A Dynamic Spinning Reserve Energy Management System to Improve Microgrid Resilience

by

Mohammadreza Shafiee

B.Sc., Electrical Engineering, Semnan University, 2009

M.Sc.E, Electrical Engineering, IAU, 2014

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Supervisors: Julian Cardenas Barrera, Ph.D., Electrical and Computer Engineering

Eugene Hill, Ph.D., Electrical and Computer Engineering

Examining Board: Eduardo Castillo Guerra, Ph.D., Electrical and Computer Engineering, Chair

Chris Rouse, Ph.D., Electrical and Computer Engineering

Wei Song, Ph.D., Computer Science

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Abstract

This thesis focuses on enhancing microgrids' resiliency and operational planning during incidents leading to islanding operations. The importance of grid resilience and the need to enhance microgrid capability during islanded operations as a probabilistic phenomenon are highlighted. The development of a dynamic spinning reserve, as well as addressing the imbalances between generation and consumption, is considered.

This work contributes by proposing a multi-objective optimization problem for maintaining a balance between resilient operation (socio-technical optimization) and economic operation (techno-economic optimization) by considering uncertainties. The research emphasizes the importance of considering low probability events with high impact on the grid, such as weather conditions, in operational planning to improve resilience and minimize load shedding. Mathematical models, objective functions, and solution methods such as Epsilon-constraint and Fuzzy Satisfaction Method (FSM) are used to accurately model the network, evaluate microgrid actors' behaviour, and solve the multi-objective optimization problem.

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List of Nomenclature

Indices and Sets

dl	Demand levels
i	Bus index
D	Load demand

Parameters and Variables

W_{Speed}	Wind speed
L_b	Line length
ldr	Shifted load
$P_{i,dl}^{D}$	i_{th} node active power and active load demand before applying DRP
$Q_{i,dl}^{D}$	i_{th} node reactive power and reactive load demand before applying DRP
$S_{i,dl}^{D}$	i_{th} node apparent power
λ_{dl}	Cost of electricity purchased from the main grid
λ_{peak}	Peak electricity consumption rate
PLF_{dl}	Price level factor at dl
DLF_{dl}	Demand level factor at dl
$P_{i,dl}^{DRP}$	Active demand after applying DRP
$SD_{P,i,dl,s}$	Shifted active power given by DRP
$SD_{Q,i,dl,s}$	Shifted reactive power given by DRP
ldr_{dl}	Amount of load contribution in DRP
DR_{dl}	Demand response factor
λ_{sell}^{P}	Selling rate of electricity to consumer
λ_{sell}^{PM}	Modified selling rate of electricity to DERO
λ_{sell}^{WTG}	Purchase rate of electricity from wind unit
$\lambda_{sell,dl}^{PDERO}$	Purchase rate of active power from DG
$\lambda_{sell,dl}^{QDERO}$	Purchase rate of reactive power from DG
P_{re}	Loads not supplied after occurrence of an event

t_{re}	Repair time to re-energized loads
$P_{k,dl,s}^{ch}$, $P_{i,dl,s}^{D}$	Selling active power to ESS/consumer
$P_{k,dl,s}^{dis,in}$	Injected power by batteries
$P_{dl,s}^{up}$	Purchased active power
$Q_{dl,s}^{up}$	Purchased reactive power
$P_{j,dl,s}^{WTG}$	Purchased active power from wind unit
$P_{j,dl}^{DG,in}$	Injected active power from DG unit
$Q_{j,dl}^{DG,in}$	Injected reactive power from DG unit
$EENS_{dl,s}$	Expected Energy Not Supplied
λ_P	EENS penalty cost
ξ_k^{dep}	Battery depreciation coefficient
η_k^{dis}	Battery discharging efficiency
η_k^{ch}	Battery charging efficiency
A_j , B_j , C_j	Expenditure coefficients for DG
$V_{i,dl,s}$	Node voltage amplitude
α_{rate}	Rate of branch failure
$\beta_{k,dl}^{ch}$, $\beta_{k,dl}^{dis}$	Battery charging/discharging binary variables

Chapter 1

Introduction

In recent years, microgrids have been coming online to connect on-site Distributed Energy Resources (DERs) to local facilities. Many research projects during the past decade have led to a better understanding of microgrids as planned entities with unique functionality for control and operations. Microgrids must meet specific requirements for interconnection and interaction with the grid, which allows active deployment to address issues and needs related to their power supply and demand [1].

Microgrids can deliver ancillary services, such as peak shaving, voltage control, and black start capability to electrical grids during their grid-connected mode individually or in clusters of microgrids called multi-microgrids [2]. During their islanded mode, they can supply power to critical loads from local generation, thereby contributing to improving power supply resilience [3].

1.1 Overview

A microgrid is defined as a group of DERs and/or Energy Storage Systems (ESS), servicing controllable and uncontrolled loads and integrated locally as a single controllable entity including controls and communication links [1], [4], [5]. The difference between a conventional grid and a microgrid supplied by distributed small-size sources is determined by the principle of coordination and management techniques of accessible assets [3]. Multiple loads and generation sources, potentially owned or operated by several parties, also make microgrids distinct from Standalone Power Systems (SPSs). Contrary to Virtual Power Plants (VPPs), the main purpose of microgrids is to balance supply and demand. Another key difference is their ability to operate in islanded mode and autonomously switch from grid-connected to islanded operation and vice versa [3], [6]. Catastrophic events like hurricanes, earthquakes, and wildfires frequently cause extended power outages, sometimes lasting hours or days. In such circumstances, the potential to reconfigure parts of the distribution system as a microgrid could provide local communities with critical services [1].

1.2 Problem Statement

Smart grids are emerging from conventional grids, where attempts are made to address the issues of conventional grids using new technologies. One of the fundamental problems in operating conventional grids is the inability to operate in an isolated mode when the upstream grid is unavailable due to failures. Due to the availability of DERs and the possibility of forming microgrids, this problem has been partially resolved. Nevertheless, in practice, due to imbalances between generation and consumption, establishing a microgrid after disconnection from the upstream grid has a low probability and is often accompanied by necessary removal of load, called load shedding.

Moreover, due to the nature of islanding and its low probability, the normal operation of the microgrid is based on economic and technical indexes. In the inception of events that could lead to islanding, definite high-scale load shedding is usually implemented. This is due to an inherent incapacity to balance consumption, generation, and corrective actions at any given time. In reliability studies a significant weight is not given to the possibility of islanding, which is due to the low probability of islanding potential. Therefore, improving the capability of the microgrid in relative preparedness for islanding, along with enhancing resilience (considering low probability events with high impact), is one of the challenges in grid operation.

1.3 Research Motivation

Resilience studies generally focus on events with low probability but high impact on the grid, while reliability emphasizes events with a high probability of occurrence. Disregarding the events with low probability in reliability studies has led to blackouts and wide area outages. On the other hand, considering events with a low probability in operational planning could decrease microgrid economic efficiency.

This research attempts to understand the impact of grid-related events and the use of possible predictions, such as weather conditions, on operational planning. The main goal is to improve resilience and minimize the Expected Energy Not Supplied (EENS) and load shedding in the event of incidents leading to islanding. In this regard, it is necessary to develop a model to assess the impact of weather conditions on outages and the islanding process. Measures can be implemented to improve resilience based on weather-related changes in the probability of line outages and their impact on EENS and load shedding. Compared to the conventional approach, this approach has the advantage that, although some economic benefits may be reduced due to potential faults, the system's capability to operate in islanded mode will likely be increased with minimal adverse effects.

1.4 Research Gaps

As a result of reviewing the literature, some research gaps were identified as follows:

1. Not many studies have explored the probability of islanding before the fault actually occurs. A situation of islanding can occur at any time. However, its probability could be estimated based on forecasts and knowledge of the underlying factors. A logical change in operational planning (from economic to resilient by considering forecasted risks) could yield technical, economic, and social benefits for all actors.

2. Microgrid systems resiliency analysis is not studied in detail for islanding scenarios.

3. Most research works consider a single spinning reserve methodology. Therefore, the microgrid cannot supply a large percentage of the loads during unplanned islanding mode.

4. Only one viewpoint (microgrid operator) has been optimized in the islanding objectives, and there is limited research on the cooperation between microgrid operators and DER owners.

5. Few studies have attempted to analyze the balance between two competing objectives (maximizing microgrid operator and DERs owner profits and maximizing a resiliency index).

6. The importance of grid resilience appears to be overlooked (before and after islanding), which is a fundamental feature of a smart grid.

1.5 Research Objectives

The main objectives of this research can be summarized as follows:

1. To increase the grid's resiliency level during time intervals with a high probability of islanding.
2. To minimize load shedding by reducing demand in high-risk time intervals and maximizing DERs readiness.
3. To develop a dynamic spinning reserve to enhance microgrid resilience since islanding is a stochastic process and extreme weather conditions increase the probability of islanding.
4. To maintain a balance between resilient operation (socio-technical optimization) and economic operation (techno-economic optimization) by considering uncertainties and introducing a dual objective optimization problem.
5. To define a fair profit-sharing mechanism among the microgrid operator, the DER owner and flexible loads to increase cooperation and reduce EENS levels.

1.6 Thesis Outline

This thesis is structured as follows: Chapter 2 provides a literature review of the types and operation modes of microgrids, the main actors and key application use cases in microgrids, operation optimization methods, microgrid energy management system, and the microgrid role in grid resiliency. In Chapter 3, the methodology presented in this study is described. In addition, operational strategies based on weather conditions, the optimization model used in the study, and methods for solving the multi-objective optimization problem are described. Chapter 4 provides a detailed case study and the results of applying the proposed methodology on the EENS reduction and the spinning reserve of the microgrid. Finally, Chapter 5 concludes the study, summarizing the main findings and contributions.

Chapter 2

Literature Review

2.1 Introduction

In 2016, Canada's installed capacity for electricity generation surpassed 146 GW. The Canadian National Energy Board projects that renewable energy generation will rise from 42 TWh in 2016 to 89 TWh in 2040, representing about 12% of all electricity generation. Most of the capacity additions will be in the natural gas, wind, and hydro sectors. Figure 1 shows the various capacity additions and retirements. Table 1 provides capacity and generation levels and shares in 2016 and 2040 [7]. In addition to hydropower, Canada has significant non-hydro renewable energy resources, such as wind, solar, biomass, and geothermal. Renewable generating technologies have grown significantly in recent years due to policy incentives and declining costs. Compared to 2010, Canada's wind, solar, and biomass generating capacity increased by more than triple by 2016 [4].

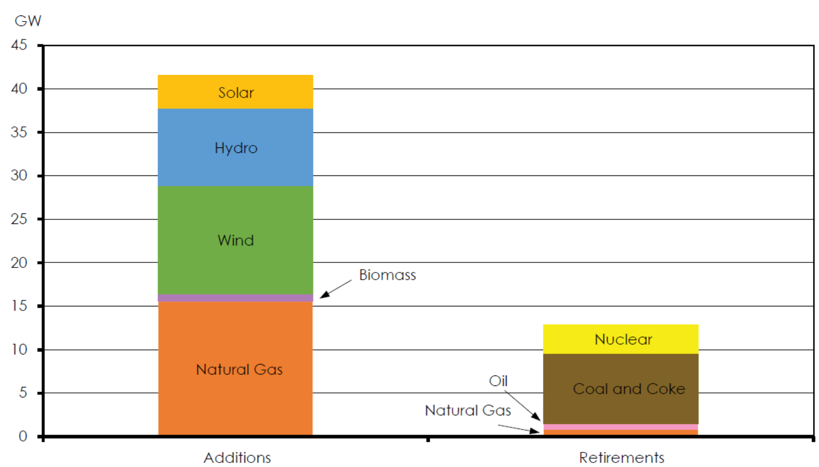


Figure 1. Capacity Additions and Retirements by 2040 [7]

Table 1. Capacity and Generation, 2016 and 2040 [7]

	Capacity in GW and %		Generation in GW.h and %	
	2016	2040	2016	2040
Hydro	80.4	89.3	382.0	424.7
	55.1%	51.2%	59.5%	59.0%
Natural Gas	21.5	35.9	61.4	113.9
	14.7%	20.6%	9.6%	15.8%
Coal and Coke	9.5	1.4	57.8	2.1
	6.5%	0.8%	9.0%	0.3%
Nuclear	14.3	11.1	95.4	88.6
	9.8%	6.4%	14.9%	12.3%
Wind	11.9	24.3	30.3	68.6
	8.2%	13.9%	4.7%	9.5%
Solar	2.3	6.1	3.2	8.5
	1.6%	3.5%	0.5%	1.2%
Biomass	2.5	3.3	8.1	12.2
	1.7%	1.9%	1.3%	1.7%
Oil	3.5	2.9	3.5	1.2
	2.4%	1.7%	0.5%	0.2%

Figure 2 illustrates how renewable energy capacity will grow to nearly 34 GW by 2040. Wind capacity is expected to increase from 12 GW in 2016 to 24 GW in 2040. By 2040, solar capacity will increase from 2.3 GW to 6.3 GW [7].

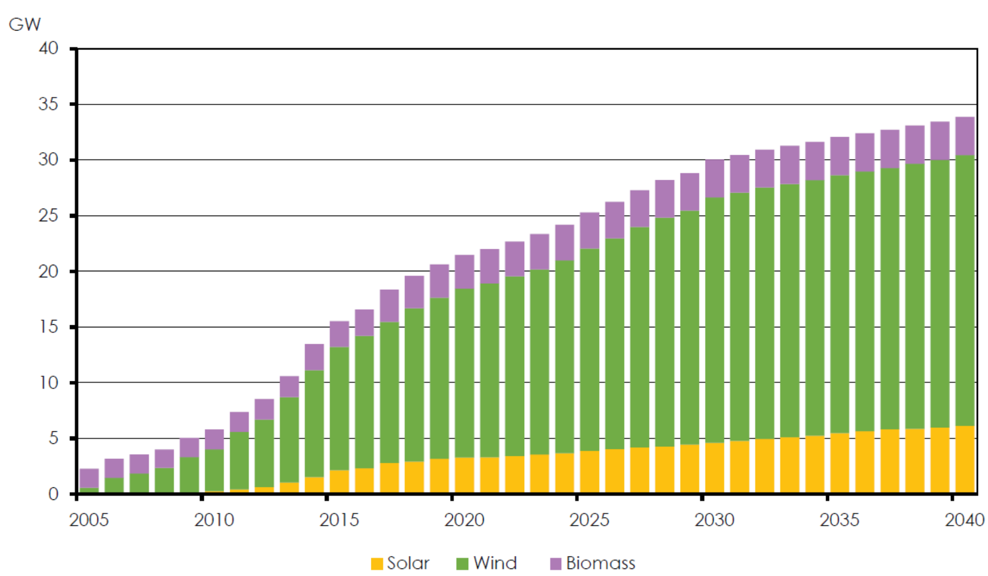


Figure 2. Predicted Non-Hydro Renewable Capacity [7]

With regard to the anticipated penetration level of DERs, microgrids are vital components of the transition from centralized bulk power systems to decentralized systems that can integrate DERs for flexibility, energy, capacity, and grid services. Moreover, microgrids can offer a variety of energy-related services to the main grid, creating new markets and improving overall energy efficiency [8].

In addition, microgrids are great ways to integrate small-scale DERs on low-voltage distribution networks and provide customers with flexibility to contribute to electricity generation [6]. The local control of the infrastructure encourages increased investment from private sectors and creates microgrid hotbeds for entrepreneurship [3]. It can also provide power to remote and regional communities where long distance transmission lines are too expensive or even impossible.

2.2 Types and Operation Modes of Microgrids

Different criteria can be used to categorize microgrids, such as geographical location, application, scale, architecture, and types of current flow. Based on their geographic location and/or application, microgrids can be categorized into urban/utility microgrids, rural microgrids, and military microgrids [9]. Urban or utility microgrids are typically designed to operate in grid-connected mode and are capable of operating in islanded mode for short periods (for instance, outage in the distribution feeder). Rural microgrids are primarily designed for rural areas supplied by a long feeder subject to significant voltage fluctuations [6].

As success criteria, the microgrid under any category must be able to: (i) manage the demand and supply sides under normal operating conditions and (ii) operate in an islanded mode either under emergency, maintenance and/or fault conditions [6], [10].

2.2.1 Types of Microgrid

In general, microgrids are classified based on the types of current flow, i.e. Alternating Current (AC), Direct Current (DC), or hybrid. AC microgrids represent the AC sources in the microgrid and can be easily connected to the utility grid via an AC bus without using bi-directional power electronic converters. In most cases, an AC microgrid adopts the voltage and frequency according to the utility grid or consumer load demand within the microgrid [6], [11]. The DC microgrid represents the DC power sources in the microgrid and has emerged in the literature due to its numerous applications in modern electronic devices and the accessibility of DC renewable energy sources, such as solar and fuel cells. The DC bus is connected to the main grid through a bi-directional DC-AC converter for power exchange to maintain the power balance. Hybrid microgrid represents both AC and DC sources in the microgrid. The AC bus can be connected directly to the main grid without the need for bi-directional power converters. The DC bus integrates the DC DERs, EES and Electrical Vehicles Supply Equipment (EVSE) and supplies the power directly to the DC loads. The advantages of the hybrid microgrid are to increase reliability, minimize conversion steps and reduce system costs [6], [11].

2.2.2 Operation Modes

In general, microgrids can be operated in two modes: islanded and/or grid-connected. A microgrid can also transfer from one mode to another using disconnect switches and controls, called a transition mode. Following is a description of the islanded, grid-connected, and transition operation modes [6].

2.2.2.1 Islanded Mode

A microgrid can operate in islanded mode by combining local generation resources with storage devices that work in grid-forming mode [12]. A microgrid may be operated in islanded mode intentionally, for example, for upstream network maintenance, or unintentionally if an upstream network is disrupted, which results in the microgrid feeding all or part of its loads, depending on the load priority list [6]. The key function of islanding is to provide power to critical or sensitive loads. Microgrids can expand their outer boundaries to provide power to non-critical/non-sensitive loads when excess power is available in the microgrid. Dispatchable DERs (e.g., diesel generators, hydropower, BESS, etc.) play an important role in power balancing by responding quickly to initial load unbalance after islanding and adjusting to the load changes [1]. Monitoring and boundary management control are essential for maintaining power balance in this mode [8].

2.2.2.2 Grid-Connected Mode

Grid-connected operation refers to the connection of microgrids to utility feeders. To integrate microgrids into the utility grid, voltage, frequency, and phase angle must all be within predetermined limits [6]. The microgrid expands its limits when connected to the grid to power both critical and non-critical loads [5]. In this mode, energy storage systems provide power to microgrids and assist in energy management (e.g., peak load control). In normal grid-connected operation, the microgrid is capable of economic dispatch to optimize the utilization of renewable power for locally-served loads [6].

