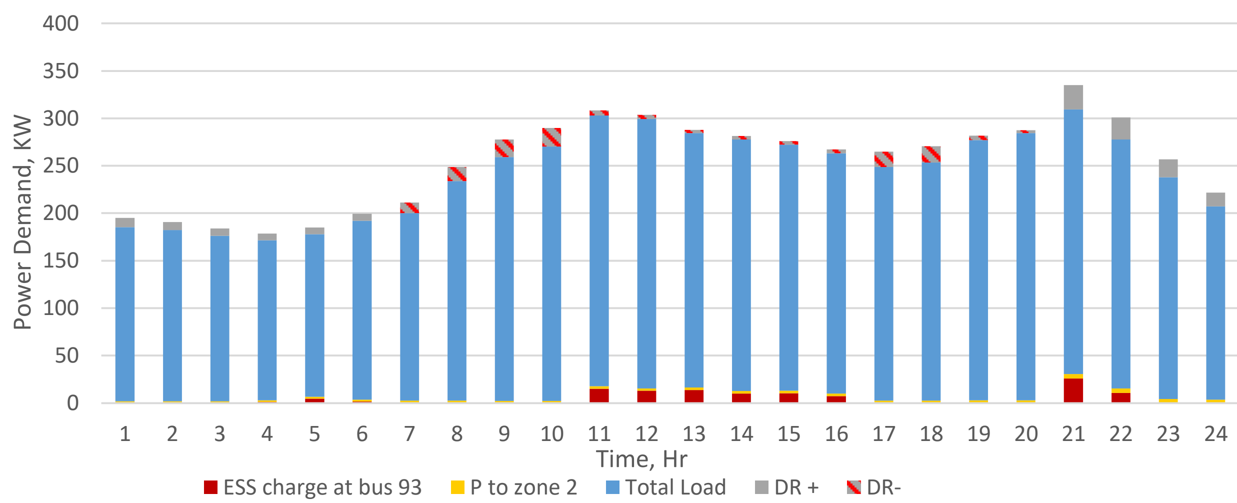

Figure 37: Power demand in zone 4 while maximizing zone generation adequacy

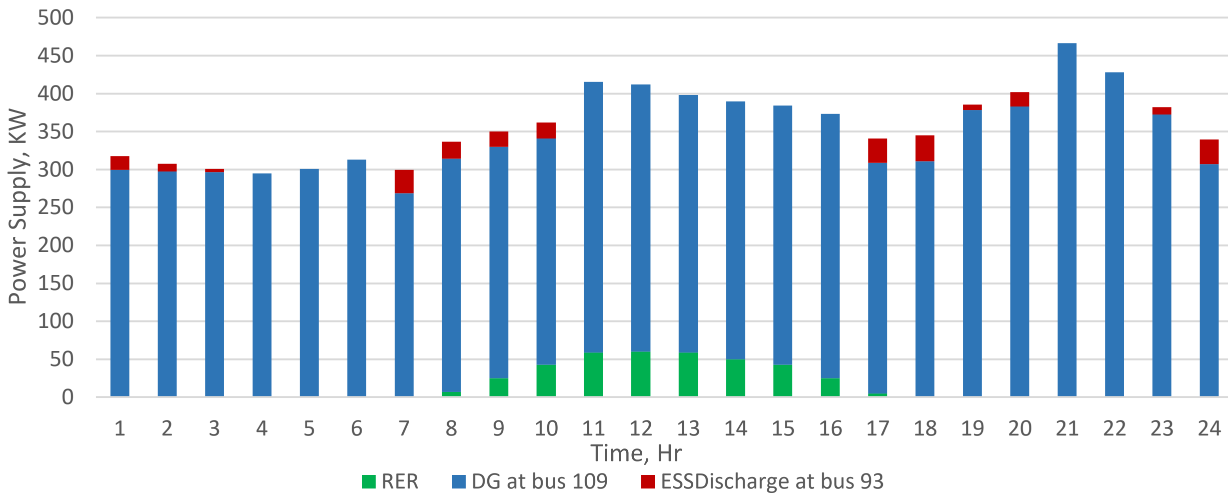

Figure 38: Power supply in zone 4 while maximizing zone generation adequacy

Finally, a comparison regarding power transfer between zones before and after changing the objective function is performed in order to test the performance of ZDIOS. Since PCC is the main power source to the distribution system, it's very difficult to significantly decrease power transfer between PCC and zone 1. In Figure 39, it's shown that power transfer to zone 1 has been decreased by 30% during most of the day. Furthermore, power transfer from zone 1 to zone 2 variates over 24 hours as shown in Figure 40, however, power transfer rate is consistently maintained around an average of 130 KW. The reason behind that is zone 2 doesn't have dispatchable DERs, hence, its main power source is the power imported from other zones. And, since ZDIOS is minimizing power transfer between zones while considering the main grid connection at zone 1, it necessitate power transfer through zone 1 in order to meet total power demand in zone 2.