2.2.2.3 Transition Mode

The transition from grid-connected to islanded mode may cause severe issues due to the microgrid's insufficient internal power generation, causing an imbalance between supply and demand. In addition, switching from islanded mode back to grid-connected mode requires the microgrid to maintain the main grid's reference voltage and frequency to allow re-synchronization [6].

2.3 Main Actors in Microgrids

A number of actors are involved in the design, operation, and energy market of microgrids. The actors are the keystone of the business models. In addition, they appear in multiple use cases. Therefore, they must be clearly defined and properly linked to the business models and use cases. Microgrid actors are categorized based on their roles as "people and organizations" and "systems and devices"[3], [13], [14].

People and organization actors represent the owners and operators of the microgrids, who can be the players in the market, including the balancing and ancillary services. Those actors must be considered in designing and operating the microgrids to either run and/or benefit from the services provided [3], [6], [13], [14]. All the actors in the "people and organization" category are defined in Table 2.

Table 2. Microgrid actors – People and Organizations [3], [6]

Actor		Type	Description
Microgrid operator		Organization	A microgrid operator that operates the microgrid and manages the local pricing policy and trading with the electrical energy market. In traditional business models and small microgrids, microgrid operators can also be in charge of the roles of the energy retailers and aggregators.
Microgrid operator	Retailer	Organization	An electrical energy market player that sells energy to consumers on behalf of the distribution network operators (DSO) or transmission system operators (TSO).

	Aggregator	Organization	An electrical energy market player that buys or sells electrical energy on behalf of two or more consumers, or DERs and storage systems owners.
	System operator	Organization	System operator is responsible for operating, providing maintenance, and, if necessary, developing the microgrid's distribution system.
Prosumer		Person/ organization	The term Prosumer refers to consumers, DER, and storage owners.
Prosumer	Consumer	Person/ organization	A consumer that acts as a private, industrial, or governmental customer. Also, the consumer may operate controllable loads.
	DER owner	Person/ organization	A DER owner that operates a DER connected to the microgrid.
	Storage owner	Person/ organization	A storage owner that provides storage and delivers the previously stored electrical energy services to the microgrid.
Overlay grid operator		Organization	A grid operator that operates the main grid before the Point of Interconnection (PoI) of the microgrid. The overlay grid operator is responsible for planning, constructing, operating and providing maintenance of the distribution and transmission networks.
Service provider		Person/ organization	The service provider assists the microgrid operator in running the microgrid by providing a variety of services (e.g., energy market analysis, load/generation profile forecasting, etc.).

Systems and devices also play a significant role in managing the microgrids' energy flow, stability, and reliability. Systems and devices can be operated and controlled by microgrid operators, prosumers, and/or overlay grid operator [3], [6], [13], [14]. Therefore, defining the systems and devices operator significantly extends the understanding of the design and operation of the microgrids. All the actors in the group "Systems and devices" are described in Table 3.

Table 3. Microgrid actors – System and Devices [3], [6]

Actor	Type	Description
Microgrid control centre	System	It controls and manages the microgrid operator's activities, and the aggregation of supply and demand.
Overlay grid control centre	System	It controls and manages the overlay grid where all necessary supervision and control duties are carried out.
DER unit	Device	DERs include distributed generation (e.g., PV plants, wind turbines, etc.) that is connected to the microgrid and can be monitored and controlled.
Storage unit	Device	A power and energy reserve provided by the storage unit that can be monitored and controlled.
Home or building energy management system	System	It connects the smart home/building (e.g., controllable loads) with the microgrid control centre to improve the microgrid operation.
Network smart device	Device	Network smart devices are intelligent devices that can be supervised and controlled at the feeder level (e.g., sensors, switches, etc.).

2.4 Key Application Use Cases in Microgrids

There are two main categories of high-level use cases: “business” and “control and management” [6]. Business use cases are primarily concerned with trading energy and providing a market platform for exchanging energy. The control and management use cases category includes the demand and supply side management, major control tasks, black start in islanded operation, protection, and microgrid infrastructure upgrades [3], [15]. Figure 3 and Figure 4 summarize the business use cases and the control and management use cases [6].

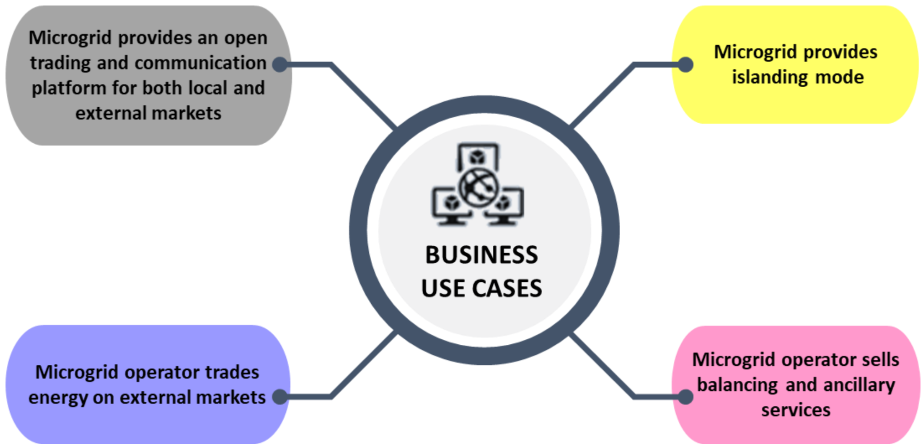


Figure 3. Overview of business use cases [3], [6]

Figure 4. Overview of the control and management use cases [3], [6]

2.5 Microgrid Operation Optimization

The primary objective of microgrid operation is to optimize specified key performance indicators, particularly economics, reliability, and resiliency. Microgrids are highly dependent on the intermittent DERs, which are in fact non-dispatchable generators, thereby making the reliability/resiliency issue more significant [6].

Power systems have been subject to an increasing number of outages due to frequent natural disasters and extreme weather conditions [6]. Additionally, the rapid growth of energy demand increases the risk of power outages [16]. Distributed energy resources convert a microgrid from a passive to an active system, allowing the entire system to gain benefits by optimizing its operation. Therefore, the microgrid can enhance the resilience of power systems. Detailed explanations of techno-economic and socio-technical optimization are provided in the following sections.

2.5.1 Techno-Economic Optimization

Techno-economic optimization is a method of analyzing the economic performance of an industrial process, product, or service [17]. It typically uses mathematical models to structure optimal objectives such as capital cost, operating cost, and revenue based on technical and financial inputs, minimizing cost and maximizing benefits [18]. Linking process inputs to financial metrics can help businesses and industries better understand the factors that influence the profitability of their technology development projects [6].

An economic objective is to minimize the microgrid costs, including the capital expenditure, cost of installation, operation, maintenance, replacement, and fuel costs of the backup generator. Revenue (profit) can also be viewed as an objective that could be maximized [19]. Table 4 provides descriptions of commonly considered economic objective functions [6].

Table 4. Commonly considered economic objectives [6]

Objective function	Definition
Minimizing generation cost	It is the overall cost of the total power produced by all the generating units in a period [20].
Minimizing capital cost	A one-time cost associated with acquiring fixed assets and making long-term investments such as buying equipment and upgrading technology [20].
Minimizing fuel cost	It is the overall fuel cost of the power produced by all the generators in a period [21].
Minimizing maintenance cost	In addition to asset management and equipment maintenance, it refers to routine inspections, reporting, regular system integration and reviews, and preventive maintenance [22].
Minimizing start-up and shut-down costs	Costs associated with turning the generators on and off, in [$/MWh] [23].
Minimizing purchase cost from the utility grid	It is the overall cost of purchasing energy from the overlay grid in a period [24].
Minimizing shortage cost	The costs associated with economically compensating consumers if the microgrid cannot satisfy their demand during a particular time slot. This can incentivize consumers to postpone demand until another time [25].
Maximizing microgrid revenue	Revenues derived from the purchase and sale of electricity to the main grid [26].
Minimizing grid cost	The objective of the cost function is to penalize deviations from the long-term economic dispatch schedule for the purchase and sale of energy from the main grid [27].
Minimizing cost of importing energy from other microgrids	It is the overall cost of purchasing energy from the other microgrids in a period [28].
Minimizing the allocation cost	It refers to the different DERs configuration costs depending on the location and natural environment of a microgrid [29].
Minimizing hourly operating and maintenance cost of ESS	An energy storage system's operating and maintenance cost is determined by the hourly discharged energy and rated power [30].
Minimizing storage cost	This objective is defined as the charging and discharging cost of energy storage systems and calculated based on charge and discharge powers, cost of ESS for periodic duty, and operation state of controllable units [26].
Minimizing total microgrid cost	This objective is the sum of all the costs incurred in the process of installation, maintenance, operation, replacement, and component fuel costs within the microgrid [31].
Maximizing Net Present Value (NPV)	In assessing the profitability of the microgrid, the NPV examines cash flows. The NPV is computed by adding up

	all incomes and expenses, considering interest and discount rates. When the NPV is positive, a project is profitable [32].
Minimizing total operational cost	This objective includes the operational costs of the microgrid once it has been installed [33].
Minimizing levelized cost of energy	The levelized cost of energy is the ratio of the total microgrid cost to the total amount of energy generated during a period [34].

2.5.2 Social Aspects Incorporated into Optimization

The difference when using a socio-technical approach lies in incorporating social parameters without dismissing the importance of the techno-economical constraints [35]. A microgrid's reliability/resilience is a socio-technical approach that aims to achieve its capability to satisfy its demand [6]. An analysis of microgrid reliability indices is crucial when scheduling the microgrid, such as loss of load probability (LLP), loss of load supply probability (LLSP), deficiency of power supply probability (DPSP), and expected energy not supplied (EENS) [19]. The descriptions of the commonly considered reliability objective functions are provided in Table 5 [6].

Table 5. Commonly considered reliability objectives [6]

Objective function	Definition
System Average Interruption Duration Index (SAIDI)	It measures the number of interrupted customers for each interruption event [36].
System Average Interruption Frequency Index (SAIFI)	It measures the number of interrupted customers for each interruption event associated with the restoration time for each interruption event [36].
Momentary Average Interruption Frequency Index (MAIFI)	It measures the number of momentary interruptions per customer [36].
Minimizing Loss of Load Supply Probability (LLSP)	This objective refers to the proportion of time for which the microgrid fails to power the loads [37].

Minimizing Loss of Load Probability (LLP)	This objective measures how often a microgrid or energy system does not meet load demands efficiently [38].
Minimizing Deficiency of Power Supply Probability (DPSP)	This objective measures how likely it is that the microgrid will fail to meet the energy demand. The reason can be a system breakdown or a low level of power generation from renewable energy sources [34].
Minimizing Expected Energy Not Supplied (EENS)	This objective denotes the expected energy that the microgrid will not supply for a given period [39].

2.6 Energy Management System

A balance between demand and generation needs to be maintained in microgrids in grid-connected and islanded operation modes while satisfying certain reliability, resiliency, power quality, and adequacy standards [6]. All DERs and loads should be directly or indirectly involved in achieving these objectives, depending on their control capabilities [1]. Localization of energy production and consumption has created opportunities for new energy management technologies, which have already shown the potential to lower energy costs and improve energy supply reliability and security [40], [41].

There are several technical and economic advantages for employing small-size distributed energy resources in the low-voltage distribution network and end-users [42]. Energy systems can be managed systemically by microgrids. The monitoring and management of microgrid assets is conducted by an energy management system (EMS) [6]. An EMS can be implemented as a hybrid system consisting of software and hardware that provides a decision support platform for microgrid operators [43]. The microgrid EMS provides various functionalities, including [6]:

- Monitoring of the microgrid under various conditions.
- Capacity to handle a wide range of threats.

- Analyzing different operational states of the system.
- Taking control actions.
- Determining the exchange of energy with the main grid.
- Making quick decisions during critical situations.

The following subsections will analyze different tasks of the EMS.

2.6.1 Monitoring system

The EMS monitoring system offers an accurate and thorough view of the continuous operation of the microgrid. Meters and sensors gather this information and transmit it to the EMS through the remote terminal units (RTUs) by means of the communication infrastructure [6]. It provides data on [43]:

- Real-time status of switches, lines, and transformers.
- Power output from DER units
- Output power and State of Charge (SOC) of energy storage systems
- Information of the reactors and capacitors.
- Fuel availability of dispatchable generators

2.6.2 Control system

EMS control strategies depend on the complexity and importance of the microgrid procedures [6]. Sometimes, the EMS controls the components directly during automatic control. A self-repairing microgrid, for example, automatically identifies the fault, isolates it, and restores the system. Supervisory control is another option in which the system operator can make direct changes to the status of switches through the EMS when needed [6], [43].

2.6.3 Optimization Features

As different load-supply strategies exist in microgrids, they require a systematic approach to make decisions [6]. The optimization tool should provide a wide range of applications based on the microgrid operation strategy and relevant economic and technical factors, outlined in the following [6], [43].

- **Unit Commitment:** This tool determines the availability of generation units to meet the load demand, taking into account the economic objectives and technical properties of DERs.
- **Economic Dispatch:** This optimization module determines the optimal output power of active DERs in microgrids.
- **Optimal Power Flow (OPF):** The OPF module can have different objectives, including cost minimization, loss minimization, and profit maximization.
- **Network Reconfiguration:** The tool calculates the best power path for the loads from different perspectives such as reduced losses and higher reliability. Reconfiguration can also be used to share the load across different lines.
- **Decision Making under Uncertainty:** It provides different methods of decision-making based on uncertainty. The module includes robust optimization, stochastic programming, information gap decision theory, and so on.

2.6.4 Centralized and Decentralized Energy Management System

Implementing an EMS can be done either in a centralized or decentralized manner. A computational core dispatches commands to local controllers to operate various components in the centralized EMS, whereas local controllers are intelligent agents that analyze and dispatch their associated components based on the local conditions in the decentralized EMS [6], [43]. A centralized EMS applies optimization procedures to manage the microgrid efficiently based on different collected information. By continually updating the input data, scheduling can reduce the effect of uncertainties. Several decision-making approaches are utilized, for example, machine learning systems, optimization, and rule-based systems. A centralized EMS is suitable for real-time applications as several microgrid components are monitored and analyzed in one place [6], [43].

Different agents schedule different parts of the microgrid in decentralized energy management [43]. The method works well on bigger-size microgrids where the DERs and loads are distributed, and centralized data gathering is not viable or feasible. In decentralized decision-making, multi-agent systems (MAS) are an important tool for power management. Each agent manages a device which makes decisions based on its own data as well as data from other agents [6], [43].

2.6.5 Hour-Ahead and Real-Time Energy Management System

As microgrids contain various energy sources, energy storage devices, etc., they have a complex structure and more data sources. Consequently, most of its energy management issues are considered to be offline optimization issues related to typical hour-ahead scheduling, which requires early prediction of renewable resource generation and consumption. Offline optimization algorithms mainly include mixed-integer programming, particle swarm optimization, robust optimization, and sequence quadratic programming [6].

Due to the uncertain and intermittent operation of microgrids, the EMS must run an optimal scheduling problem as closely as possible to the real-time operation. Indeed, EMS requires a framework that applies hour-ahead scheduling over the hours of the operation horizon, for example, 24 hours ahead, and then uses real-time scheduling for energy management over smaller time steps near the real-time operation time [6], [44].

Real-time EMS strategies have been proposed to solve hour-ahead EMS drawbacks by dividing the timeline into small intervals to improve energy management efficiency [45]. As shown in Figure 5, hour-ahead EMS can be run hourly for the following hours, applying the updated data until the end of the operation horizon [44]. Next, the results are applied to the real-time EMS that is repeated in 15-minute time steps. Even though real-time microgrid EMS schedules the operation for the next time steps at the end of the current time-step, the system's next hour forecasted condition is indirectly considered by utilizing the latest hour-ahead scheduling results [6], [44].

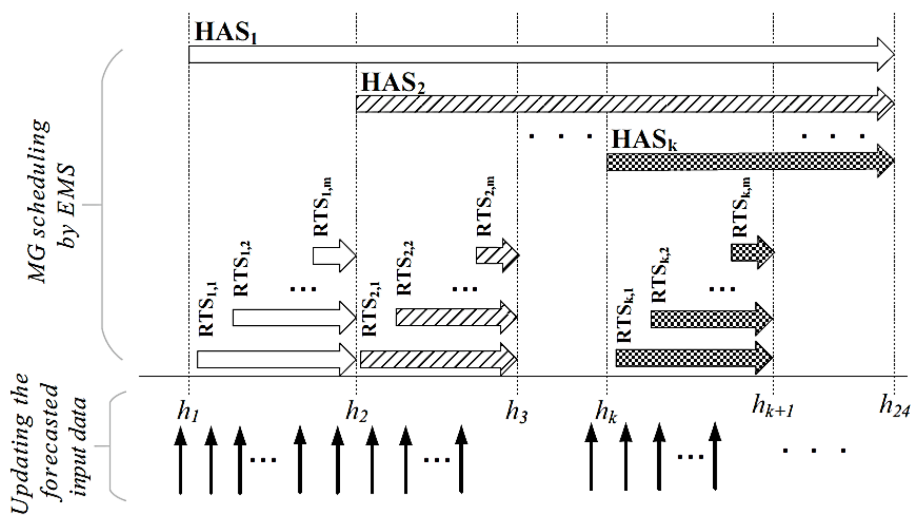


Figure 5. Scheduling of microgrid in hour-ahead scheduling (HAS) and real-time scheduling (RTS) [43]

2.6.6 System Operation Strategies

EMS can employ various operation strategies/objectives. Overall, the operation strategies are categorized as techno-economic and socio-technical strategies [6], [46]. The EMS operation strategies are summarized in Figure 6. Microgrids should be designed optimally to achieve a use case's main goal(s). In such a case, the components can be operated optimally based on one or a set of objective functions subject to a set of constraints. The objective functions and constraints may vary from one use case to another. Therefore, defining the use case is the keystone to identify the relevant objective function(s) and constraint(s) [6], [43].