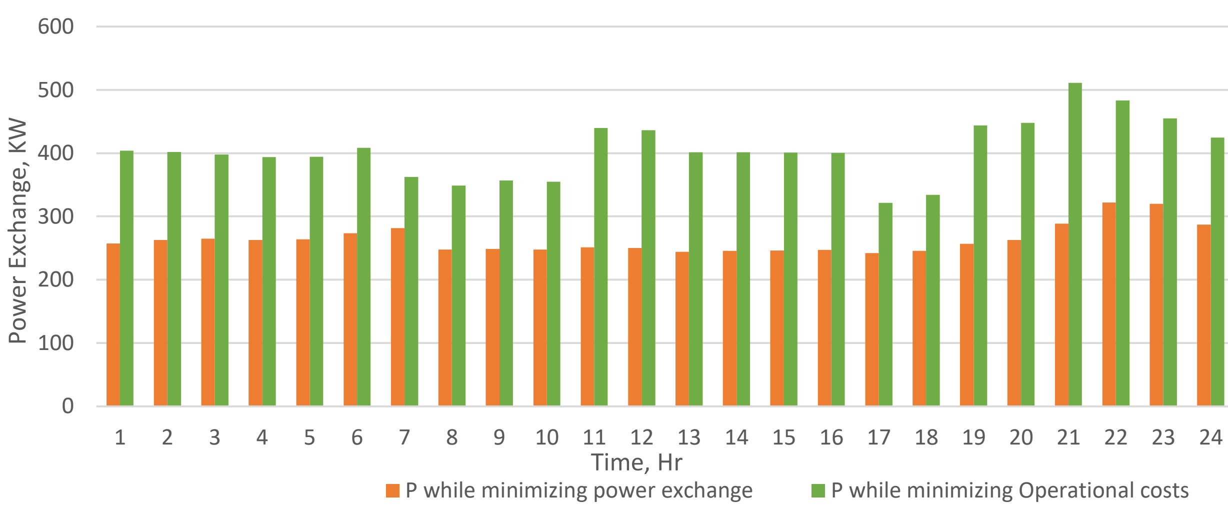

Figure 39: Comparison about Power exchange between PCC and Zone 1

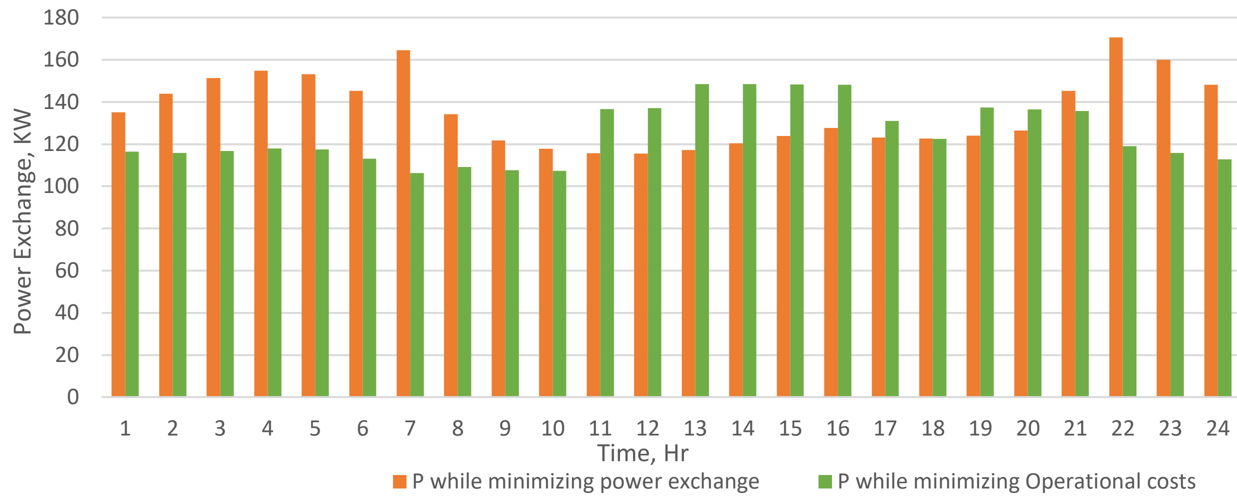

Figure 40: Comparison about Power exchange between Zone 1 and Zone 2

In addition to that, the effect of RER power generation can be clearly noticed on the power transfer pattern during the day. Around high level of RER power generation, a significant amount of power demand in the zone 2 can be met, therefore, ZDIOS could be able to minimize power transfer to a lower level than the case of the minimizing operational costs. However, during times of low RER generation, power transfer to zone 2 exceeds the transfer amount of the first case. Furthermore, Figure 41 and Figure 42 show power exchange between zones 2 and 3 as well as between zones 2 and 4, respectively. Power exchange between the zones has been approximately eliminated, compared to power exchange in the case of minimizing operational costs. To conclude, the operational strategy of ZDIOS when using DR policies and available DERs has tremendously increased the generation adequacy for zones 3 and 4.

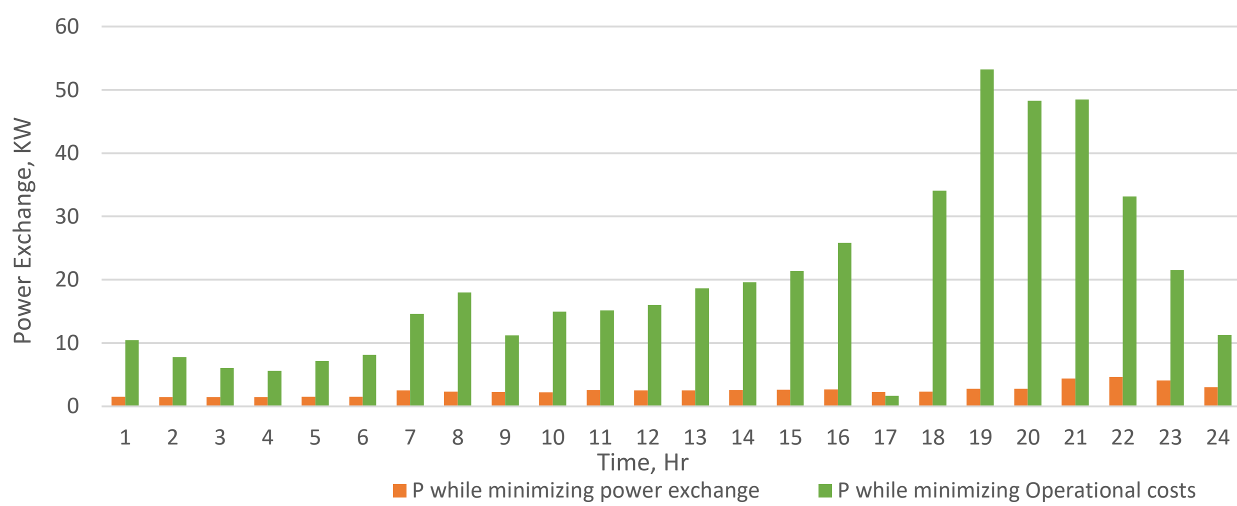

Figure 41: Comparison about Power exchange between Zone 2 and Zone 3

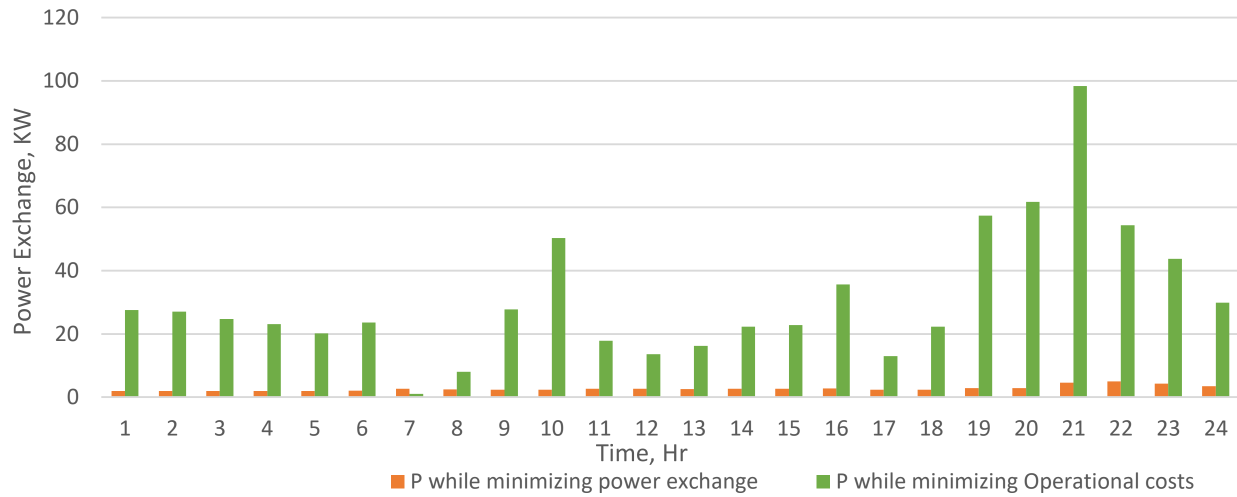

Figure 42: Comparison about Power exchange between Zone 2 and Zone 4

4.2.3 Case 3: Multi objective ZDOS taking into consideration DR programs.

One of the crucial features of ZDOS is the ability to incorporate a number of objective functions for every individual zone depending on the preferences of customers on that zone. Here we compare the results of multi-objective ZDOS against that of single objective ZDOS when minimizing operational costs for the whole system without considering the preferences of customers in each zone. Furthermore, a comparison is performed for every zone analyzing the two different cases to see how different approaches meet the preferences of customers in the system

In this case, the abilities of ZDIOS are utilized where for each zone we define an objective function and requirements. We define the set of objective functions and DR requirements for each zone as follow:

1) Residential zone 1: Minimize the operational costs taking into account power generation prices and DR costs.
2) Commercial zone 2: Minimize Gas emission in the zone. It doesn't have any DGs; but we assume that DG at bus 77 in zone 4 is close enough to zone 2 to affect its environment. Therefore, the objective is to penalize power transfer from zone and promote power transfer to zone 4 in order to reduce the utilization of this DG in supplying power demand in zone 4. Furthermore, DR is fully implemented while neglecting it costs.
3) Industrial zone 3: Maximize generation adequacy and increase reserve capacity by penalizing power transfer from zone 2.
4) Residential zone 4: minimize P losses to regulate the voltage and increase zone's load-ability.

The customers of zone 1 are residential, hence, the default preference of this type of customers would be to minimize operational costs. Hence, the objective function of zone 1 is not readjusted. The results of ZDOS for zone 1 are indeed very important in evaluating the performance of the algorithm since they will give a strong indication on how well would ZDOS tradeoff between optimizing the objective of zone 1 and optimizing the objectives of other zones compared with the results of single objective ZDOS for zone 1 in minimizing operational costs. As shown in Figure 43, the performance of multi objective ZDOS is shown to be very competitive when compared against single objective ZDOS, both techniques are at the same level of performance during four time intervals, moreover, multi objective ZDOS has outperformed the results of that of single objective during eight time intervals.

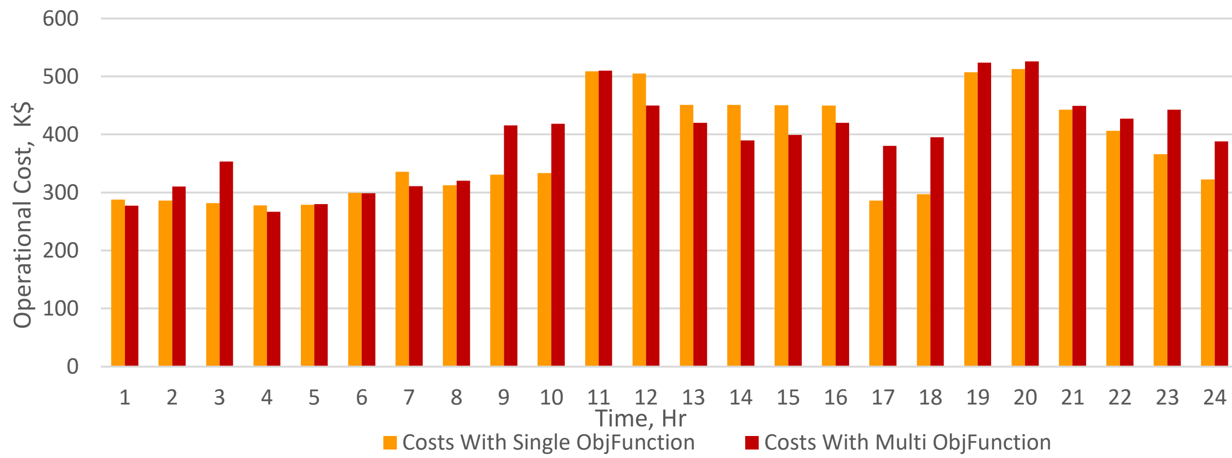

Figure 43: Comparison about Operational costs in Zone 1

Furthermore, it assumed that all the customer in zone 2 are commercial where all participants are promoting the reduction of Greenhouse gas emissions, hence, all of the installed DERs on this zone are already RERs. Since there are no air polluting DERs in the zone to be controlled by ZDOS for the sake of reducing emissions, the goal of multi objective ZDOS in this case is tricky. It's assumed that diesel generator on zone 4 at bus 77 is affecting the environment in zone 2, therefore, the objective of zone 2 in ZDOS is to minimize the utilization of this diesel generator by paying incentives to zone 4. Tapping into the results, multi objective ZDOS clearly surplus the performance of single objective as shown in Figure 44. During most of the operational horizon, Greenhouse gas emission was significantly reduced by half. Furthermore, the impact of minimizing operational costs on zone 1 can be clearly observed during morning and evening TOU peak times where gas emissions couldn't be reduced further.