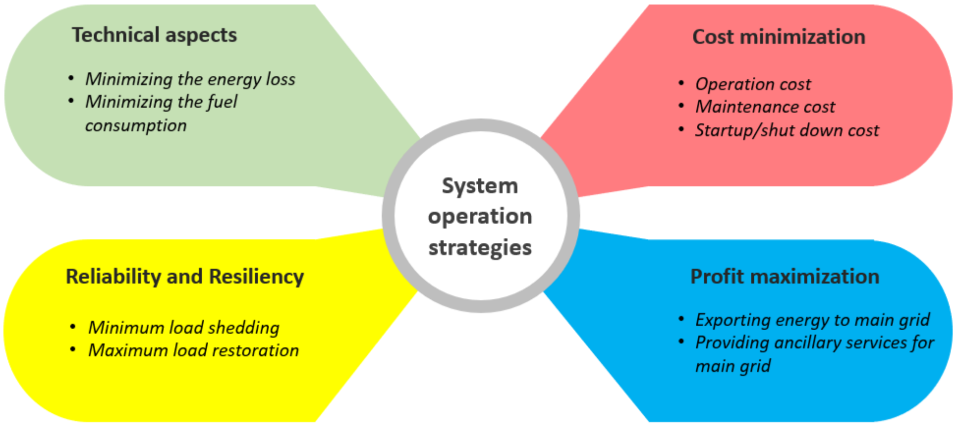


Figure 6. System operation strategies of EMS [6], [43]

2.7 Microgrid Roles on Grid Resiliency

The increasing penetration of DERs makes microgrids a viable solution to control and scalability problems [47]. A microgrid could also supply power to critical end-use loads during low-frequency, high-impact events, improving overall system resiliency [1], [6]. Catastrophic events like hurricanes, earthquakes, and wildfires frequently cause extended power outages, sometimes lasting days or weeks [48]. In such circumstances, the potential to reconfigure parts of the distribution system as microgrids could provide local communities with critical services, such as providing power to local hospitals, temporary shelters, and community centres while the rest of the power system is repaired. Microgrids can play an important role in resiliency in these situations [6].

2.7.1 Modeling for Resiliency

Microgrids must provide a stable platform for operations to support resiliency. During normal and expected abnormal events, it must be able to maintain a stable frequency and voltage. When grid-connected, this requires sufficient generation to supply the load plus losses in combination with the main grid [1], [6]. Microgrids must be able to maintain system stability while operating during routine operations in addition to steady-state considerations [49]. In complex transitions between grid-connected and islanded operations after catastrophes, where the microgrids may be operating in conditions different from those studied during design, these various forms of stability analysis become even more critical [6]. Power supply, balance, and system stability are included [50]. Microgrid stability behaviours can differ from interconnected bulk power systems. The following are specific issues that must be addressed by microgrids [1], [6]:

- System voltage stability.
- Unintentional islanding, where short-term frequency stability could become relevant.
- Small disturbance stability related to either balance stability and power supply (voltage and frequency stability) or to control system stability (electric machinery and converter stability).
- Large load starting, including inrush, that could result in short-term frequency stability and long-term voltage stability.
- Fault response that could result in long-term electric machine and converter stability and short-term voltage stability.

Chapter 3

Methodology

3.1 Introduction

The backbone of a microgrid is the one or more lateral lines which spread out from the Point Of Interconnection (POI) to the Main Grid, and on which are interspersed tens or hundreds of buses feeding customer loads. Also present at any, and many, points of these lateral lines there may be Distributed Energy Resources consisting of gas-fired Distributed Generators (DG), renewable sources such as wind turbines (WT) or solar installations, and energy storage components (ESS) such as batteries. There are at least two entities with operational, business and monetary interests on the microgrids. These are the Microgrid System Operator (MSO) and the Distributed Energy Resource Owners (DERO).

The MSO purchases power from the Main Grid and sells to the load customers each hour of the day, but the MSO can also purchase from the DERO. The MSO does day ahead planning in matching generation resources with the load, and also assuring a suitable spinning reserve so that the system operates reliably. The MSO must also include in its planning the possibility of reduced reliability due to environmental factors such as wind speed, which could possibly result in isolated operation of the microgrid.

The DERO consists of private businesses who purchase equipment to be installed on the microgrid including DG, wind turbines, and energy storge elements such as batteries which can enhance the microgrid operation, but which also provide a business opportunity for the DERO.

Both the MSO and the DERO have valid business roles and each have legitimate monetary objectives. When these monetary objectives are structured in mathematical terms, they are referred to as Objective Functions (OF). Therefore, the monetary objectives of the MSO may be designated as OF_1 and the monetary objectives of the DERO may be designated as OF_2. Businesses exist to make money and to maximize their profits to the greatest extent possible, but in this, as in most practical multi objective circumstances, there is a conflict of objectives. There is no guarantee that a single solution simultaneously optimizes/maximizes each objective. The answer is to arrive at a set of solutions that define the best tradeoff between the competing objectives, and then though some process choose the "best" solution from among the solution set. The methodology of this chapter lays out a structure for the multi objective problem inherent in microgrids.

The proposed approach also aims to recognize and mitigate the impact of adverse weather conditions before the fault initiation. Consequently, the network operates in a mode that is more prepared for emergencies (hours with a high probability of faults) by changing certain operational conditions, and deviating from purely economic operation. If there is an event during these hours, the energy not supplied would be less than what it could be through purely economic operations.

This research proposes a Microgrid Energy Management System (M-EMS) approach for achieving optimal operational planning while considering line outages caused by extreme weather conditions. It also focuses on improving microgrid resilience, minimizing the EENS, and reducing load shedding in the event of incidents leading to islanding. The main idea is to increase microgrid resilience through dynamic adjustments to the generation reserve and Demand Response Program (DRP) by considering weather conditions and islanding probability. In order to increase the readiness of the microgrid against load shedding during islanded mode, values of Expected Energy Not Supplied (EENS) are estimated by considering changes in demand level, generation of DGs, Energy Storage System (ESS), and the failure rate of branches. Accordingly, resource scheduling and DRP are modified to minimize total operational costs, including the cost of EENS. The profits from decreased EENS are split between the MSO and the DERO by selecting the optimal solution.

3.2 Fundamentals of the Proposed Method

The optimization of operational planning problems can be divided into two categories. The first category involves planning under normal conditions, focusing on improving economic and technical objectives. The second category involves planning under emergency conditions to enhance resiliency and meet the load. Adverse weather conditions often lead to electricity disruptions, resulting in numerous customers facing outages. Therefore, the main concern of microgrid operators is to ensure a resilient and affordable network operation during extreme weather events.

The impact of weather conditions on the outage rate of the Main Grid lines is investigated, considering the associated uncertainties. It is necessary to develop an accurate model for the cost of the MSO and DERO by taking into account the cost of load shedding and EENS. Based on these models, the behaviour of each actor can be evaluated under probabilistic conditions, and accordingly, mechanisms for operational planning and profit sharing can be implemented. Finally, the solution method should be suitable for nonlinear behaviour and interdependent parameters. Mathematical methods based on Mixed Integer Nonlinear Program (MINLP) are applied to solve the problem. Compared to conventional approaches, this approach has the advantage that, although some economic benefits may be reduced due to potential risks, the system's capability to operate in islanded mode will be increased with minimal side effects.

A schematic of the proposed method is shown in Figure 7. The proposed methodology demonstrates that short-term daily planning can significantly impact the actors' profits and reduce costs associated with blackouts during adverse weather conditions.

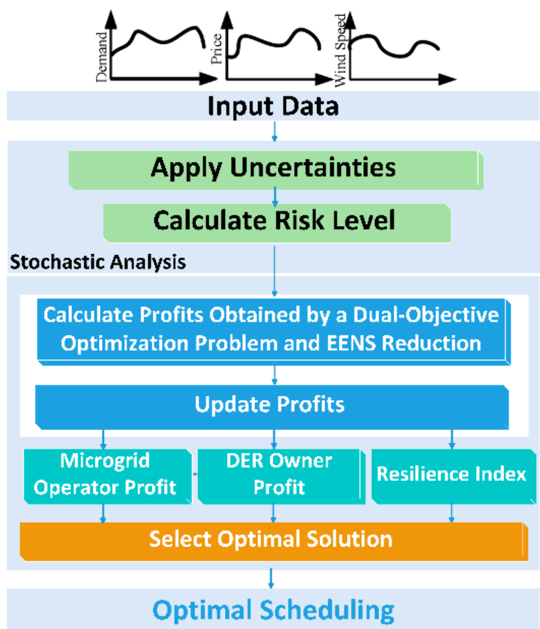


Figure 7. Schematic of the proposed methodology

3.3 Mathematical Formulation

In order to proceed to develop objective functions, it is first necessary to outline the parameters which go into the objective functions. The first of these is load models. Gas turbines, ESs, WT, and upstream power grids provide electricity to consumers. Notably, this study assumes that weather conditions and failure rates of branches are fixed in the scenarios.

For modelling the load demand, as symbolized by D, each day is divided into 24 levels, denoted as N_{dl} or just *dl*, representing 24 different demand levels. At any bus *i*, the 24-hour load model is determined by multiplying the base load parameter ($P^D_{i,base}$ and $Q^D_{i,base}$) by the Demand Level Factor (DLF). The symbol *s* is used to identify the scenario number in later studies.

$$P^D_{i,dl,s} = P^D_{i,base} \times DLF_{dl,s} \tag{1}$$

$$Q^D_{i,dl,s} = Q^D_{i,base} \times DLF_{dl,s} \tag{2}$$

$$S^D_{i,dl,s} = P^D_{i,dl,s} + jQ^D_{i,dl,s} \tag{3}$$

The cost of electricity purchased from the Main Grid (λ_{dl}) fluctuates at different levels. It is calculated by multiplying the peak electricity consumption rate (λ_{peak}) by the price level factor (PLF_{dl}). The pricing model can be explained as follows:

$$\lambda_{dl} = \lambda_{peak} \times PLF_{dl} \tag{4}$$

3.3.1 EENS Formulation

In this thesis, EENS refers to all load outages during grid-connected mode or curtailed loads during islanding operation. EENS, as defined in equation (5), serves as an indicator of resilient operation, since it encompasses the costs associated with the consequences of outages. Outages refer to those occurring in the Main Grid, not in the microgrid. In the given equation, N_b represents the total number of branches within the Main Grid, and α_{rate} denotes the rate at which branches fail. Furthermore, the equation takes into account the length of lines L_b, N_{bus} indicating the number of disconnected buses during both outage and repair periods, P_{re} denoting the loads not supplied after occurrence of an event, and t_{re} representing the duration of fault continuity.

$$EENS_{dl,s} = \sum_{b=1}^{N_b} \alpha_{rate} \times L_b \times (\sum_{re=1}^{N_{bus}} P_{re,dl,s} \times t_{re}) \tag{5}$$

3.3.2 Price Signal to the DERO

In normal grid-connected mode, the EENS value is low. So, the main objective function is to increase the profits of the microgrid actors. The type of optimization in the grid-connected mode is a techno-economic optimization. However, adverse weather conditions can result in a higher value of EENS. In this case, the main goal of the EMS is to be prepared for islanded operation mode. Therefore, all the resources and flexible loads must be rescheduled as a day-ahead energy management system.

The costs incurred by the microgrid operator each hour consist of the expenses related to procuring electricity from the upstream Main Grid and potential fines for any interruptions during those hours. Hence, the microgrid's actual cost for each hour is influenced by the factors outlined in equation (6), an expression appearing in the literature and modified by research experience. λ_P represents the penalty imposed for insufficient supply of the loads. This equation shows that the MSO increases the proposed price (λ_{sell}^{PM}) to the DERO in order to encourage the DERO to cooperate during high-risk time intervals (higher EENS values).

$$\lambda_{sell,dl,s}^{PM} = \lambda^{PDERO} + \frac{0.5 \times \lambda_P \times EENS_{dl,s}}{\sum_{i=1}^{N_{load}} P_{i,dl,s}} \tag{6}$$

Since prices are determined for the following day, the DERO has enough time to respond to the MSO requests. This time allows the DERO to adjust production and consumption patterns to meet the MSO needs, potentially increasing profits. This approach uses price signals to convey the MSO's demands. As a result of setting prices in a manner that encourages the DERO to adjust its generation and consumption patterns in line with the network's requirements.

Using price signals as an interface between the MSO and the DERO improves system resilience. As an effective tool, these signals allow the MSO to communicate their needs and requirements to the DERO and encourage cooperation in the private sector.

3.3.3 Weather Impact

Various studies have revealed that severe weather events are the main causes of most failures in electrical distribution grids [51]. As can be seen in Figure 8, there is a strong correlation between the line failure rate and wind speed.

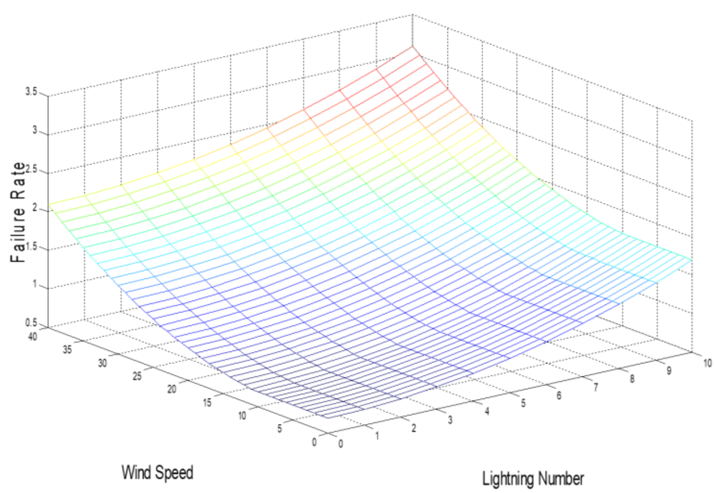


Figure 8. Graph of line failure rate versus wind speed and lightning number [51]

In a smart grid system, recording data of these events can significantly enhance the grid performance under such conditions. Proper analysis of the impact of severe weather on the frequency of outages requires utilizing the correlations presented in [52] for modelling purposes. In this study, the relationship between outages and wind speed is described as a polynomial fit of observed data (ignoring lightning effects) [52]:

$$\alpha_{wind} = 0.0012{W_{speed}}^2 - 0.0131W_{speed} \tag{7}$$

This work focuses on the average wind speed within specific time intervals. The non-weather-based outage rate is assumed to be 0.0002 in this study. The obtained value for weather-based outage rate (α_{wind}) is added to the non-weather-based outage rate to update the line failure rate (α_{rate}). Extreme weather conditions necessitate longer repair times. It is assumed that repair time averaged 4 hours under normal conditions but increased to an estimated 6 hours under extreme conditions [52].

3.3.4 Demand Response Program (DRP)

To minimize the expenses and increase the readiness of the microgrid to operate in islanded mode, EMS employs DRP to modify the consumption patterns of the customers. This program aims to shift the load from high-risk intervals to times when adverse weather conditions are not expected. The shifted demand by consumers is restricted in this study, with only 25% of the total load being utilized in the DRP. The employed DRP follows a time-of-use mechanism because the high-risk intervals are known. Additionally, it is assumed that the transfer of both active and reactive power loads from all busses occurs at a constant percentage, while the load transfer from each individual bus is associated with a constant power factor specific to that bus. DRP can be modeled as shown in Figure 9.

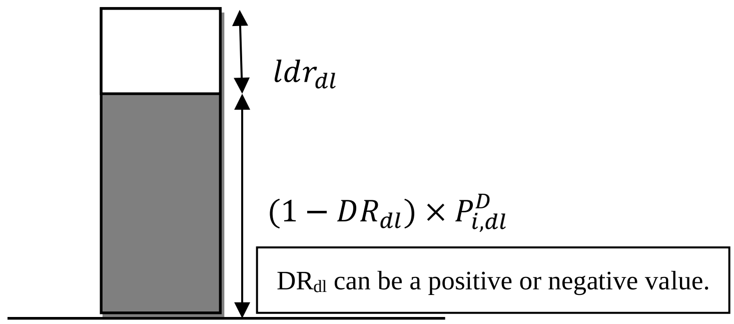


Figure 9. Demand response based load modeling

For load bus i during hour dl, and in scenario s, the DRP equations are as follows.

$$P_{i,dl,s}^{DR} = P_{i,dl,s}^{D} - ldr_{P,dl,s} \tag{8}$$

$$Q_{i,dl,s}^{DR} = Q_{i,dl,s}^{D} - ldr_{Q,dl,s} \tag{9}$$

$$ldr_{P,dl,s} = DR_{dl,s} \times P_{i,dl,s}^{D} \tag{10}$$

$$ldr_{Q,dl,s} = DR_{dl,s} \times Q_{i,dl,s}^{D} \tag{11}$$

$$\sum_{h=1}^{24} ldr_{dl,s} = 0 \tag{12}$$

$$DR^{min} \leq DR_{dl,s} \leq DR^{max} \tag{13}$$

The adjustable demand at each load level possesses a variable value, as denoted in equation (10) and equation (11). The index denotes the extent of consumer involvement in DRP. Equation (12) states that the energy under the DRP adjusted load profile is unchanged from the original in any 24-hour time frame. Equation (13) restricts the DRP activity during any given period.

3.3.5 Multi-Objective Optimization Problem

One of the primary objectives of optimization is to reinforce system resilience. This work introduces the EENS resiliency index to emphasize the significance of system uncertainty.

The performance model encompasses DERs and ESs units. Maximizing the daily profit from power trading while reducing the EENS value serves as the primary focus of the optimization framework. Equation (14) presents the mathematical representation of the MSO profit.

$$OF_1 = \text{MAX} \sum_{t=1}^{N_{dl}} \left\{ \begin{array}{l} \sum_{i=1}^{N_{load}} \lambda_{sell,dl,s}^{P} . P_{i,dl,s}^{D} + \sum_{k=1}^{N_k} (\lambda_{sell,dl,s}^{P} . P_{k,dl,s}^{ch} - \lambda_{sell,dl,s}^{PM} . P_{k,dl,s}^{dis,in}) \\ - \sum_{up=1}^{N_{UP}} \lambda_{dl,s} . P_{dl,s}^{up} - \sum_{up=1}^{N_{UP}} \lambda_{Qfix} . Q_{dl}^{up,pu} - \lambda_{P,h} EENS_{dl,s} \\ - \sum_{j=1}^{N_{WT}} \lambda_{sell,dl}^{WT} . P_{j,dl,s}^{WT,pu} - \sum_{j=1}^{N_{DG}} \lambda_{sell,dl,s}^{PM} . P_{j,dl,s}^{DG,in} - \sum_{j=1}^{N_{DG}} \lambda_{sell,dl,s}^{QDERO} . Q_{j,dl,s}^{DG,in} \end{array} \right\} \tag{14}$$

The Objective Function (*OF₁*) in equation (14) encompasses the revenue gained from selling energy to customers, expenses incurred from purchasing energy from the upstream Main Grid, EENS costs, and the cost of purchasing energy from DERO, including DGs, ESs, and wind turbines.

Turning to the DERO, equation (15) is the mathematical representation of the DERO revenue which is to be maximized. The DERO is able to sell its energy via bilateral contracts at a fixed price. The profits obtained by selling energy to the MSO, the benefits derived from utilizing ESs, the costs associated with charging batteries, the expenses related to battery depreciation, and the costs incurred by DGs for power generation are all considered in the second Objective Function (OF_2) in equation (15). These considerations are subject to certain constraints.

$$OF_2 = \text{Max}\sum_{t=1}^{N_{dl}}\left\{\begin{array}{l}\sum_{j=1}^{N_{DG}}\lambda_{sell,dl,s}^{PM}.P_{j,h,s}^{DG}+\sum_{j=1}^{N_{DG}}\lambda_{sell,dl,s}^{QDERO}.Q_{j,h,s}^{DERO}\\+\sum_{j=1}^{N_{WTG}}\lambda_{sell,dl}^{WT}.P_{j,h,s}^{WTG}+\sum_{k=1}^{N_k}\lambda_{sell,dl,s}^{PM}.P_{k,\mathrm{dl},s}^{dis}\\-\sum_{k=1}^{N_k}\lambda_{sell,dl,s}^{P}.P_{k,\mathrm{dl},s}^{ch}-C_k^{deg}(\sum_{k=1}^{N_k}\frac{P_{k,dl,s}^{dis}}{\eta_k^{dis}}+\eta_k^{ch}.P_{k,\mathrm{dl},s}^{ch})\\-\sum_{j=1}^{N_{DG}}(A_jP_{j,\mathrm{dl},s}^{DG^2}+B_jP_{j,dl,s}^{DG}+C_j)-\sum_{j=1}^{N_{DG}}Q_{j,dl}^{DERO}.CT_j^{Q}\end{array}\right\} \tag{15}$$

The load distribution restrictions and equations are to be applied to the i_{th} bus at the dl_{th} level, as described below. Power balance equations representing net power injection at a bus and power outflow over the power system can be modelled as follows:

$$\begin{array}{c}P_{dl,s}^{us}+P_{i,dl,s}^{DERO}-\left((1-DR_{dl,s})\times P_{i,dl,s}^{D}+ldr_{P,dl,s}\right)\\+\sum_{k=1}^{N_k}(P_{k,dl,s}^{dis}-P_{k,dl,s}^{ch})=V_{i,dl,s}\sum_{j}V_{j,dl,s}(G_{ij}\cos\delta_{i,dl,s}+B_{ij}\sin\delta_{j,dl,s})\end{array} \tag{16}$$

$$\begin{array}{c}Q_{dl,s}^{us}+Q_{i,dl,s}^{DERO}-\left((1-DR_{dl,s})\times Q_{i,dl,s}^{D}+ldr_{Q,dl,s}\right)=\\V_{i,dl,s}\sum_{j}V_{j,dl,s}(G_{ij}\cos\delta_{i,dl,s}-B_{ij}\sin\delta_{j,dl,s})\end{array} \tag{17}$$

It is imperative to maintain the voltage of a node within the designated range at all times.

$$V_i^{min}\le V_{i,dl,s}\le V_i^{max} \tag{18}$$

Energy interaction of the microgrid with the upstream Main Grid is limited based on technical constraints and market regulation (equations (19) and (20)). Each DG must have a generation capacity that falls within its allowed range (equations (21) and (22)).

$$P_{up}^{min} \leq P_{up,dl} \leq P_{up}^{max} \tag{19}$$

$$Q_{up}^{min} \leq Q_{up,dl} \leq Q_{up}^{max} \tag{20}$$

$$P_{DG}^{min} \leq P_{i,dl}^{DG} \leq P_{DG}^{max} \tag{21}$$

$$Q_{DG}^{min} \leq Q_{i,dl}^{DG} \leq Q_{DG}^{max} \tag{22}$$

The transmission line KVAs are constrained by thermal limits.

$$0 \leq S_{ij,dl,s} \leq S_{ij}^{max} \tag{23}$$

Equations (24-28) represent the limitations associated with the ESs. Constraints 24 and 26 depict the boundaries of battery charging and discharging, as well as the energy stored in the ESs. Equation (27) reveals that the battery within the ESS can only operate in one mode (charging or discharging) at a time. The dynamic model of the ESs is stated in equation (28).

$$0 \leq P_{k,dl,s}^{ch} \leq \beta_k^{ch} P_k^{ch,max} \tag{24}$$

$$0 \leq P_{k,dl,s}^{dis} \leq \beta_k^{dis} P_k^{dis,max} \tag{25}$$

$$EN_k^{min} \leq EN_{k,dl,s} \leq EN_k^{max} \tag{26}$$

$$\beta_{k,h,s}^{ch} + \beta_{k,h,s}^{disc} = 1 \tag{27}$$

$$EN_{k,dl+1,s} = EN_{k,dl,s} + (\eta_k^{ch} \times P_{k,dl,s}^{ch} - \frac{P_{k,dl,s}^{dis}}{\eta_k^{dis}}) \tag{28}$$

3.4 Solution Method

To address the challenge of dual-objective optimization, the ε-constraint technique [53] is utilized in the General Algebraic Modeling System (GAMS) software. Furthermore, the

Fuzzy Satisfaction Method (FSM) method [54] utilizes Pareto optimal solutions to achieve the best possible Pareto front. The salient technical features of the methodology are summarized in the following paragraphs.

The EMS aims to increase system resilience to protect the network against issues such as insufficient power generation, interruptions in supply, and other potential disruptions during adverse weather conditions. It is necessary to establish a collaboration between the MSO and the DERO to reschedule the generation plan according to the predicted weather conditions, such as windstorms. DERs, batteries, and demand response programs can be intelligently utilized in order to enhance grid resiliency. Resource rescheduling refers to the process of adjusting energy generation, energy storage, and load consumption in accordance with the actual demand. This intelligent approach helps microgrid operators optimize energy management, minimize load shedding, and increase grid resiliency in cases with a high probability of islanding occurrence. The goal is to address the incidents with low frequency but high impact on the grid.

Predicting the weather conditions for the next day is possible, and this information is used for hourly scheduling. Hourly demand and wind speed level are entered into the GAMS software. To measure the EENS, the effect of wind speed on line failure rates is formulated in GAMS (equations (5) and (7)). Changes in load, wind speed, and output of energy resources can indeed cause hourly changes in risk levels. As for resilience planning, the EMS control system initially evaluates risk levels for each time interval by calculating EENS. By means of the price signal, the MSO collaborates and coordinates with the DERO in the second phase to develop a new plan for DERs, batteries, and controllable loads. A price signal method depending on the EENS is proposed in section 3.3.2.

The EMS control system facilitates collaboration between the MSO and the DERO by solving the multi-objective optimization problem defined in section 3.3.5. The epsilon constraint method is used to solve the multi-objective optimization problem (OF_1 and OF_2). Additionally, alongside this method, the Fuzzy Satisfaction Method (FSM) is utilized. This method creates a membership function for all obtained solutions and selects the best solution using the minimum-maximum approach.

3.4.1 Epsilon-Constraint method

The ε-constraint approach is an efficient method for solving non-convex Pareto front problems. This approach transforms the multi-objective problem into a single-objective problem by converting the second objective into a constraint.

The first step is to calculate the upper and lower limits of OF_1 and OF_2. Initially, OF_1 is considered as the single objective function. The problem is solved by maximizing OF_1. The calculated OF_1 is the upper limit of this objective function. Using the optimized variables, the OF_2 is calculated and called the lower limit of OF_2. In the next step, OF_2 is considered as the single objective function. Similarly, the upper limit of OF_2 and the lower limit of OF_1 are calculated. By doing this, an upper and lower bound is obtained for both objective functions, and this range is divided to obtain more solutions for OF_1 and OF_2, ultimately resulting in the Pareto front.

The Pareto front is obtained by varying the ε vector in equation (29). Therefore, in the proposed problem, while maximizing OF_1, OF_2 is considered as a constraint.

$$OF = \max(\mathrm{OF}_1) \tag{29}$$

$$s.t.\begin{cases} OF_2 \le \varepsilon & \varepsilon_1 \le \varepsilon \le \varepsilon_n \\ All\ Constraints \end{cases}$$

Based on equation (29) and Figure 10, it is evident that OF_2 is constrained by ε. OF_2 gradually increases between its minimum and maximum values by pushing ε to its extreme value (in n steps) while maximizing the objective function (OF_1). The single-objective function is solved for each value of ε, and an optimal solution, such as point C in Figure 10, is obtained. It should be noted that in this method, all the constraints related to multi-objective optimization functions are also considered. The set of all obtained solutions for the entire range of ε variations represents the Pareto front for the multi-objective optimization problem.

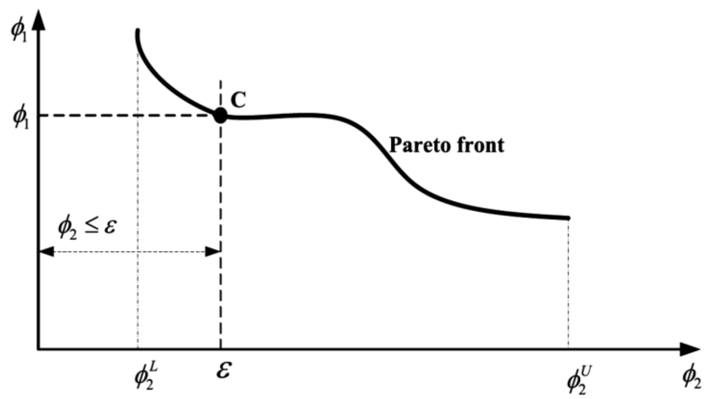


Figure 10. Representing the Pareto front in ε constraint method [55]

A summary of the solution method implemented in GAMS software is explained as follows:

1. Select one of the objective functions as the primary objective function.
2. Solve the problem for each objective function, obtaining the optimal and non-optimal values (upper and lower limits) for each objective.
3. Divide the interval between two optimal values into a predetermined number of divisions and obtain a table of values for $\varepsilon_1, \ldots, \varepsilon_n$.

4. Solve the problem for each value of $\varepsilon_1, \ldots, \varepsilon_n$ using the primary objective function.

5. Report the obtained Pareto solutions.

3.4.2 Fuzzy Satisfaction Method (FSM)

FSM is a well-known method for selecting the best solution from the *Np* optimal solutions of the Pareto front. FSM prioritizes the objective functions to ensure meaningful comparisons and obtain the optimal solution, aiming to maximize the benefits of the objective functions. Consider an optimization problem involving k objective functions. The membership function for the nth solution of the k^{th} objective function is expressed as the following equation.

$$\mu_k^n = \begin{cases} 1 & f_k^n \le f_k^{\min} \\ \dfrac{f_k^{\max} - f_k^n}{f_k^{\max} - f_k^{\min}} & f_k^{\min} \le f_k^n \le f_k^{\max} \\ 0 & f_k^n \ge f_k^{\max} \end{cases} \tag{30}$$

In the relation mentioned above, the maximum and minimum values of the objective functions ($f_k^{\max}$ and $f_k^{\min}$) are present in the optimized solutions of the Pareto front. In this context, it represents the degree of optimization of the nth solution for the k^{th} objective function. The membership function of the n^{th} solution is calculated as follows.

$$\mu^n = \min(\mu_1^n, \ldots, \mu_N^n) \tag{31}$$

$$n = 1, \ldots, N_P$$

The membership function's value indicates how much (on a scale of 0 to 1) a solution is satisfying the objective. The minimum value of all membership functions for a specific combination represents the optimal value of the combination. Therefore, a combination with a larger minimum value of membership functions is more favourable since it can lead to more objective functions tending to their individual optimum values. Thus, among all possible optimum solutions, one should seek a combination for which the minimum value of all the membership functions is maximum. Therefore, for a multi-objective optimization problem with k objective functions, the following index (φ) can be calculated. According to equation (32), the Pareto set's optimal solution would be the Pareto solution, for which φ is the maximum [54].

$$\varphi = \max(\mu^1, \dots, \mu^{Np}) \tag{32}$$

These principles are illustrated through the numerical results in the following Chapter.

Chapter 4

Simulation Results

4.1 Case Study

The proposed methodology is studied in the IEEE 33-bus benchmark system. This test system has been widely used in the literature. The topology of the test system to address the optimal operation problem is shown in Figure 11.

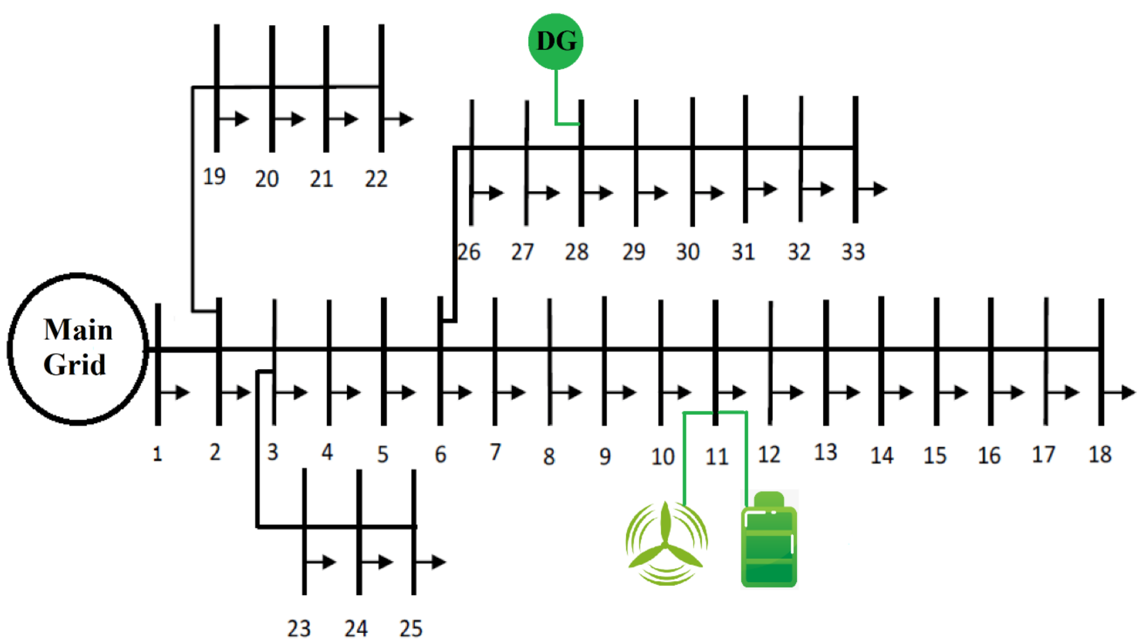


Figure 11. IEEE 33-bus test system

This system has 33 buses numbered from 1 to 33, 32 lines that connect the buses and four main branches. The microgrid Point of Interconnection (PoI) to the Main Grid is located at bus number 1. The microgrid's total nominal load is 3.715 MW. The load of each bus within the microgrid is provided in Table 6. A list of the line characteristics is provided in

Appendix A. The ratios of the reactances to the resistances are relatively low. Furthermore, the voltage limits range from 0.95 p.u. to 1.05 p.u. for all buses.

Table 6. Peak loading summary of the IEEE 33-bus test system

Bus ID	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Nominal Load (kW)	0	100	90	120	60	60	200	200	60	60	45
Bus ID	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**
Nominal Load (kW)	60	60	120	60	60	60	90	90	90	90	90
Bus ID	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**
Nominal Load (kW)	90	420	420	60	60	60	120	200	150	210	60

The benchmark system has been modified in order to implement and analyze the proposed methodology. In Figure 11, resources in green are added to the test system. A DG and Wind Turbine with a nominal capacity of 1 MW and 0.6 MW respectively are located at buses 28 and 11, respectively. Additionally, a storage system with a capacity of 0.8 MWh, capable of charging and discharging at a level of 0.5 MW, is situated at bus 11. The stored energy in this unit ranges from 0.1 to 0.8 MWh.

The summation of the microgrid resources is chosen to be less than the total load in order to analyze the effectiveness of the proposed methodology. The total nominal generation is 2.1 MW, while the total nominal load is 3.715 MW. It is more challenging to find an optimized schedule in this case compared to a system with more generation than consumption.

4.2 Input Data and Parameters

This section provides the input data and parameters used to model the case study and optimize the defined problem.

4.2.1 Load Profile and Demand Level Factor

The daily load profile is modelled by the multiplication of two parameters. The first one is the base peak load provided in Table 6. The second parameter is the Demand Level Factor (DLF). This factor defines the forecasted value of the "load to peak load ratio" in each hour and varies between 0 and 1. The DLF used in this study is shown in Figure 12. As occurs in many European countries, the peak load occurs between 9 p.m. and 11 p.m., and the minimum load is between 2 a.m. and 6 a.m.

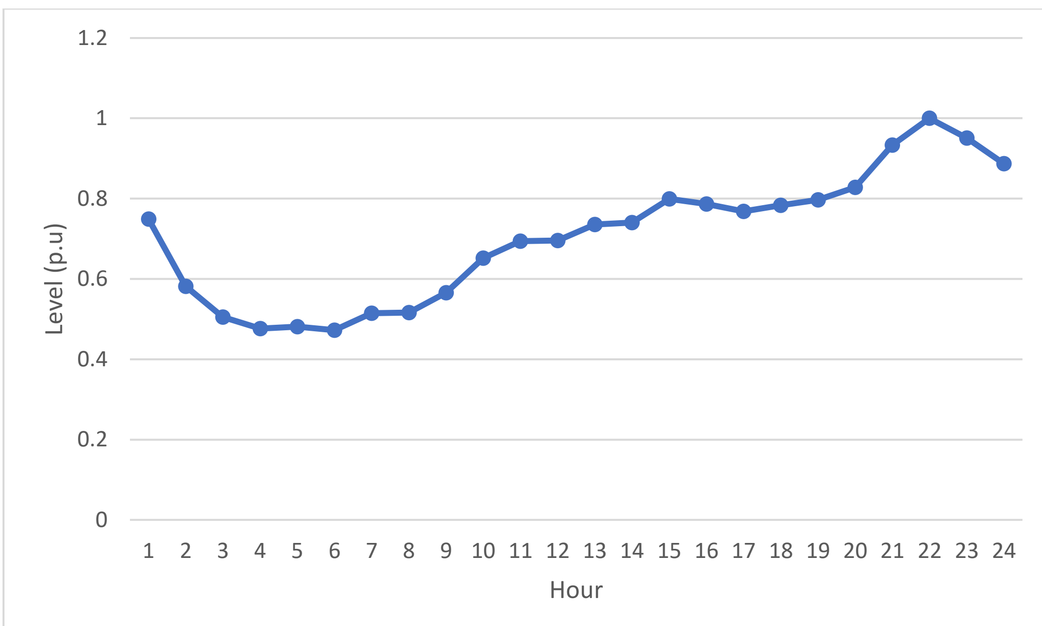


Figure 12. Demand Level Factor

4.2.2 Parameters

The formulation of the problem and all the equations used to solve the multi-objective optimization problem are presented in Chapter 3. The parameters used in this study, as typically appear in the literature, are listed in Table 7 along with their definitions, values, and units.