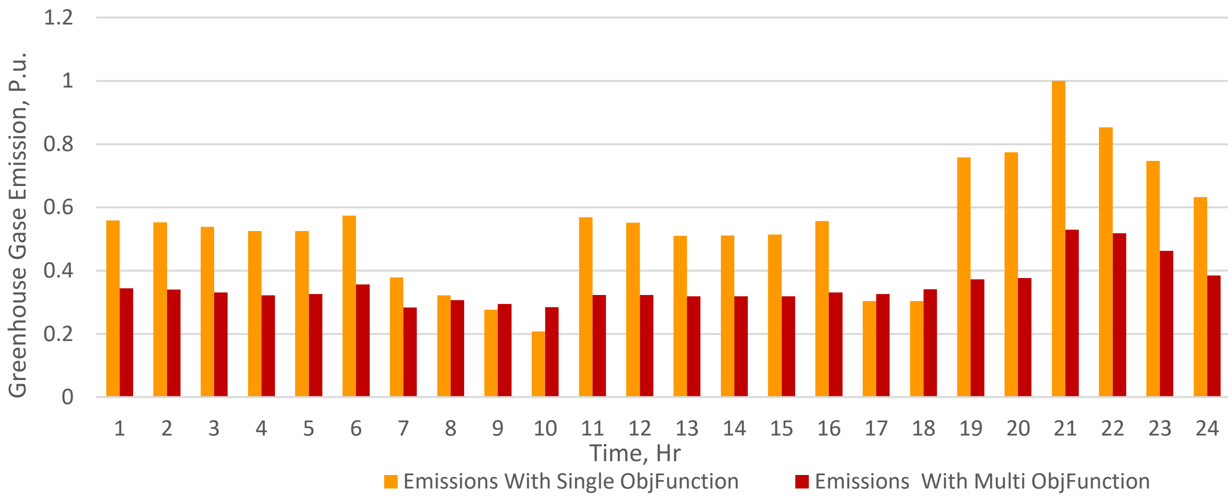

Figure 44: Comparison about Greenhouse Gas Emission near Zone 2

In the areas of industrial customers, generation adequacy in the system is considered as one of the important concepts since operational process at industrial level needs a highly reliable power sources. To increase the reliability of the system and power quality delivered to the customer, the ZDOS increases the utilization of available resources in zone 3, and decreases power transfer from zone 2. By doing so, it protects zone 2 from operational failure caused by any faults on other zones of the system. As seen in Figure 45, power transfer in the case of single objective ZDOS starts to increase around 7:00 when it reaches 15 kW. Furthermore, power transfer reaches its highest level of 52 kW at 19:00, between these time intervals power transfer fluctuate around an average of 25 KW. Whereas in the case of utilizing multi objective ZDOS, power transfer maintained below 10 KW at all times. Moreover, the performance of the latter technique can be further evaluated by observing the difference in the results around working hours of industrial loads from 7:00 to 17:00; in the case of power interruption at the connection with zone 2, industrial customers would need to cut off as twice as power demand in the case of multi objective ZDOS.

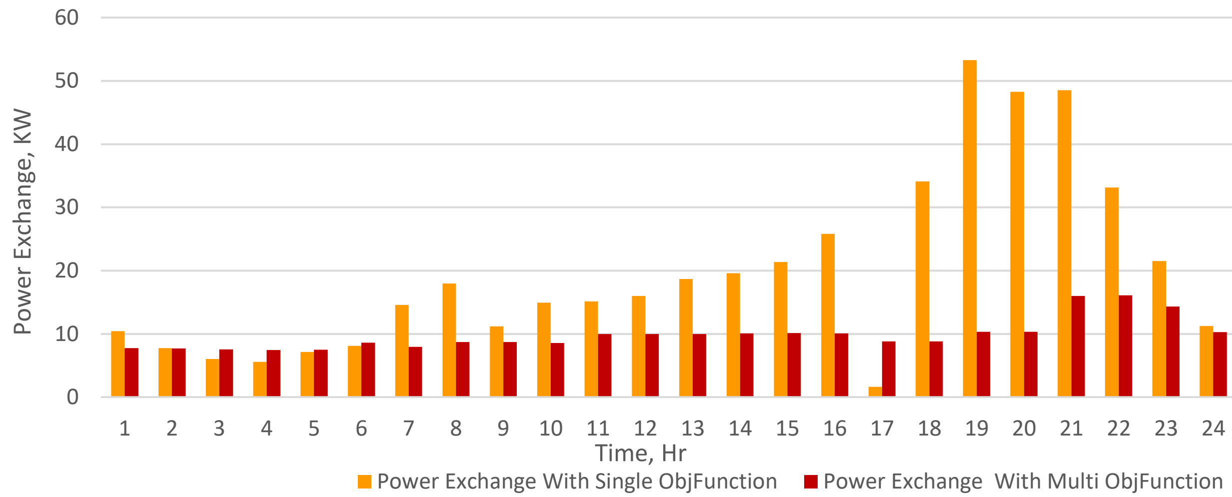

Figure 45: Comparison about Power Exchange between Zone 2 and Zone 3

In case of zone 4, it's assumed that the power utility set the objective function to minimize the losses in order to enhance the network efficiency in this area because of certain limitations on the physical structure and the installed equipment. Figure 46 shows that power losses in zone 4 using multi objective ZDOS has been decreased around TOU off-peak and mid-peak times when compared with the results of single objective ZDOS. It's noticed that multi objective ZDOS during TOU peak times has the same results as the first technique, that's because the latter technique is taking into consideration optimizing the operational preferences of other zones which would enormously increases the complexity of the operation.

Figure 46: Comparison about Power Losses in Zone 4

4.3 Summary

This chapter presented a profound analysis and comparisons in order to evaluate the performance of ZDOS. The system considered for the case studies is very complex as it applies the studied scenarios on modified 123-Bus Test Feeder that incorporates many power components of DERs, RERs such as PVs and WTs as well as ESSs. The results of ZDOS are first validated on energy management problem while minimizing operational costs without considering DR, by investigating supply demand balance on every zone individually and for the whole system. After that, the effectives of ZDOS algorithm in utilizing DR as well as the effectiveness in considering the preferences of different type of customers are also evaluated.

The analysis has shown that ZDOS can be effectively utilize in energy management since it shows a high improvements in the results when applying DR programs and accommodating multi objective function for the purpose of meeting a variety of preferences that are set by the operator of the customers. In case 1, it has been proven the results of ZDOS are indeed valid. Furthermore, applying DR policies on the case study using ZDOS in case 2 has shown a significant improvement on the performance of the system as whole in terms of minimizing operational costs. Whereas in case 3, it’s has been proven that by using multi objective ZDOS the efficiency of the system can be enhanced when considering number of objective to meet certain needs on different parts of the system using the zoning concepts proposed by the algorithm.

Chapter 5

Conclusion

5.1 Summary

Smart Grids are becoming crucial and challenging topic as they adopt new technologies and enabling higher capabilities for existing and new distribution system infrastructure. Operational planning for active distribution systems is very complex problem since incorporate a large number of network components, bidirectional power flow as well as supplies different type of customers that requires high satisfaction of self-preference. The thesis proposes Zone Distributed Optimization System for energy management of SG taking into consideration zonal architecture of SG incorporating zone specific objectives and constraints.

Chapter 1 present motivation of the proposed work, followed by literature review covering different approaches and techniques that are developed for the subject of energy management. In particular, approaches were categorized into two main types: Centralized EMS and Decentralized EMS. For both approaches, recent studies has been surveyed, concluded with advantages and disadvantages of each. After that, the research objectives and thesis organization are briefly laid out.

Chapter 2 a general over view about smart grid and the operational paradigm of EMS is presented. The concept of DSM and its various strategies, in particular, the implementation of DR programs and DLC are discussed. Last but not least, background about OPF problem is included, describing the details of different objective functions, physical and operational constraints that are generally considered in formulating the problem. Followed by a detailed mathematical formulation of OPF using SDP as well as DSDP.

Chapter 3 presents the details of ZDOS. In particular, the methodology of ZDOS describing how ZDOS controls the SM as a set of unique connected zones, where each zone has its own ZSOS that locally controls the zones taking into account local objective of local customers and constraints. After that, a comprehensive mathematical formulation of ZDOS for energy management starting from basic physical constraints of the network and extended to the operational constraints and limitations of various power sources such as DERs, RERs and ESSs. In addition to that, the formulation included DR policies customized for every type of customers.

Chapter 4 present simulation and analysis of ZDOS performance on modified 123-bus test feeder that includes DERs, RERs and ESSs. Firstly, the solution of ZDOS is validated by comparing power supply demand for different scenarios. Then, DR policies are considered in second case where the performance of the ZDOS has proven to be effective. Furthermore, ZDOS showed exceptional improvement in the third case of multi objective ZDOS where it optimizes specific goals for every zone simultaneously.

5.2 Contribution of the work

1) The proposed ZDOS is a decentralized EMS framework that is capable of simultaneously addressing the preferences of both the operator and the customers while considering network operational constraints.
2) The novelty of proposed approach is based on dividing the SG into a set of virtual zones according to the customers' requirements and characteristics such that each virtual zone can operate properly using ZSOS that optimize shared preferences and constraints within the virtual zone.
3) In this work, DSDP-OPF is utilized since it properly lend itself to the framework of the proposed ZDOA. The formulation of DSDP-OPF is extended to handle the EMS, regulate power flow between virtual zones and to accommodate for the objectives of different zones in the SG and DSM programs.

5.3 Future work

The following ideas can be extended for future work based on the findings of this thesis:

1) Develop mathematical formulation of ZDOS to include solving unbalanced distribution systems. In addition to that, the formulation can be further improved by utilizing stochastic optimization to consider uncertainty in power generation and load profiles.
2) Develop ZDOS to operate multi-microgrid systems including buying/selling power between different operators.
3) Incorporate different load models and forecasting techniques for PVs and WTs generation.

References

[1] C. Li, X. Yu, W. Yu, and S. Member, "Efficient Computation for Sparse Load Shifting in Demand Side Management," *IEEE Trans. Smart Grid*, vol. 8, no. 1, pp. 250–261, 2017.

[2] M. C. Bozchalui, "Optimal Operation of Energy Hubs in the Context of Smart Grids," University of Waterloo, 2011.

[3] R. Missaoui, G. Warkozek, and S. Bacha, "PV Integration by Building Energy Management System," in *Power Engineering, Energy and Electrical Drives (POWERENG), 2011 International Conference on*, 2011, pp. 1–8.

[4] M. Wang, Yanzhi and Lin, Xue and Pedram, "Adaptive Control for Energy Storage Systems in Households With Photovoltaic Modules," *IEEE Trans. Smart Grid*, vol. 5, no. 2, pp. 992–1001, 2014.

[5] A. Mohsenian-Rad, Amir-Hamed and Leon-Garcia, "Optimal Residential Load Control with Price Prediction in Real-Time Electricity Pricing Environments," *IEEE Trans. Smart Grid*, vol. 1, no. 2, pp. 120–133, 2010.

[6] I. Pedrasa, MA and Spooner, ED and MacGill, "Robust scheduling of residential distributed energy resources using a novel energy service decision-support tool Robust Scheduling of Residential Distributed Energy Resources Using a Novel Energy Service Decision-Support Tool," *Innov. Smart Grid Technol. (ISGT), 2011 IEEE PES*, pp. 1–8, 2011.

[7] M. G. Zhao, Peng and Suryanarayanan, Siddharth and Simes, "An Energy Management System for Building Structures Using a Multi-Agent Decision-Making Control Methodology," *{EEE Trans. Ind. Appl.*, vol. 49, no. 1, pp. 322–330, 2013.

[8] M. R. R. Hidalgo and C. A. G. Joo, "Energy storage system scheduling for an isolated microgrid," *IET Renew. power Gener.*, vol. 5, no. 2, pp. 117–123, 2011.

[9] I. Bendato, A. Bon, M. Brignone, F. Del, F. Pampararo, and R. Procopio, "A real-time Energy Management System for the integration of economical aspects and system operator requirements : Definition and validation," *Renew. Energy*, vol. 102, pp. 406–416, 2017.

[10] F. Guo, Li and Liu, Wenjian and Li, Xialin and Liu, Yixin and Jiao, Bingqi and Wang, Wei and Wang, Chengshan and Li, "Energy Management System for Stand-Alone Wind-Powered-Desalination Microgrid," *IEEE Trans. Smart Grid*, vol. 7, no. 2, pp. 1079–1087, 2016.

[11] S. M. Moradi, Mohammad H and Eskandari, Mohsen and Hosseinian, "ooperative control strategy of energy storage systems and micro sources for stabilizing microgrids in different operation modes," *Int. J. Electr. Power \& Energy Syst.*, vol. 78, pp. 390–400, 2016.

[12] R. Palma-behnke *et al.*, "A Microgrid Energy Management System Based on the Rolling Horizon Strategy," *IEEE Trans. Smart Grid*, vol. 4, no. 2, pp. 996–1006, 2013.

[13] M. Parvizimosaed, F. Farmani, and H. Monsef, "A multi-stage Smart Energy Management System under multiple uncertainties : A data mining approach," *Renew. Energy*, vol. 102, pp. 178–189, 2017.

[14] A. Molderink *et al.*, "Management and Control of Domestic Smart Grid Technology," *IEEE Trans. Smart Grid*, vol. 1, no. 2, pp. 109–119, 2010.