Table 7. Problem parameters

Parameter	Definition	Value	Unit
λ_{sell}^{DERO}	Purchase rate of power from DERO	80	\$/MWh
λ_{sell}^{P}	Selling rate of electricity to consumers	85	\$/MWh
λ_P	EENS penalty cost	400	\$/MWh
A_j	Cost function coefficients for DG	0.0075	–
B_j	Cost function coefficients for DG	40	–
C_j	Cost function coefficients for DG	25	–
η_k^{ch}	Battery charging efficiency	0.95	–
η_k^{dis}	Battery discharging efficiency	0.85	–
C_k^{deg}	Battery depreciation coefficient	2.7	\$/MWh

4.2.3 Day-Ahead Main Grid Price

The MSO uses a market platform to purchase energy from the upstream Main Grid, which is typically the distribution companies (DISCOs). Energy prices are variable per hour and depend on the Market Clearing Price (MCP), determined by the Independent System Operator (ISO) of the Main Grid. The rates are determined on a day-ahead basis, so the MSO can coordinate with the DERO to manage microgrid resources. Figure 13 shows the day-ahead energy price (λ_{dl}) used for buying energy from the upstream Main Grid, consistent with the hourly load pattern. It can be seen from this figure that the peak price of energy occurs between hours 21 and 23 when consumption is at its highest.

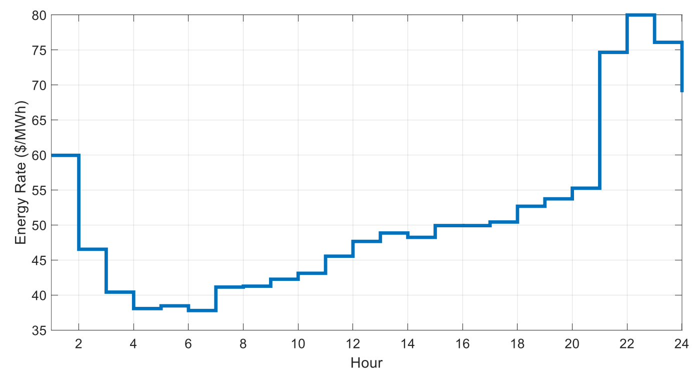


Figure 13. Upstream energy price (λ_{dl})

4.2.4 Wind Speed

Wind speed directly affects Main Grid power outages, as described in Chapter 3. This study investigates the effectiveness of the proposed resilient-economic operation in reducing EENS and increasing profits of microgrid actors based on hourly forecasted wind speed. Weather forecasts are available on a day-ahead basis and are provided to EMS by third-party data providers. Daily wind patterns are widely variable and Figure 14 shows the forecasted wind speed used in this study. This thesis identifies high-risk time intervals as hours 13-16 when maximum wind speed occurs.

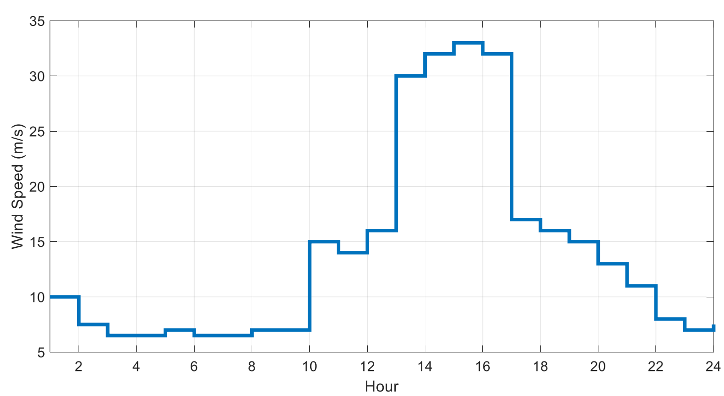


Figure 14. Forecasted wind speed

4.3 Simulation Tool

GAMS is used to solve the introduced multi-objective optimization problem. GAMS is a modelling tool for mathematical programming and optimization purposes. The modified IEEE 33-bus benchmark system and the methodology described in Chapter 3 are modelled in GAMS. The multi-objective optimization problem in this study includes continuous and discrete variables and non-linear objective functions. Therefore, a DIscrete and Continuous OPTimizer (DICOPT) solver is used to solve the Mixed Integer Nonlinear Program (MINLP). The developed codes in GAMS are provided in Appendix B.

4.4 Simulation Results

The proposed methodology has been applied to the IEEE 33-bus benchmark system introduced in Section 4.1. The time frame for model programming is set at one hour. The goal is to demonstrate the effectiveness of the proposed M-EMS methodology through various scenarios. The following scenarios are examined:

- Scenario 1: Normal operation without considering islanded operation possibility.
- Scenario 2: Resilient operation considering islanded operation possibility.

It was indicated earlier that the customer loads on the 33 buses have a total peak value of 3.715 MW. The DERO sources are 1 MW of DG, 0.6 MW of wind turbines, and a battery discharging capacity of 0.5 MW for a total DERO supply capability of 2.1 MW. It is clear that operation of the system depends on purchase of power from the Main Grid. Since unit commitment is beyond the scope of this thesis research, the optimization methodology schedules both DERO sources and the Main Grid source in every hour based on the cost of power and energy from each of these composite sources.

While there is no certainty that it will happen in any hour, there is always the possibility that the Main Grid source may become unavailable in an hour. The effect of the Main Grid unavailability is EENS expressed as the product of the MW it was supplying in that hour multiplied by the probabilistic rate of unavailability expressed as α. One of the factors that significantly impacts the value of α in any hour is the wind speed. Based on this discussion, it is obvious that there are only two ways to reduce the EENS:

a) Try to shift at least part of the load from those hours in which the load is high through the DRP mechanism.

b) Try to make the DERO sources supply as much of the load as possible in high wind hours by paying the DERO at an attractively high rate for power and energy, thus reducing the purchase from the relatively unreliable Main Grid.

Scenario 1 has two characteristics. It looks at applying, and not applying, the DRP mechanism to the high load hours. More importantly, it downplays the significance or importance of EENS, and it does this by removing the cost-of-EENS term from the objective function OF_1 (for this scenario only). The thesis refers to this as "Normal operation without considering islanding operation possibility". It is expected that the EENS will be relatively high in Scenario 1.

Scenario 2 has two characteristics. It looks at applying, and not applying, the DRP mechanism to the high load hours. More importantly, it proposes to pay the DERO sources at an attractively high rate for power during strong wind hours. While this makes the cost of operation of the system more expensive, because it positions the system to be more resilient and have a lower value of EENS the thesis refers to this as "Resilient operation considering islanded operation possibility".

The constraints defined in Chapter 3 (equation (12), equation (13), and equations (16-28)) are the same for both scenarios.

In the following sections, various sets of Pareto solutions are obtained for the system across all examined scenarios. Then, the FSM technique is implemented to determine the optimal Pareto solution. The MSO and DERO benefits and the resulting EENS costs are reported with and without demand response programs.

4.4.1 Scenario 1: Techno-Economic Optimization

Table 8 shows 20 Pareto solutions for the MSO and DERO profits and EENS costs in the first scenario with and without DRP. The results show that DRP contributes to increased MSO and DERO profits while reducing EENS costs.

As noted earlier in the discussion of the end points, the highest MSO profit of $3678.68 is achieved in solution 1. The highest Pareto solution for DERO profit is number 20, which yields $758.04 in profit.

Table 8. Pareto solutions- Scenario 1

Solution	**Scenario 1-with DRP**			**Scenario 1-without DRP**		
	MSO Profit ($/day)	DERO Profit ($/day)	EENS Cost ($/day)	MSO Profit ($/day)	DERO Profit ($/day)	EENS Cost ($/day)
1	3678.684	451.0632	2482.487	3600.968	292.4973	2549.168
2	3667.012	470.2495	2483.124	3588.86	315.6887	2547.919
3	3654.974	489.4359	2477.892	3576.537	338.88	2546.158
4	3642.684	508.6223	2474.569	3562.877	362.0714	2542.361
5	3629.887	527.8086	2469.306	3548.634	385.2628	2534.564
6	3615.92	546.995	2467.376	3533.816	408.4541	2526.97
7	3600.279	566.1813	2466.034	3518.504	431.6455	2520.965
8	3584.463	585.3677	2464.767	3502.436	454.8368	2518.757

9	3568.374	604.554	2463.432	3485.688	478.0282	2516.702
10	3551.368	623.7404	2461.928	3467.489	501.2195	2514.338
11	3531.124	642.9267	2461.506	3448.392	524.4109	2512.717
12	3509.446	662.1131	2461.592	3428.666	547.6022	2511.135
13	3486.678	681.2995	2461.821	3408.456	570.7936	2509.377
14	3463.655	700.4858	2462.133	3387.569	593.985	2507.618
15	3424.966	719.6722	2474.183	3366.027	617.1763	2506.122
16	3406.009	738.8585	2472.381	3339.668	640.3677	2505.923
17	3381.543	758.0449	2472.008	3312.663	663.559	2505.88
18	3381.543	758.0449	2472.008	3281.829	686.7504	2502.793
19	3381.543	758.0449	2472.008	3235.954	709.9417	2501.745
20	3381.543	758.0449	2472.008	3225.13	733.1331	2511.737

The Fuzzy Satisfaction Method (FSM) is used to determine the best Pareto solution among the calculated 20 solutions. This method creates a membership function for all obtained solutions and selects the best solution using the minimum-maximum approach.

Table 9 shows the calculated membership functions for all the solutions as per equation (30) of Chapter 3. μ_{OF1} and μ_{OF2} denote the membership functions for the objective functions OF_1 and OF_2, respectively. The best membership function for Scenario 1 with DRP is 0.4375 in solution 10. The best membership function is 0.421053 in solution 12 for Scenario 1 without DRP. Therefore, among the Pareto front solutions in Scenario 1, solutions 10 and 12 are the optimal ones for cases with and without DRP, respectively. The optimal profit values of MSO, DERO, and EENS cost considering DRP are \$3551.37, \$623.74, and \$2461.93, respectively.

Table 9. Calculated membership functions- Scenario 1

Solution	**Scenario 1-with DRP**				**Scenario 1-without DRP**			
	MSO Profit (OF_1)	μ_{OF1}	DERO Profit (OF_2)	μ_{OF2}	MSO Profit (OF_1)	μ_{OF1}	DERO Profit (OF_2)	μ_{OF2}
1	3678.68	0	451.063	1	3600.96	0	292.497	1
2	3667.01	0.0392	470.249	0.937	3588.86	0.0322	315.688	0.94736
3	3654.97	0.0797	489.435	0.875	3576.53	0.0650	338.88	0.89473
4	3642.68	0.1211	508.622	0.812	3562.87	0.1013	362.071	0.84210
5	3629.88	0.1642	527.808	0.75	3548.63	0.1392	385.262	0.78947
6	3615.92	0.2112	546.995	0.687	3533.81	0.1786	408.454	0.73684
7	3600.27	0.2638	566.181	0.625	3518.50	0.2194	431.645	0.68421
8	3584.46	0.3170	585.367	0.562	3502.43	0.2621	454.836	0.63157
9	3568.37	0.3712	604.554	0.5	3485.68	0.3067	478.028	0.57894
10	**3551.36**	0.4384	**623.740**	**0.437**	3467.48	0.3551	501.219	0.52631
11	3531.12	0.4965	642.926	0.375	3448.39	0.4059	524.410	0.47368
12	3509.44	0.5695	662.113	0.312	**3428.66**	0.4584	**547.602**	**0.42105**
13	3486.67	0.6461	681.299	0.25	3408.45	0.5122	570.793	0.36842
14	3463.65	0.7236	700.485	0.187	3387.56	0.5677	593.985	0.31578
15	3424.96	0.8538	719.672	0.125	3366.02	0.6251	617.176	0.26315
16	3406.00	0.9176	738.858	0.062	3339.66	0.6952	640.367	0.21052
17	3381.54	1	758.044	1.11E-15	3312.66	0.7670	663.559	0.15789
18	3381.54	1	758.044	1.11E-15	3281.82	0.8491	686.750	0.10526
19	3381.54	1	758.044	1.11E-15	3235.95	0.9712	709.941	0.05263
20	3381.54	1	758.044	0	3225.13	1	733.133	0

The graphical presentation of the membership functions in Figure 15 confirms the best solution for Scenario 1 with DRP.

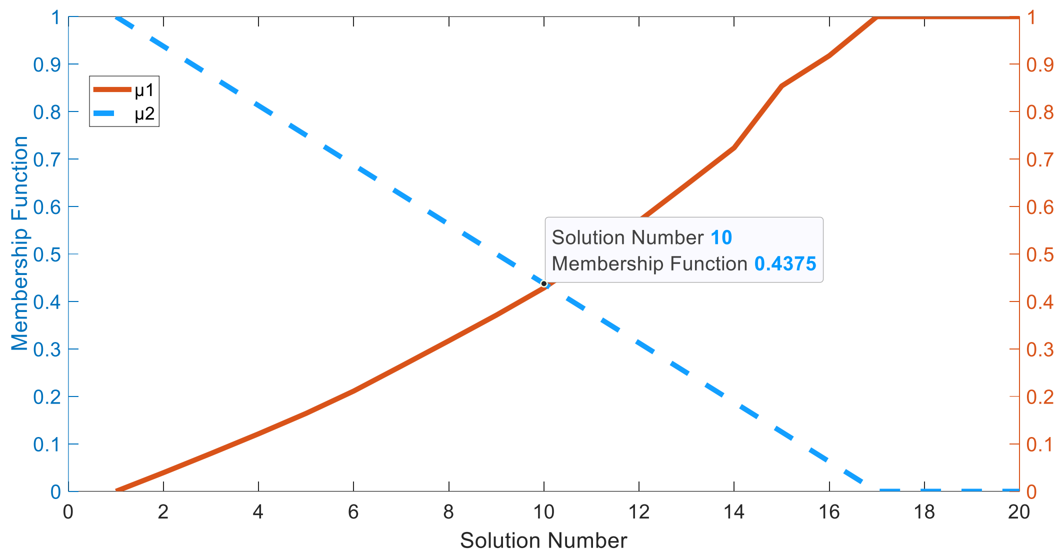


Figure 15. Graphical presentation of the membership functions- Scenario 1- with DRP

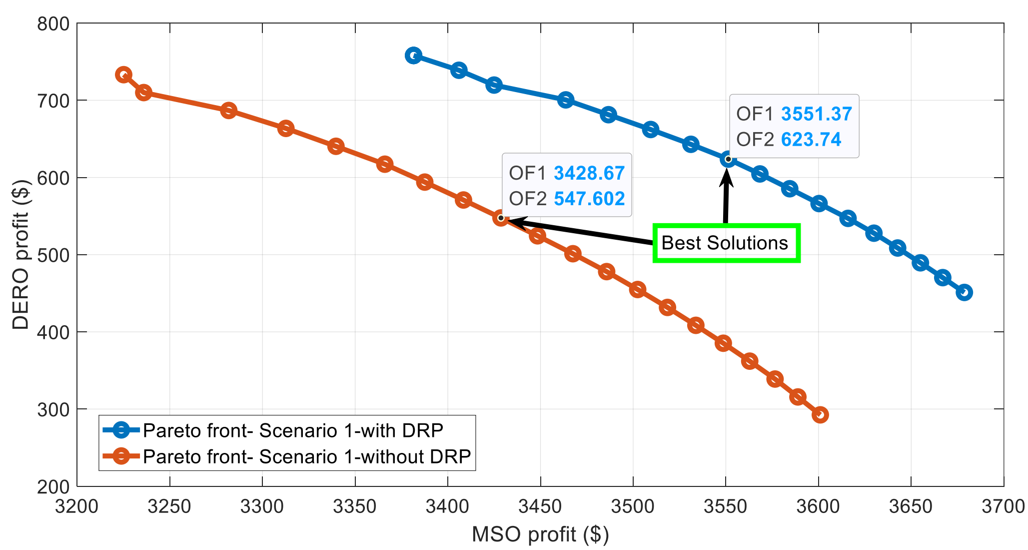


Figure 16. Pareto-optimal front- Scenario 1

The Pareto-optimal front for the first scenario is shown in Figure 16. The graphical presentation confirms that the MSO and DERO gained more profits with the implementation of DRP. According to this figure, the optimal Pareto solutions represent the closest solution to fairly maximizing the benefits for both MSO and DERO.

4.4.2 Scenario 2: Resilient-Economic Optimization

Table 10 shows 20 Pareto solutions for MSO and DERO profits and EENS costs in the second scenario with and without DRP. The highest MSO profit of $4046.9 is achieved in solution 1. The highest Pareto solution for the DERO is number 20, which yields a profit of $1022.567.

Table 10. Pareto solutions- Scenario 2

Solution	**Scenario 2-with DRP**			**Scenario 2-without DRP**		
	MSO Profit ($/day)	DERO Profit ($/day)	EENS Cost ($/day)	MSO Profit ($/day)	DERO Profit ($/day)	EENS Cost ($/day)
1	4046.901	640.8056	2105.015	3792.843	454.3864	2390.297
2	4030.949	660.8983	2103.153	3773.606	481.5604	2385.892
3	4013.893	680.9909	2101.967	3754.082	508.7344	2381.546
4	3996.503	701.0836	2100.701	3734.138	535.9084	2378.512
5	3978.57	721.1763	2099.256	3713.967	563.0824	2375.262
6	3973.976	741.269	2099.149	3693.606	590.2564	2371.983
7	3960.619	761.3617	2097.654	3673.073	617.4303	2368.615
8	3941.694	781.4543	2096.044	3652.318	644.6043	2365.385
9	3922.109	801.547	2093.944	3630.319	671.7783	2363.085
10	3902.208	821.6397	2092.506	3606.782	698.9523	2361.474
11	3881.589	841.7324	2090.802	3582.777	726.1263	2359.751
12	3859.93	861.8251	2090.412	3558.14	753.3003	2357.871
13	3835.29	881.9177	2090.84	3532.701	780.4743	2355.884
14	3807.439	902.0104	2092.303	3506.708	807.6483	2353.471
15	3787.352	922.1031	2089.962	3475.719	834.8222	2349.52
16	3780.908	942.1958	2084.129	3446.77	861.9962	2351.363
17	3775.644	962.2885	2084.16	3409.086	889.1702	2349.324

18	3746.451	982.3811	2084.396	3400.772	916.3442	2346.133
19	3746.451	982.3811	2084.396	3386.083	943.5182	2346.224
20	3701.994	1022.567	2084.509	3353.614	970.6922	2346.673

The Fuzzy Satisfaction Method (FSM) is used to determine the best Pareto solution among the calculated 20 solutions by creating membership functions for all the obtained solutions.

Table 11 shows the calculated membership functions for all the solutions. μ_{OF1} and μ_{OF2} denote the membership functions for the objective functions OF_1 and OF_2, respectively. The best membership function for Scenario 2 in both cases with and without DRP is 0.473684 in solution 11. Therefore, among the Pareto front solutions in Scenario 2, solution 11 is the optimal solution. The optimal profit values of MSO, DERO, and EENS cost considering DRP are $3881.59, $841.73, and $2090.80, respectively.

Table 11. Calculated membership functions- Scenario 2

Solution	**Scenario 2-with DRP**				**Scenario 2-without DRP**			
	MSO Profit (OF_1)	μ_{OF1}	DERO Profit (OF_2)	μ_{OF2}	MSO Profit (OF_1)	μ_{OF1}	DERO Profit (OF_2)	μ_{OF2}
1	4046.9	0	640.805	1	3792.84	0	454.386	1
2	4030.9	0.04624	660.898	0.94736	3773.60	0.04379	481.560	0.94736
3	4013.8	0.0957	680.990	0.89473	3754.0	0.0882	508.73	0.8947
4	3996.5	0.1461	701.083	0.84210	3734.13	0.13365	535.908	0.84210
5	3978.5	0.1981	721.176	0.78947	3713.96	0.17957	563.082	0.78947
6	3978.9	0.1969	741.269	0.73684	3693.60	0.22593	590.256	0.73684
7	3960.6	0.2501	761.361	0.68421	3673.07	0.27268	617.430	0.68421
8	3941.6	0.3050	781.454	0.63157	3652.31	0.31993	644.604	0.63157
9	3922.1	0.3618	801.547	0.57894	3630.31	0.37002	671.778	0.57894
10	3902.2	0.4195	821.639	0.52631	3606.78	0.42360	698.952	0.52631
11	**3881.5**	0.4792	**841.732**	**0.47368**	**3582.77**	0.47826	**726.126**	**0.47368**
12	3859.9	0.5420	861.825	0.42105	3558.14	0.53435	753.300	0.42105
13	3835.2	0.6135	881.917	0.36842	3532.70	0.59227	780.474	0.36842

14	3807.4	0.6942	902.010	0.31578	3506.70	0.65144	807.648	0.31578
15	3787.3	0.7525	922.103	0.26315	3475.71	0.72200	834.822	0.26315
16	3797.9	0.7219	942.195	0.21052	3446.77	0.78791	861.996	0.21052
17	3775.6	0.7864	962.288	0.15789	3409.08	0.87370	889.170	0.15789
18	3746.45	0.8711	982.381	0.10526	3417.77	0.85393	916.344	0.10526
19	3746.4	0.8711	982.381	0.10526	3386.08	0.92607	943.518	0.05263
20	3701.9	1	1022.56	0	3353.61	1	970.692	0

The graphical presentation of the membership functions in Figure 17 confirms the best solution for Scenario 2 with DRP.

The Pareto-optimal front for the second scenario is shown in Figure 18. The graphical presentation confirms that the MSO and DERO gained more profits with the implementation of DRP. According to this figure, the optimal Pareto solutions represent the closest solution to fairly maximizing the benefits for both MSO and DERO.

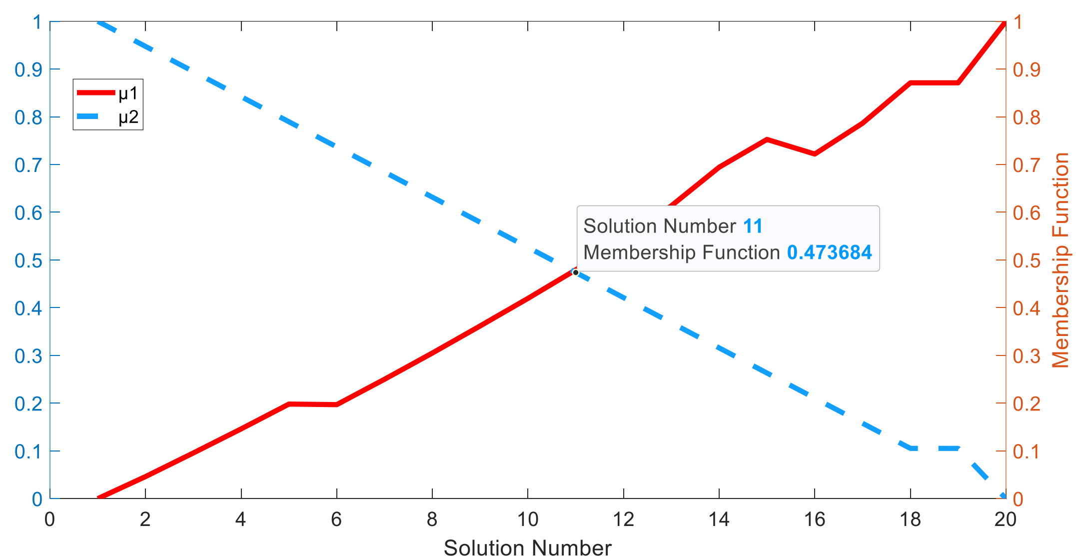


Figure 17. Graphical presentation of the membership functions- Scenario 2- with DRP

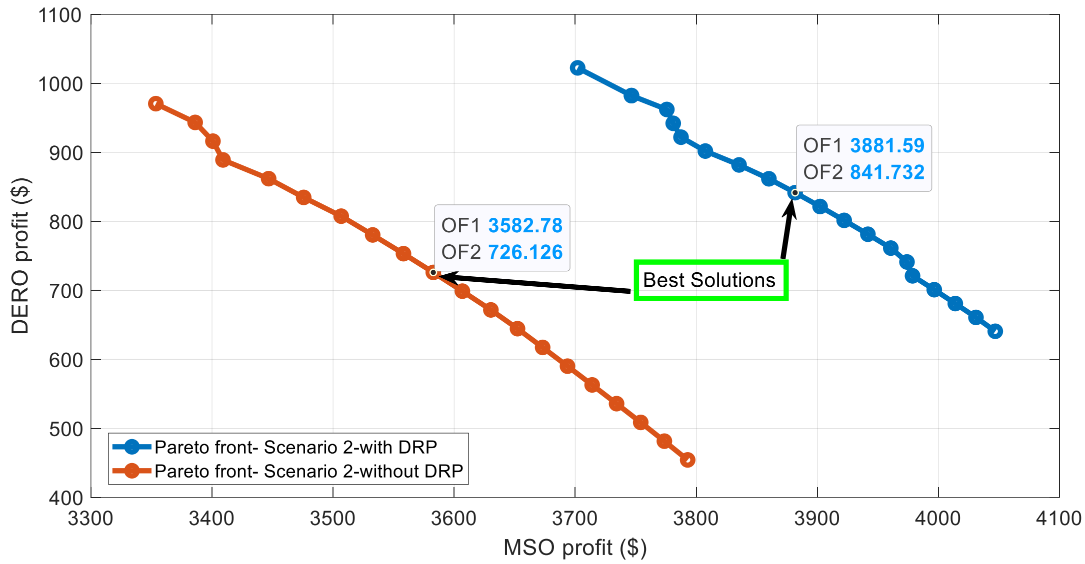


Figure 18. Pareto-optimal front- Scenario 2

4.4.3 Results Comparison

Table 12 compares the results obtained by solving the multi-objective optimization problem for Scenarios 1 and 2. In the first scenario, considering DRP, MSO and DERO profits and EENS costs are $3551.37, $623.74, and $2461.93, respectively.

In Scenario 2, costs associated with EENS affect energy rates. DERO receives a price signal that is influenced by EENS. It is important to note that the cost of EENS is high in high-risk time intervals (adverse weather conditions), resulting in the modified energy rate always being higher than the base rate for the private sector. DERO consistently achieves greater profits following the price change, encouraging collaboration with the MSO.

In the second scenario considering DRP, MSO and DERO profits and EENS costs are $3881.59, $841.73, and $2090.8, respectively. Consequently, MSO and DERO's benefits are 9.3% and 34.9% higher compared to the first scenario, respectively, whereas the EENS cost is 15.07% lower. Reducing EENS expenditures positively impacts MSO and DERO profits.

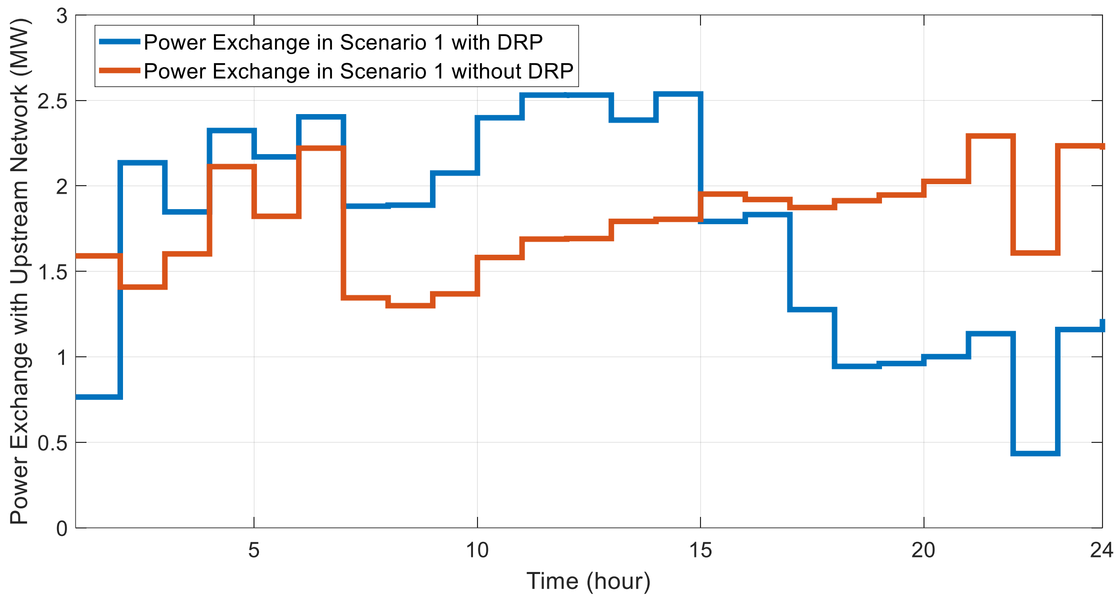
Table 12. Results comparison

Scenario		Best Solution Number	MSO Profit ($/day)	DERO Profit ($/day)	EENS Cost
Scenario 1	No DRP	12	3428.666	547.6022	2511.135
	With DRP	10	3551.368	623.7404	2461.928
Scenario 2	No DRP	11	3606.782	698.9523	2361.474
	With DRP	11	3881.589	841.7324	2090.802

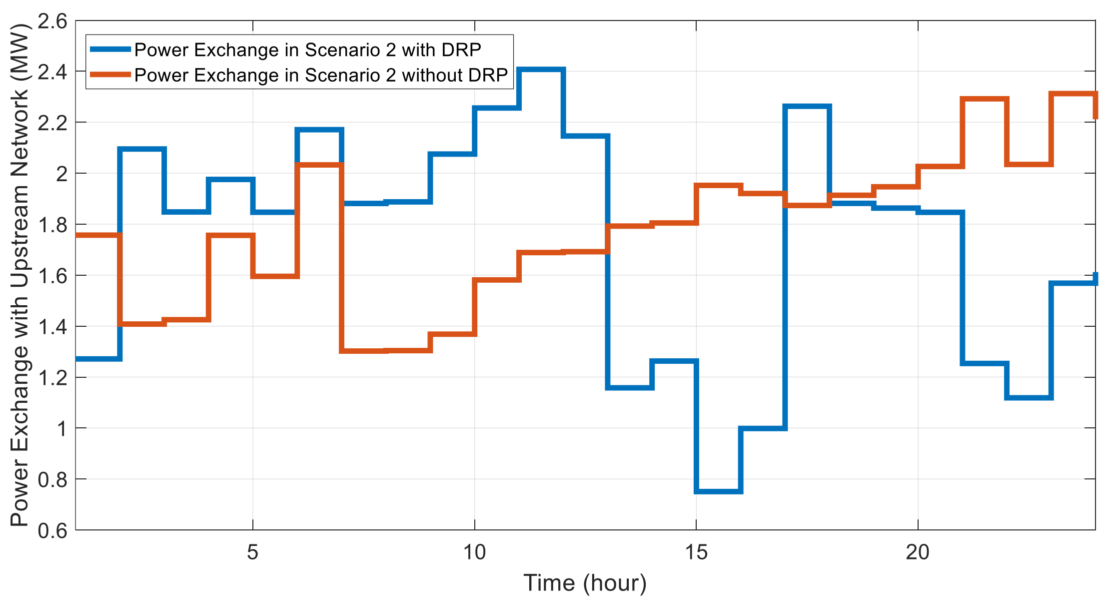
4.5 Power Exchange with Upstream Network

Power imported from the upstream network (also called power exchange) in Scenarios 1 and 2 is presented in Figure 19. The comparison between scenarios provided in Figure 20 demonstrates that in the proposed resilient operation method, the energy purchased from the Main Grid upstream network is reduced by 48.66% in high-risk hours (high wind speed), and the MSO tends to rely on local resources. It helps to serve consumers in the transition from grid-connected to islanded mode.

On the other hand, if adverse weather conditions result in a fault in the first scenario and the microgrid must be operated in islanded mode, a large portion of the load cannot be met. This is because of an imbalance between generation and consumption during the transition from grid-connected to islanded mode.



(a)



(b)

Figure 19. Power exchange with the upstream network (a) Scenario 1 (b) Scenario 2

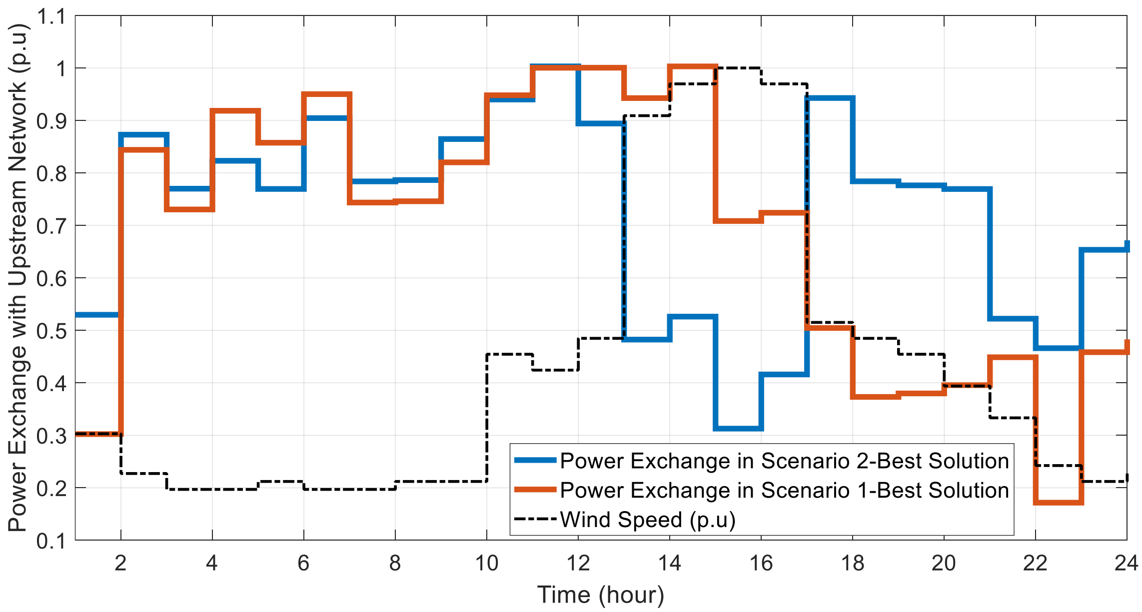


Figure 20. Power exchange with the upstream network- Best solutions

4.6 Spinning Reserve

4.6.1 Demand Response Program

In this study, DRP is used as a spinning reserve in the microgrid for maintaining a balance between generation and consumption in a day with a high possibility of islanding operation. The hourly original load as well as the microgrid load after implementing DRP in scenarios 1 and 2, are shown in Table 13 which indicates that the DRP modifies the load in every hour. The shifted load by consumers is restricted in this study, with only up to 25% of the total load possibly being involved. As shown in Table 13, the overall energy consumption in both scenarios is 62.83944 MWh, the same as the original load.

Table 13. The effect of DRP on microgrid hourly load

Hours	Original Load (MW)	Scenario 1 (MW)	Scenario 2 (MW)
1	2.784422	2.127666	2.619947
2	2.161844	2.671754	2.675161

3	1.877479	2.320317	2.320317
4	1.768559	2.185706	2.185706
5	1.786592	2.207992	2.207992
6	1.755159	2.169145	2.169145
7	1.910621	2.361275	2.361275
8	1.916713	2.368805	2.368805
9	2.102389	2.598276	2.598276
10	2.420378	2.991268	2.851193
11	2.579982	3.159846	3.084626
12	2.584856	3.167953	2.980939
13	2.733497	3.264979	2.066678
14	2.751526	3.364846	2.07184
15	2.968638	2.94534	2.243873
16	2.921851	2.978094	2.22858
17	2.852893	2.458332	2.818392
18	2.91162	2.224862	3.004318
19	2.960595	2.262285	3.146579
20	3.077558	2.35166	3.18136
21	3.467187	2.649388	2.766665
22	3.715	2.823041	3.038041
23	3.533953	2.680681	2.958284
24	3.29613	2.505933	2.891453
Sum (MWh)	**62.83944**	**62.83944**	**62.83944**

As part of the proposed method, the microgrid operator uses a DRP to change customers' consumption patterns in order to minimize EENS costs. The resilient-economic method aims to shift the load from high-risk time intervals (13-16) and from peak consumption hours having high upstream electricity rates (21-23) to other periods. The effectiveness of the proposed method is shown in Figure 21. It is evident that energy consumption during high-risk hours (13-16) is reduced by 20% in Scenario 2. DRP implemented in Scenario 1 led to an increase in load during this period.

Both scenarios contributed to decrease the load during peak consumption hours (21-23).