[15] M. Modeling *et al.*, "Mixed-Integer-Linear-Programming-Based Energy Management System for Hybrid PV-Wind-Battery Experimental Verification," *IEEE Trans. Power Electron.*, vol. 32, no. 4, pp. 2769–2783, 2017.

[16] C. Wang, Y. Liu, X. Li, L. Guo, L. Qiao, and H. Lu, "Energy management system for stand-alone diesel-wind-biomass microgrid with energy storage system," *Energy*, vol. 97, pp. 90–104, 2016.

[17] J. Wang, Y. Jing, and C. Zhang, "Optimization of capacity and operation for CCHP system by genetic algorithm," *Appl. Energy*, vol. 87, no. 4, pp. 1325–1335, 2010.

[18] J. Soares, M. Ali, F. Ghazvini, Z. Vale, and P. B. D. M. Oliveira, "A multi-objective model for the day-ahead energy resource scheduling of a smart grid with high penetration of sensitive loads," *Appl. Energy*, vol. 162, pp. 1074–1088, 2016.

[19] A. Safdarian, S. Member, M. Fotuhi-firuzabad, and S. Member, "A Stochastic Framework for Short-Term Operation of a Distribution Company," *IEEE Trans. Power Syst.*, vol. 28, no. 4, pp. 4712–4721, 2013.

[20] S. Leonori, E. De Santis, A. Rizzi, and F. M. F. Mascioli, "Optimization of a Microgrid Energy Management System based on a Fuzzy Logic Controller," in *Industrial Electronics Society, IECON 2016-42nd Annual Conference of the IEEE*, 2016, pp. 6615–6620.

[21] S. Chakraborty, S. Member, M. D. Weiss, M. G. Simões, and S. Member, "Distributed Intelligent Energy Management System for a Single-Phase High-Frequency AC Microgrid," *IEEE Trans. Ind. Electron.*, vol. 54, no. 1, pp. 97–109, 2007.

[22] K. Balasubramaniam, P. Saraf, R. Hadidi, and E. B. Makram, "Energy management system for enhanced resiliency of microgrids during islanded operation," *Electr. Power Syst. Res.*, vol. 137, pp. 133–141, 2016.

[23] A. Bagherian and S. M. M. Tafreshi, "A developed Energy Management System for a Microgrid in the Competitive Electricity Market," in *PowerTech, 2009 IEEE Bucharest*, 2009, pp. 1–6.

[24] S. Teleke *et al.*, "Control Strategies for Battery Energy Storage for Wind Farm Dispatching," *IEEE Trans. Energy Convers.*, vol. 24, no. 3, pp. 725–732, 2009.

[25] X. Li, S. Member, D. Hui, and X. Lai, "Battery Energy Storage Station (BESS) -Based Smoothing Control of Photovoltaic (PV) and Wind Power Generation Fluctuations," *IEEE Trans. Sustain. Energy*, vol. 4, no. 2, pp. 464–473, 2013.

[26] M. Marzband, H. Alavi, S. Samaneh, H. Uppal, and T. Fernando, "Optimal energy management system based on stochastic approach for a home Microgrid with integrated responsive load demand and energy storage," *Sustain. Cities Soc.*, vol. 28, pp. 256–264, 2017.

[27] E. Sortomme and S. Member, "Optimal Power Flow for a System of Microgrids with Controllable Loads and Battery Storage," in *Power Systems Conference and Exposition, 2009. PSCE'09. IEEE/PES*, 2009, pp. 1–5.

[28] C. Cecati, C. Citro, and P. Siano, "Combined Operations of Renewable Energy Systems and Responsive Demand in a Smart Grid," *IEEE Trans. Sustain. Energy*, vol. 2, no. 4, pp. 468–476, 2011.

[29] C. H. Antunes, A. Soares, and Á. Gomes, "An Energy Management System for Residential Demand Response Based on Multi- objective Optimization," in *Smart Energy*

Grid Engineering (SEGE), 2016 IEEE, 2016, pp. 90–94.

[30] L. Meng, E. Riva, A. Luna, T. Dragicevic, J. C. Vasquez, and J. M. Guerrero, “Microgrid supervisory controllers and energy management systems : A literature review,” *Renew. Sustain. Energy Rev.*, vol. 60, pp. 1263–1273, 2016.

[31] A. G. Tsikalakis, S. Member, N. D. Hatziargyriou, and S. Member, “Centralized Control for Optimizing Microgrids Operation,” in *Power and Energy Society General Meeting, 2011 IEEE*, 2011, pp. 1–8.

[32] D. E. Olivares, C. A. Cañizares, M. Kazerani, and S. Member, “A Centralized Optimal Energy Management System for Microgrids,” in *Power and Energy Society General Meeting, 2011 IEEE*, 2011, pp. 1–6.

[33] M. S. Rahman and A. M. T. Oo, “Distributed multi-agent based coordinated power management and control strategy for microgrids with distributed energy resources,” *Energy Convers. Manag.*, vol. 139, pp. 20–32, 2017.

[34] H. S. V. S. K. Nunna and S. Doolla, “Energy Management in Microgrids Using Demand Response and Distributed Storage — A Multiagent Approach,” *IEEE Trans. Power Deliv.*, vol. 28, no. 2, pp. 939–947, 2013.

[35] W. Ma, J. Wang, S. Member, V. Gupta, and C. Chen, “Distributed Energy Management for Networked Microgrids Using Online ADMM with Regret,” *IEEE Trans. Smart Grid*, pp. 1–9, 2016.

[36] H. S. V. S. K. Nunna, S. Member, and S. Doolla, “Multiagent-Based Distributed-Energy-Resource Management for Intelligent Microgrids,” *IEEE Trans. Ind. Electron.*, vol. 60, no. 4, pp. 1678–1687, 2013.

[37] H. S. V. S. K. Nunna, A. Mohan, A. Sesetti, S. Battula, S. Doolla, and D. Srinivasan, “Multi-agent based Demand Response management system for combined operation of smart microgrids,” *Sustain. Energy, Grids Networks*, vol. 6, pp. 25–34, 2016.

[38] B. M. Radhakrishnan and D. Srinivasan, “A multi-agent based distributed energy management scheme for smart grid applications,” *Energy*, vol. 103, pp. 192–204, 2016.

[39] Z. Zhou, F. Zhao, and J. Wang, “Agent-Based Electricity Market Simulation With

Demand Response From Commercial Buildings," *IEEE Trans. Smart Grid*, vol. 2, no. 4, pp. 580–588, 2011.