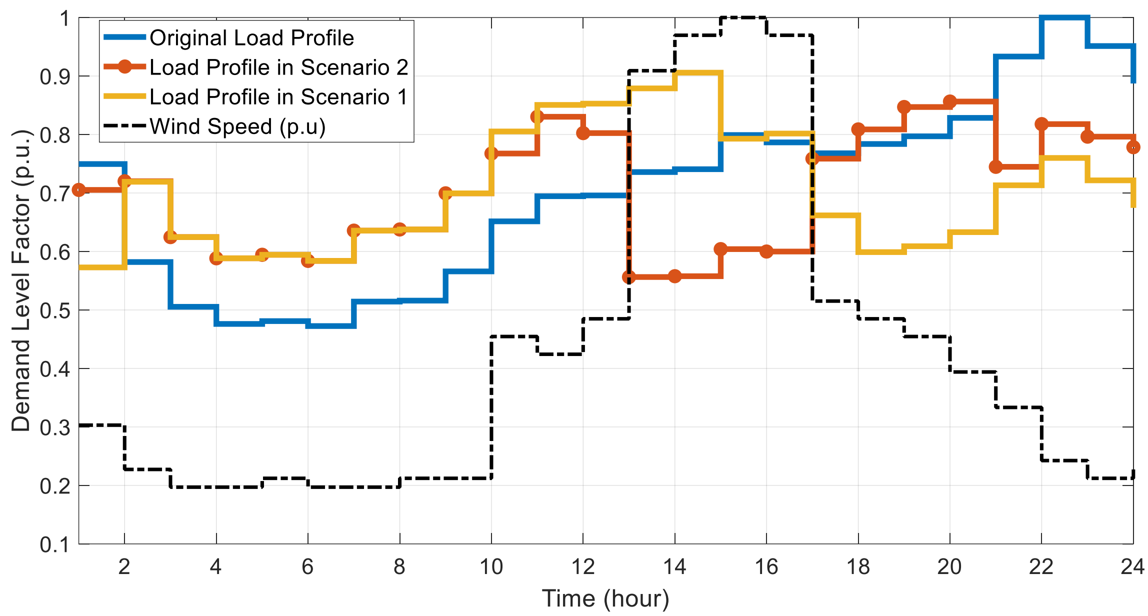


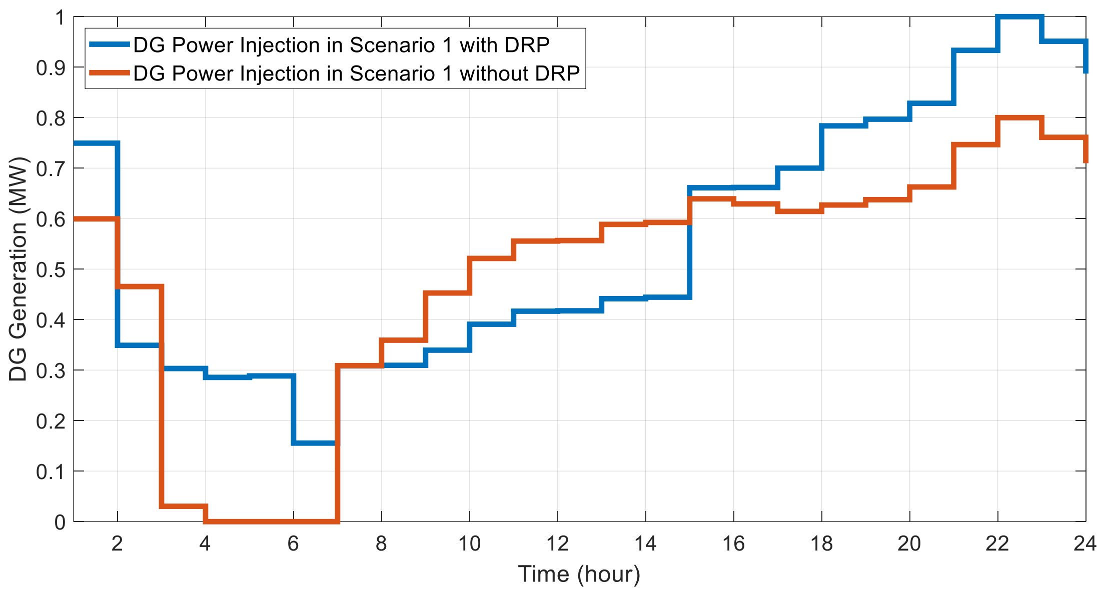
Figure 21. Effect of resilient operation on load curve

4.6.2 DG and ES

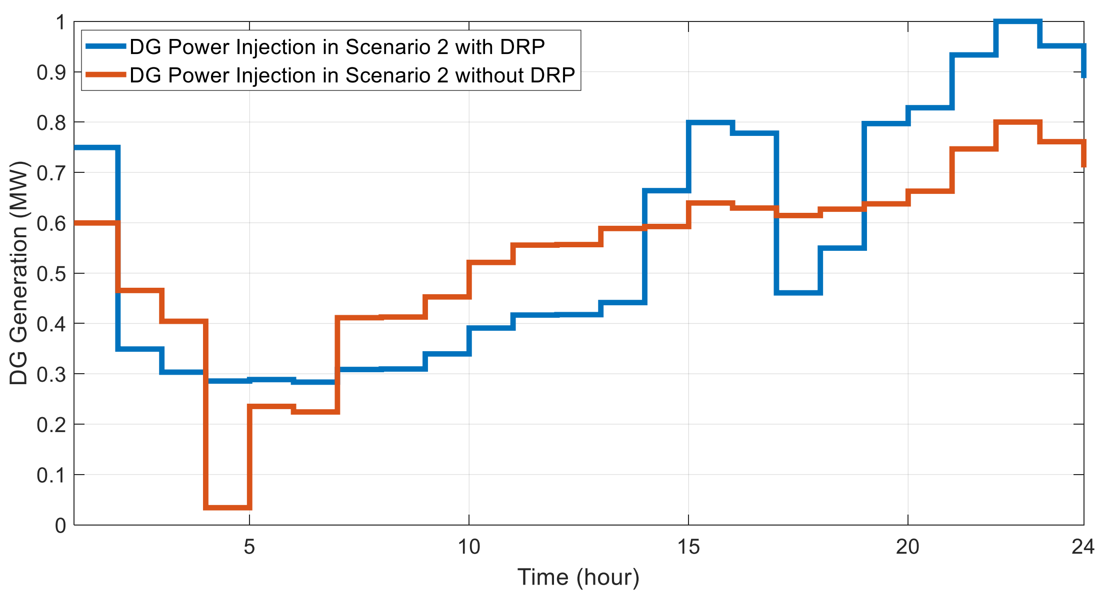
In the proposed method, the generation of the DG unit and power injection of ES is increased due to higher prices offered by MSO to DERO in high-risk time intervals. This results in higher actors' profits as well as reduced load shedding during periods of possible islanding.

In Scenario 1, DGs do not operate during off-peak hours because their operational costs are higher than upstream grid fees. The proposed revised prices are higher than conventional operational planning prices, prompting the DGs to sell electricity. The changes to the operation scheduling of DG in both scenarios are demonstrated in Figure

22. Figure 23 shows that DG power injection is modified compared to the Scenario 1 during both the peak of consumption (21-23) and high-risk hours of power outages (13-16). The average DG power injection in Scenario 2 is 33.44% higher than in Scenario 1 during times with high islanding possibility.



(a)



(b)

Figure 22. DG Power Injection (a) Scenario 1 (b) Scenario 2

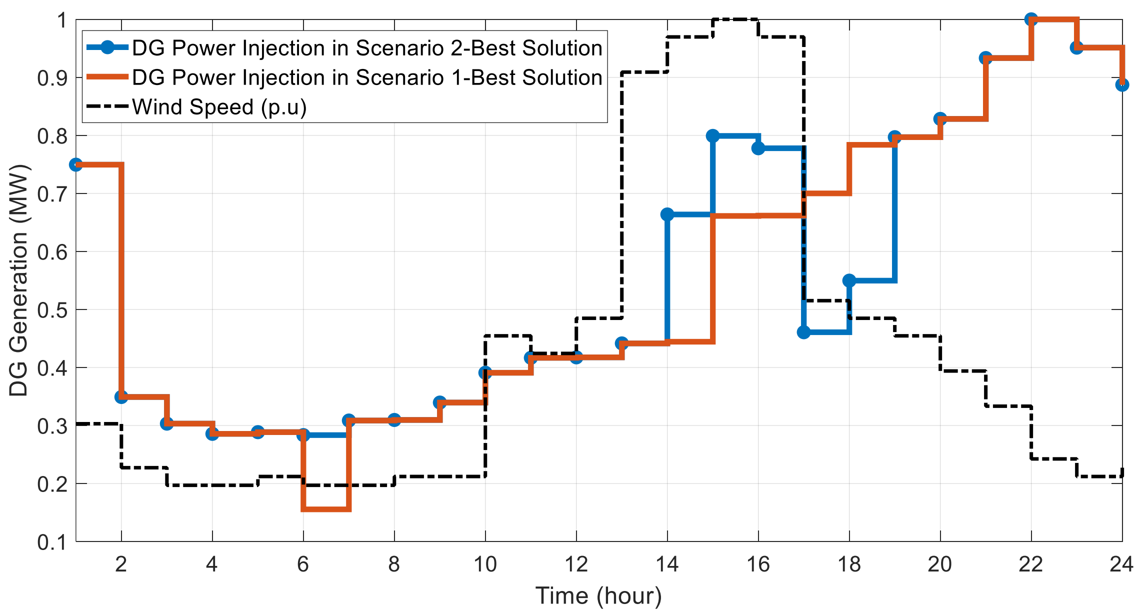


Figure 23. Effect of resilient operation on DG generation

Similarly, in Scenario 1, the ES is charged during the light load hours to take advantage of lower energy rates. It then injects power into the distribution grid during peak load periods. However, the electricity rate is influenced by EENS expenditure in the proposed methodology. Consequently, when severe weather conditions are forecasted with a high probability of outages and islanding operation, the DERO's rate increases, resulting in the discharge of the storage unit. Table 14 shows the ES scheduling in Scenarios 1 and 2.

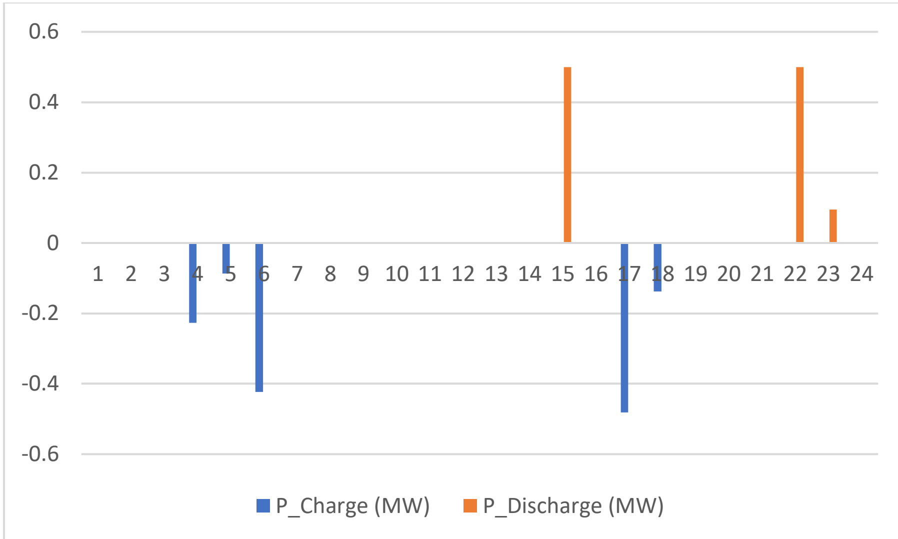
Table 14. ES scheduling in scenarios 1 and 2

Hours	**Scenario 1**			**Scenario 2**		
	State of Charge (MWH)	P_Charge (MW)	P_Discharge (MW)	State of Charge (MWH)	P_Charge (MW)	P_Discharge (MW)
1	0.1			0.1		

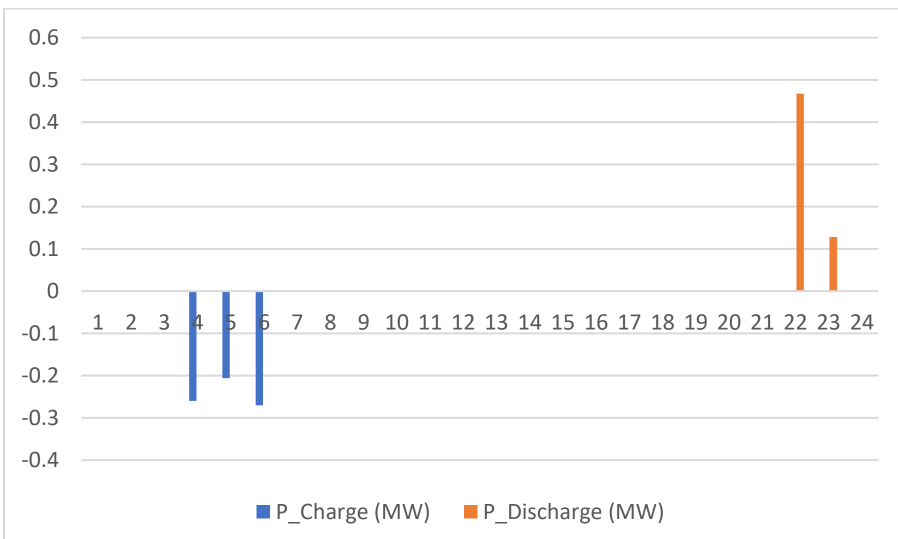
2	0.1			0.1		
3	0.1			0.1		
4	0.347103	0.260109		0.31544	0.226779	
5	0.54309	0.206301		0.39786	0.086755	
6	0.8	0.270431		0.8	0.423307	
7	0.8			0.8		
8	0.8			0.8		
9	0.8			0.8		
10	0.8			0.8		
11	0.8			0.8		
12	0.8			0.8		
13	0.8			0.8		
14	0.8			0.8		
15	0.8			0.21176		0.5
16	0.8			0.21176		
17	0.8			0.66882	0.481112	
18	0.8			0.8	0.138082	
19	0.8			0.8		
20	0.8			0.8		
21	0.8			0.8		
22	0.250416		0.467146	0.21176		0.5
23	0.1		0.127853	0.1		0.095
24	0.1			0.1		

The effectiveness of the proposed method in the operational scheduling of ES during high-risk time intervals is shown in Figure 24. It shows that ES power injection is modified compared to Scenario 1 during high-risk hours of power outages (13-16).

The ES in Scenario 2 injects 0.5 MW at hour 15, when the wind speed is at its maximum, whereas Scenario 1 does not make use of ES during high-risk intervals.



(a)



(b)

Figure 24. Operation scheduling of ES (a) Scenario 2 (b) Scenario 1

4.6.3 Spinning Reserve Conclusion

An essential objective of this study is to prepare the microgrid for islanded operation before the fault initiation. Power systems typically operate with a predefined spinning reserve. In this case, if a fault occurs, the chance of a successful islanding operation due to an imbalance between internal generation and load is low. This thesis introduces a methodology to use weather forecasts to dynamically change the spinning reserve of microgrid with the knowledge of incoming adverse weather conditions. The increased internal generation during the high-risk intervals will increase the chances of a successful transition from grid-connected to islanded mode. This means that internal reserves of the microgrid reduce the generation-consumption gap.

The results of this study prove the effectiveness of the proposed method to increase the generation of internal resources in high-risk time intervals. As an example, the results show that the microgrid can be operated in islanded mode since 616.11 kW more power is internally generated during maximum wind speed (in hour 15), which is 16.6% of the peak load.

4.7 Resiliency Metric

The resilient-economic operation approach proposed in this thesis aims to satisfy microgrid demand in adverse weather conditions. Therefore, an analysis of microgrid resiliency is crucial when scheduling the microgrid. EENS is chosen as the resiliency metric in this study. EENS denotes the expected energy that the microgrid can not supply for a given period. The mathematical presentation of the EENS is provided in Section 3.3.1. The value of EENS is influenced by various factors, such as outage rate, repair time, available resources per hour, and loading. It is assumed that repair time averaged 4 hours under normal conditions but increased to 6 hours under extreme conditions (hours 13-16). The obtained value for weather-based outage rate (α_{wind}) is added to non-weather-based outages to update the lines failure rate (α_{rate}).

The calculated EENS values in optimal solutions of Scenarios 1 and 2 are provided in Table 15. The proposed approach results in 15.07% lower EENS in Scenario 2 than the Scenario 1 in 24 hours. Moreover, EENS improved by 33.03% during high-risk intervals (13-16).

Table 15. EENS values

Hour	**EENS (MW/h)**	
	Scenario 2	Scenario 1
1	0.177024	0.114772
2	0.136364	0.136364
3	0.130211	0.130211
4	0.130534	0.133331
5	0.137011	0.139737
6	0.094559	0.095919
7	0.114972	0.114972
8	0.110077	0.110077
9	0.120740	0.120740
10	0.176175	0.222571
11	0.178652	0.215909
12	0.194226	0.260106
13	0.475414	0.779383
14	0.539764	0.896926
15	0.596998	0.790340
16	0.573176	0.796559
17	0.209208	0.200043
18	0.195744	0.176006
19	0.189362	0.163349
20	0.177823	0.140816
21	0.162005	0.131222
22	0.141448	0.101662
23	0.131229	0.092706
24	0.134288	0.091096
Sum	5.227006	6.154820

Chapter 5

Conclusions

In this thesis, a novel approach is introduced to optimize the operation of a microgrid with islanded operation capability in response to the dynamic risk of outages. The proposed approach is designed to consider the possibility of preparing the system for islanded operation before the fault initiation.

This thesis meets every element presented in the thesis proposal. Overall, the effectiveness of the proposed methodology was demonstrated by simulation results, including improved resiliency, minimized expected energy not supplied, maximized DERs readiness, and a fair profit-sharing mechanism between the microgrid actors.

The main contributions of this work are summarized as follows:

1- The proposed methodology is implemented in GAMS software as an optimization tool. The developed GAMS program has around 550 lines of code. The code can be modified based on the needs and requirements of the microgrid operator and owner. The program can also be applied to any other microgrid system.

2- This research provides practical implications in Microgrid Energy Management Systems (M-EMS) for enhancing resiliency and operational planning during time intervals with a high possibility of islanding occurrence, such as conditions of high wind.

3- A logical change from economic operation (techno-economic optimization) to resilient operation (socio-technical optimization) is implemented in the multi-objective optimization problem, ensuring that the microgrid can serve consumers effectively even in extreme weather conditions.