[40] H. S. V. S. K. Nunna and S. Doolla, "Demand Response in Smart Microgrids," in *Innovative Smart Grid Technologies-India (ISGT India), 2011 IEEE PES*, 2011, pp. 131–136.

[41] D. A. Ramachandran, Bhuvaneswari and Srivastava, Sanjeev K and Edrington, Chris S and Cartes, "An Intelligent Auction Scheme for Smart Grid Market Using a Hybrid Immune Algorithm," *IEEE Trans. Ind. Electron.*, vol. 58, no. 10, pp. 4603–4612, 2011.

[42] G. Li, Z. Bie, Y. Kou, J. Jiang, and M. Bettinelli, "Reliability evaluation of integrated energy systems based on smart agent communication," *Appl. Energy*, no. August, 2016.

[43] W. Liu, S. Member, W. Gu, W. Sheng, and X. Meng, "Decentralized Multi-Agent System-Based Cooperative Frequency Control for Autonomous Microgrids With Communication Constraints," *IEEE Trans. Sustain. Energy*, vol. 5, no. 2, pp. 446–456, 2014.

[44] J. Gu, Wei and Liu, Wei and Zhu, Junpeng and Zhao, Bo and Wu, Zaijun and Luo, Zhao and Yu, "Adaptive Decentralized Under-Frequency Load Shedding for Islanded Smart Distribution Networks," *IEEE Trans. Sustain. Energy*, vol. 5, no. 3, pp. 886–895, 2014.

[45] S. Koohi-kamali and N. Abd, "Coordinated control of smart microgrid during and after islanding operation to prevent under frequency load shedding using energy storage system," *Energy Convers. Manag.*, vol. 127, pp. 623–646, 2016.

[46] K. Logenthiran, Thillainathan and Naayagi, Ramasamy Thaiyal and Woo, Wai Lok and Phan, Van-Tung and Abidi, "Intelligent Control System for Microgrids Using Multiagent System," *IEEE J. Emerg. Sel. Top. Power Electron.*, vol. 3, no. 4, pp. 1036–1045, 2015.

[47] M. R. B. Khan, R. Jidin, and J. Pasupuleti, "Multi-agent based distributed control architecture for microgrid energy management and optimization," *Energy Convers. Manag.*, vol. 112, pp. 288–307, 2016.

[48] C. Karavas, G. Kyriakarakos, K. G. Arvanitis, and G. Papadakis, "A multi-agent decentralized energy management system based on distributed intelligence for the design and control of autonomous polygeneration microgrids," *Energy Convers. Manag.*, vol. 103, pp. 166–179, 2015.

[49] L. Xi, Z. Zhang, B. Yang, L. Huang, and T. Yu, "Wolf pack hunting strategy for automatic generation control of an islanding smart distribution network q," *Energy Convers. Manag.*, vol. 122, pp. 10–24, 2016.

[50] E. F. Hamad, Amr A and Azzouz, Maher Abdelkhalek and El-Saadany, "Multiagent Supervisory Control for Power Management in DC Microgrids," *IEEE Trans. Smart Grid*, vol. 7, no. 2, pp. 1057–1068, 2016.

[51] G. J. Meng L, Dragicevic T, Roldan-Perez J, Vasquez J, "Modeling and Sensitivity Study of Consensus Algorithm-Based Distributed Hierarchical Control for DC Microgrids," *IEEE Trans. Smart Grid*, vol. 7, no. 3, pp. 1504–1515, 2016.

[52] United States Department of Energy Office of Electric Transmission and Distribution, "' GRID 2030 ' A NATIONAL VISION FOR ELECTRICITY'S SECOND 100 YEARS," 2003.

[53] F. C. Puttgen, Hans B and Macgregor, Paul R and Lambert, "Distributed Generation: Semantic Hype or the Dawn of a New Era?," *IEEE power and energy magazine*, no. 99, pp. 22–29, 2003.

[54] M. S. Doug Houseman, "Smart Grid : Leveraging Technology to Transform T & D Operating Models."

[55] Litos Strategic Communication, "the SMART GRID :an introduction.," 2010.

[56] and C. G. BERKOWITZ, David G., "Glossary of terms related to load management," *IEEE Trans. power Appar. Syst.*, pp. 2381–2386, 1985.

[57] R. Davito, Brandon and Tai, Humayun and Uhlaner, "The smart grid and the promise of demand-side management," *McKinsey Smart Grid*, vol. 3, pp. 8–44, 2010.

[58] T. R. US Dept. Energy, Washington, DC, USA, "Benefits of demand response in electricity markets and recommendations for achieving them," 2006.

[59] S. Mohagheghi, J. Stoupis, Z. Wang, and Z. Li, "Demand Response Architecture: Integration into the Distribution Management System Salman," in *Smart Grid Communications (SmartGridComm), 2010 First IEEE International Conference on*, 2010, pp. 501–506.

[60] J. Deng, Ruilong and Yang, Zaiyue and Chow, Mo-Yuen and Chen, "A Survey on Demand Response in Smart Grids : Mathematical Models and Approaches," *IEEE Trans. Ind. Informatics*, vol. 11, no. 3, pp. 570–582, 2015.

[61] P. Siano, "Demand response and smart grids — A survey," *Renew. Sustain. Energy Rev.*, vol. 30, pp. 461–478, 2014.

[62] A. Cain, Mary B and O'neill, Richard P and Castillo, "History of Optimal Power Flow and Formulations," *Fed. Energy Regul. Comm.*, no. December, pp. 1–36, 2012.

[63] and A. J. C. Nogales, Francisco J., Francisco J. Prieto, "A Decomposition Methodology Applied to the Multi-Area Optimal Power Flow Problem," *Ann. Oper. Res.*, vol. 120, no. 1, pp. 99–116, 2003.

[64] B. Zhang, A. Y. S. Lam, and A. Dom, "An Optimal and Distributed Method for Voltage Regulation in Power Distribution Systems," *IEEE Trans. Power Syst.*, vol. 30, no. 4, pp. 1714–1726, 2015.

[65] M. Irving, MR and Sterling, "Efficient Newton-Raphson algorithm for load-flow calculation in transmission and distribution networks," in *IEE Proceedings C (Generation, Transmission and Distribution)*, 1987, pp. 325–330.

[66] K. Paudyal, Sumit and Canizares, Claudio A and Bhattacharya, "Three-phase Distribution OPF in Smart Grids : Optimality versus Computational Burden," *Innov. Smart Grid Technol. (ISGT Eur. 2011 2nd IEEE PES Int. Conf. Exhib.*, pp. 1–7, 2011.

[67] D. Forner, T. Erseghe, S. Tomasin, P. Tenti, U. Padova, and V. G. G. B, "On Efficient Use of Local Sources in Smart Grids with Power Quality Constraints," in *Smart Grid Communications (SmartGridComm), 2010 First IEEE International Conference on*, 2010, pp. 555–560.

[68] Y.-Y. Lu, Feng-Chang and Hsu, "Fuzzy dynamic programming approach to reactive power/voltage control in a distribution substation," *IEEE Trans. power Syst.*, vol. 12, no. 2, pp. 681–688, 1997.

[69] Z. Luo, A. M. So, Y. Ye, and S. Zhang, "Semidefinite relaxation of quadratic optimization problem," *IEEE Signal Processing Magazine*, no. 27–3, pp. 20–34, 2010.

[70] D. T. Ton and M. A. Smith, “The U.S. Department of Energy’s Microgrid Initiative,” *Electr. J.*, vol. 25, no. 8, pp. 84–94, 2012.

Appendix A

From	To	R, Ω	X, Ω
1	2	0.044	0.045
1	3	0.063	0.064
1	7	0.026	0.061
3	4	0.050	0.051
3	5	0.082	0.083
5	6	0.063	0.064
7	8	0.017	0.041
8	12	0.057	0.057
8	9	0.057	0.057
8	13	0.026	0.061
9	14	0.107	0.108
13	34	0.038	0.038
13	18	0.073	0.164
14	11	0.063	0.064
14	10	0.063	0.064
15	16	0.094	0.096
15	17	0.088	0.089
18	19	0.063	0.064
18	21	0.027	0.060
19	20	0.082	0.083
21	22	0.132	0.134
21	23	0.022	0.050
23	24	0.138	0.140
23	25	0.024	0.055
25	26	0.030	0.071
25	28	0.018	0.040
26	27	0.024	0.056
26	31	0.057	0.057
27	33	0.126	0.128
28	29	0.027	0.060
29	30	0.031	0.069
31	32	0.076	0.077
34	15	0.025	0.026
35	36	0.056	0.133
35	40	0.022	0.051
36	37	0.076	0.077
36	38	0.063	0.064
38	39	0.082	0.083

From	To	R, Ω	X, Ω
40	41	0.082	0.083
40	42	0.022	0.051
42	43	0.126	0.128
42	44	0.017	0.041
44	45	0.050	0.051
44	47	0.022	0.051
45	46	0.076	0.077
47	48	0.013	0.030
47	49	0.022	0.050
49	50	0.022	0.050
50	51	0.022	0.050
52	53	0.017	0.041
53	54	0.011	0.026
54	55	0.024	0.056
54	57	0.031	0.071
55	56	0.024	0.056
57	58	0.063	0.064
57	60	0.066	0.151
58	59	0.063	0.064
60	61	0.049	0.109
60	62	0.072	0.036
62	63	0.050	0.025
63	64	0.101	0.050
64	65	0.122	0.061
65	66	0.094	0.046
67	68	0.050	0.051
67	72	0.024	0.055
67	97	0.022	0.050
68	69	0.069	0.070
69	70	0.082	0.083
70	71	0.069	0.070
72	73	0.069	0.070
72	76	0.017	0.040
73	74	0.088	0.089
74	75	0.101	0.102
76	77	0.035	0.082
76	86	0.061	0.141
77	78	0.009	0.020

From	To	R, Ω	X, Ω
78	79	0.019	0.046
78	80	0.041	0.097
80	81	0.041	0.097
81	82	0.022	0.051
81	84	0.170	0.172
82	83	0.022	0.051
84	85	0.120	0.121
86	87	0.039	0.092
87	88	0.044	0.045
87	89	0.024	0.056
89	90	0.057	0.057
89	91	0.019	0.046
91	92	0.076	0.077
91	93	0.019	0.046
93	94	0.069	0.070
93	95	0.026	0.061
95	96	0.050	0.051
97	98	0.024	0.055
98	99	0.048	0.111
99	100	0.026	0.061
101	102	0.057	0.057
101	105	0.024	0.055
102	103	0.082	0.083
103	104	0.176	0.179
105	106	0.057	0.057
105	108	0.028	0.066
106	107	0.145	0.147
108	109	0.113	0.115
109	110	0.076	0.077
110	111	0.145	0.147
110	112	0.031	0.032
112	113	0.132	0.134
113	114	0.082	0.083
18	35	0.033	0.076
115	1	0.035	0.082
13	52	0.035	0.082
60	67	0.030	0.071
97	101	0.022	0.050

Table 5: Lines Parameters for modified 123-IEEE Test Feeder

	Load	
Bus	P, Kw	Kvar
1	20	10
2	10	5
3	0	0
4	20	10
5	10	5
6	20	10
7	10	5
8	0	0
9	20	10
10	10	5
11	20	10
12	10	5
13	0	0
14	0	0
15	0	0
16	20	10
17	10	5
18	0	0
19	20	10
20	20	10
21	0	0
22	20	10
23	0	0
24	20	10
25	0	0
26	0	0
27	0	0
28	20	10
29	20	10
30	20	10
31	10	5
32	10	5
33	20	10
34	20	10
35	20	10
36	0	0
37	20	10
38	10	5
39	10	5

	Load	
Bus	P, Kw	Kvar
40	0	0
41	10	5
42	10	5
43	20	10
44	0	0
45	10	5
46	10	5
47	18	13
48	35	25
49	23	16
50	20	10
51	10	5
52	20	10
53	20	10
54	0	0
55	10	5
56	10	5
57	0	0
58	10	5
59	10	5
60	10	5
61	0	0
62	20	10
63	20	10
64	25	12
65	16	11
66	25	12
67	0	0
68	10	5
69	20	10
70	10	5
71	20	10
72	0	0
73	20	10
74	20	10
75	20	10
76	41	30
77	20	10
78	0	0

	Load	
Bus	P, Kw	Kvar
79	20	10
80	20	10
81	0	0
82	20	10
83	10	-190
84	10	5
85	20	10
86	10	5
87	20	10
88	20	-30
89	0	0
90	20	-30
91	0	0
92	20	-30
93	0	0
94	20	10
95	10	5
96	10	5
97	0	0
98	20	10
99	20	10
100	20	10
101	0	0
102	10	5
103	20	10
104	20	10
105	0	0
106	20	10
107	20	10
108	0	0
109	20	10
110	0	0
111	10	5
112	10	5
113	20	10
114	10	5
115	0	0

Table 6: Loads on modified 123-IEEE Test Feeder