4- A fair profit-sharing mechanism is implemented among the MSO and the DERO, incentivizing cooperation between the microgrid's main actors.

5- The microgrid resiliency increased by the resilient-economic operation approach proposed in this thesis. The simulation results show that the EENS is reduced by 15.07% and 33.03% within 24 hours and during high-risk periods, respectively.

6- A dynamic spinning reserve is developed to increase the readiness of the microgrid internal resources in high-risk intervals. The simulation results showed that the DG and ES inject 616.11 kW more power during the intervals of maximum wind speed.

7- The proposed method employs DRP to reduce possible load shedding during the transition to islanding operation by shifting the loads from high-risk periods to other times.

The successful design and assessment of microgrid energy management systems can open other avenues for future research works. Such research work may include:

- The analysis of combining the proposed methodology with the microgrid reconfiguration strategies to maximize resiliency and load balancing.
- To investigate the grid resiliency in the multi-microgrid systems.
- The analysis of the effects of selling power to the Main Grid by the microgrid.

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Appendix A

Line characteristics in the IEEE 33-bus test system

From	To	R (Ω)	X (Ω)	Current Capacity (Amp)
1	2	0.0922	0.047	500
2	3	0.493	0.2511	500
3	4	0.366	0.1864	500
4	5	0.3811	0.1941	500
5	6	0.819	0.707	500
6	7	0.1872	0.6188	500
7	8	0.7114	0.2351	500
8	9	1.03	0.74	500
9	10	1.044	0.74	500
10	11	0.1966	0.065	500
11	12	0.3744	0.1238	500
12	13	1.468	1.155	500
13	14	0.5416	0.7129	500
14	15	0.591	0.526	500
15	16	0.7463	0.545	500
16	17	1.289	1.721	500
17	18	0.732	0.574	500
2	19	0.164	0.1565	500
19	20	1.5042	1.3554	500
20	21	0.4095	0.4784	500
21	22	0.7089	0.9373	500
3	23	0.4512	0.3083	500
23	24	0.898	0.7091	500
24	25	0.896	0.7011	500
6	26	0.203	0.1034	500
26	27	0.2842	0.1447	500
27	28	1.059	0.9337	500
28	29	0.8042	0.7006	500
29	30	0.5075	0.2585	500
30	31	0.9744	0.963	500
31	32	0.3105	0.3619	500
32	33	0.341	0.5302	500

Appendix B

GAMS Code

```
$title Resilient-Economic Multi-Objective Optimization Problem for IEEE
33-bus network

$onText

------------------------------------------------------------------------
------
Model type: MINLP
------------------------------------------------------------------------
------
Contributed by
Mohammadreza Shafiee
email: shafiee21@gmail.com
We do request that publications derived from the use of the developed GAMS
code
explicitly acknowledge that fact by citing
Mohammadreza Shafiee, J. L. Cardenas-Barrera, E. F. S. Hill, and Chris
Diduch.
"Socio-Economic Oriented Microgrid Energy Management System with Islanding
Capability
during Adverse Weather Conditions", 7th IEEE Conference on Energy Internet
and Energy
System Integration, 2023
* To protect intellectual property, a few lines of code have been removed.
$offText

SETS
it iteration /1*20/
G  Main Grid /G1/
DGG DG Generation/DGG1/
N  buses /N1*N33/
DL demand level /dl1*dl24/
WG wind Generation/WG1/
BS battery storage /bs1/

MAP1(G,N) PoI connected in bus 1  /G1.N1/
 MAP4(WG,N) wind connected   /WG1.N11/
MAP3(DGG,N) DG connected   /DGG1.N28/
```

```
Map6(BS,N)  battery storage connected in bus /bs1.N11/

scalar Ybase   /0.049925/
A1  /0.0075/
B1  /40/
C1  /25/

parameter
time(DL)  period of demand level /dl1*dl24 1/

price(DL) price of 1mw for any demand level /dl1 59.96,dl2 46.55,dl3
40.43,dl4 38.08 ,dl5 38.47,
            dl6 37.8,dl7 41.15,dl8 41.28,dl9 42.27,dl10 43.12,dl11
45.56,dl12 47.67,
            dl13 48.87,dl14 48.25,dl15 49.93,dl16 49.927,dl17 50.44,dl18
52.69 ,
            dl19 53.75,dl20 55.27,dl21 74.67,dl22 80,dl23 76.10,dl24
68.97/


df(DL)    demand factor /dl1 0.749508,dl2 0.581923,dl3 0.505378,dl4
0.476059,dl5 0.480913,dl6 0.472452,
                      dl7 0.514299,dl8 0.515939,dl9 0.565919,dl10
0.651515,dl11 0.694477,dl12 0.695789,
                      dl13 0.7358,dl14 0.740653,dl15 0.799095,dl16
0.786501,dl17 0.767939,dl18 0.783747,
                      dl19 0.79693,dl20 0.828414,dl21 0.933294,dl22 1,dl23
0.951266,dl24 0.887249/

speed(DL) wind speed /dl1 10,dl2 7.5,dl3 6.5,dl4 6.5,dl5 7,dl6 6.5,dl7
6.5,dl8 7,dl9 7,dl10 15,dl11 14,dl12 16,
                    dl13 30,dl14 32,dl15 33,dl16 32,dl17 17,dl18 16,dl19
15,dl20 13,dl21 11,dl22 8,dl23 7,dl24 7.5/


PLOAD(N)
/N1 0,N2 .1,N3 0.09,N4 0.12,N5 0.06,N6 0.06,N7 0.2,N8 0.2,N9 0.06,N10
0.06,N11 0.045,N12 0.06,N13 0.06,N14 0.12,N15 0.06,N16 0.06,N17 0.06,N18
0.09,N19 .09,N20 0.09,N21 0.09,N22 0.09,N23 0.09,N24 0.42,N25 0.42,N26
0.06,N27 0.06,N28 0.06,N29 0.12,N30 0.2,N31 0.15,N32 0.21,N33 0.06 /
QLOAD(N)
/N1 0,N2 .06,N3 0.04,N4 0.08,N5 0.03,N6 0.02,N7 0.1,N8 0.1,N9 0.02,N10
0.02,N11 0.03,N12 0.035,N13 0.035,N14 0.08,N15 0.01,N16 0.02,N17 0.02,N18
0.04,N19 .04,N20 0.04,N21 0.04,N22 0.04,N23 0.05,N24 0.2,N25 0.2,N26
0.025,N27 0.025,N28 0.02,N29 0.07,N30 0.6,N31 0.07,N32 0.1,N33 0.04 /
```

```
;

TABLE GDATA(G,*)
      PMIN   PMAX   QMIN   QMAX
*    (MW)    (MW)  (MVAR)(MVAR)
G1     0      1     -0.4   0.4    ;


TABLE YLDATA(N,N)
       N1        N2        N3        N4        N5        N6        N7
N8        N9        N10       N11       N12       N13       N14       N15
N16       N17       N18       N19       N20       N21       N22       N23
N24       N25       N26       N27       N28       N29       N30       N31
N32       N33

N1     194.4407  194.4407  0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0
N2     194.4407  316.2553  36.2402   0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         88.3607   0         0         0         0
0         0         0         0         0         0         0         0
0         0
N3     0         36.2402   121.4151  48.7150   0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0
36.6763   0         0         0         0         0         0         0
0         0         0
N4     0         0         48.7150   95.5911   46.8761   0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0
N5     0         0         0         46.8761   65.0039   18.5093   0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0
N6     0         0         0         0         18.5093   130.5919  31.0815
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         88.3814   0         0         0         0         0
0         0
```

```
N7    0       0       0       0       0       31.0815 51.3491
26.7535 0       0       0       0       0       0       0
0       0       0       0       0       0       0       0
0       0       0       0       0       0       0       0
0       0
N8    0       0       0       0       0       0       26.7535
42.0990 15.8043 0       0       0       0       0       0
0       0       0       0       0       0       0       0
0       0       0       0       0       0       0       0
0       0
N9    0       0       0       0       0       0       0
15.8043 31.4674 15.6632 0       0       0       0       0
0       0       0       0       0       0       0       0
0       0       0       0       0       0       0       0
0       0
N10   0       0       0       0       0       0       0
0       15.6632 112.0574 97.0006 0      0       0       0
0       0       0       0       0       0       0       0
0       0       0       0       0       0       0       0
0       0
N11   0       0       0       0       0       0       0
0       0       97.0006 147.7590 50.7588 0      0       0
0       0       0       0       0       0       0       0
0       0       0       0       0       0       0       0
0       0
N12   0       0       0       0       0       0       0
0       0       0       50.7588 60.9590 10.7269 0      0
0       0       0       0       0       0       0       0
0       0       0       0       0       0       0       0
0       0
N13   0       0       0       0       0       0       0
0       0       0       0       10.7269 32.8710 22.3811 0
0       0       0       0       0       0       0       0
0       0       0       0       0       0       0       0
0       0
N14   0       0       0       0       0       0       0
0       0       0       0       0       22.3811 47.4990
25.3454 0       0       0       0       0       0       0
0       0       0       0       0       0       0       0
0       0       0
N15   0       0       0       0       0       0       0
0       0       0       0       0       0       25.3454
46.9926 21.6998 0       0       0       0       0       0
0       0       0       0       0       0       0       0
0       0       0
```

```
N16  0  0  0  0  0  0  0
0  0  0  0  0  0  0
21.6998  30.7329  9.3197  0  0  0  0  0
0  0  0  0  0  0  0  0
0  0  0
N17  0  0  0  0  0  0  0
0  0  0  0  0  0  0  0
9.3197  30.6596  21.5655  0  0  0  0  0
0  0  0  0  0  0  0  0
0  0
N18  0  0  0  0  0  0  0
0  0  0  0  0  0  0  0
0  21.5655  21.5655  0  0  0  0  0
0  0  0  0  0  0  0  0
0  0
N19  0  88.3607  0  0  0  0  0
0  0  0  0  0  0  0  0
0  0  0  98.2552  9.8975  0  0  0
0  0  0  0  0  0  0  0
0  0
N20  0  0  0  0  0  0  0
0  0  0  0  0  0  0  0
0  0  0  9.8975  41.6581  31.8244  0  0
0  0  0  0  0  0  0  0
0  0
N21  0  0  0  0  0  0  0
0  0  0  0  0  0  0  0
0  0  0  0  31.8244  48.8465  17.0414  0
0  0  0  0  0  0  0  0
0  0
N22  0  0  0  0  0  0  0
0  0  0  0  0  0  0  0
0  0  0  0  0  17.0414  17.0414  0
0  0  0  0  0  0  0  0
0  0
N23  0  0  36.6763  0  0  0  0
0  0  0  0  0  0  0  0
0  0  0  0  0  0  0
54.1622  17.5137  0  0  0  0  0  0
0  0  0
N24  0  0  0  0  0  0  0
0  0  0  0  0  0  0  0
0  0  0  0  0  0  0
17.5137  35.1278  17.6142  0  0  0  0  0
0  0  0
```

N25 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0
17.6142 17.6142 0 0 0 0 0 0
0 0
N26 0 0 0 0 0 88.3814 0
0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0
0 0 151.1913 62.8099 0 0 0 0
0 0
N27 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0
0 0 62.8099 76.6257 14.1848 0 0 0
0 0
N28 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0
0 0 0 14.1848 32.9957 18.8110 0 0
0 0
N29 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0
0 0 0 0 18.8110 53.6572 35.2126 0
0 0
N30 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0
0 0 0 0 0 35.2126 49.3642
14.6396 0 0
N31 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0
0 0 0 0 0 0 14.6396
56.7025 42.0983 0
N32 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0
0 0 0 0 0 0 0
42.0983 69.4768 27.3972
N33 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0
27.3972 27.3972

```
;

  TABLE TETALDATA(N,N)
       N1         N2         N3         N4         N5         N6         N7
N8         N9         N10        N11        N12        N13        N14        N15
N16        N17        N18        N19        N20        N21        N22        N23
N24        N25        N26        N27        N28        N29        N30        N31
N32        N33

N1     -26.5651  153.4349  0          0          0          0          0
0          0          0          0          0          0          0          0
0          0          0          0          0          0          0          0
0          0          0          0          0          0          0          0
0          0
N2     153.4349  -31.2941  153.0635  0          0          0          0
0          0          0          0          0          0          0          0
0          0          0          136.4321  0          0          0          0
0          0          0          0          0          0          0          0
0          0
N3     0          153.0635  -29.1833  153.0605  0          0          0
0          0          0          0          0          0          0          0
0          0          0          0          0          0          0
145.6105  0          0          0          0          0          0          0
0          0          0
N4     0          0          153.0605  -26.9915  152.9545  0          0
0          0          0          0          0          0          0          0
0          0          0          0          0          0          0          0
0          0          0          0          0          0          0          0
0          0
N5     0          0          0          152.9545  -30.9266  139.2032  0
0          0          0          0          0          0          0          0
0          0          0          0          0          0          0          0
0          0          0          0          0          0          0          0
0          0
N6     0          0          0          0          139.2032  -38.7192
106.8016  0          0          0          0          0          0          0
0          0          0          0          0          0          0          0
0          0          0          153.2085  0          0          0          0
0          0          0
N7     0          0          0          0          0          106.8016  -
47.9486  161.7589  0          0          0          0          0          0
0          0          0          0          0          0          0          0
0          0          0          0          0          0          0          0
0          0          0
```

```
N8      0         0         0         0         0         0
161.7589  -24.6989  144.3255  0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0
N9      0         0         0         0         0         0         0
144.3255  -35.4922  144.6918  0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0
N10     0         0         0         0         0         0         0
0         144.6918  -20.4557  161.9166  0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0
N11     0         0         0         0         0         0         0
0         0         161.9166  -18.1726  161.6570  0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0
N12     0         0         0         0         0         0         0
0         0         0         161.6570  -21.7632  141.8393  0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0
N13     0         0         0         0         0         0         0
0         0         0         0         141.8393  -48.0844  127.1777  0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0
N14     0         0         0         0         0         0         0
0         0         0         0         0         127.1777  -46.8665
138.3906  0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0
N15     0         0         0         0         0         0         0
0         0         0         0         0         0         138.3906  -
39.1023  143.8264  0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0
N16     0         0         0         0         0         0         0
0         0         0         0         0         0         0
143.8264  -41.2631  126.8165  0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0
```

```
N17     0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
126.8165  -42.6234  141.9191  0         0         0         0         0
0         0         0         0         0         0         0         0
0         0
N18     0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         141.9191  -38.0809  0         0         0         0         0
0         0         0         0         0         0         0         0
0         0
N19     0         136.4321  0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         -43.4172  137.9285  0         0         0
0         0         0         0         0         0         0         0
0         0
N20     0         0         0         0         0         0         0
0         0         0         0         137.9285  0         0         0
0         0         0         137.9285  -47.7530  130.4826  0         0
0         0         0         0         0         0         0         0
0         0
N21     0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         130.4826  -50.6954  127.1042  0
0         0         0         0         0         0         0         0
0         0
N22     0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         127.1042  -52.8958  0
0         0         0         0         0         0         0         0
0         0
N23     0         0         145.6105  0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         -
35.6579  141.6850  0         0         0         0         0         0
0         0         0
N24     0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0
141.6850  -38.1876  141.9391  0         0         0         0         0
0         0         0
N25     0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
141.9391  -38.0609  0         0         0         0         0         0
0         0
```

```
N26    0         0         0         0         0         153.2085  0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         -26.8312  153.1131  0         0         0         0
0         0
N27    0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         153.1131  -29.5418  138.6229  0         0         0
0         0
N28    0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         138.6229  -41.1814  138.9662  0         0
0         0
N29    0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         138.9662  -31.8875  152.9838  0
0         0
N30    0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         152.9838  -32.1688
135.3559  0         0
N31    0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         135.3559  -
48.0753  130.7321  0
N32    0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0
130.7321  -48.1981  133.4458
N33    0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
133.4458  -46.5542
;

TABLE Pl(N,*)
```

	N1	N2	N3	N4	N5	N6	N7	N8	N9	N10	N11	N12	N13	N14	N15	N16
N2	0	0.1	0.09	0.12	0.06	0.06	0.2	0.2	0.06	0.06	0.045	0.06	0.06	0.12	0.06	0.06
N3	0	0	0.09	0.12	0.06	0.06	0.2	0.2	0.06	0.06	0.045	0.06	0.06	0.12	0.06	0.06
N4	0	0	0	0.12	0.06	0.06	0.2	0.2	0.06	0.06	0.045	0.06	0.06	0.12	0.06	0.06
N5	0	0	0	0	0.06	0.06	0.2	0.2	0.06	0.06	0.045	0.06	0.06	0.12	0.06	0.06
N6	0	0	0	0	0	0.06	0.2	0.2	0.06	0.06	0.045	0.06	0.06	0.12	0.06	0.06
N7	0	0	0	0	0	0	0.2	0.2	0.06	0.06	0.045	0.06	0.06	0.12	0.06	0.06
N8	0	0	0	0	0	0	0	0.2	0.06	0.06	0.045	0.06	0.06	0.12	0.06	0.06
N9	0	0	0	0	0	0	0	0	0.06	0.06	0.045	0.06	0.06	0.12	0.06	0.06

	N17	N18	N19	N20	N21	N22	N23	N24	N25	N26	N27	N28	N29	N30	N31	N32	N33
N2	0.06	0.09	0.09	0.09	0.09	0.09	0.09	0.42	0.42	0.06	0.06	0.06	0.12	0.2	0.15	0.21	0.06
N3	0.06	0.09	0	0	0	0	0.09	0.42	0.42	0.06	0.06	0.06	0.12	0.2	0.15	0.21	0.06
N4	0.06	0.09	0	0	0	0	0	0	0	0.06	0.06	0.06	0.12	0.2	0.15	0.21	0.06
N5	0.06	0.09	0	0	0	0	0	0	0	0.06	0.06	0.06	0.12	0.2	0.15	0.21	0.06
N6	0.06	0.09	0	0	0	0	0	0	0	0.06	0.06	0.06	0.12	0.2	0.15	0.21	0.06
N7	0.06	0.09	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N8	0.06	0.09	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N9	0.06	0.09	0	0	0	0	0										

```
0       0       0       0       0       0       0       0
0       0
N10     0       0       0       0       0       0       0
0       0       0.06    0.045   0.06    0.06    0.12    0.06
0.06    0.06    0.09    0       0       0       0       0
0       0       0       0       0       0       0       0
0       0
N11     0       0       0       0       0       0       0
0       0       0       0.045   0.06    0.06    0.12    0.06
0.06    0.06    0.09    0       0       0       0       0
0       0       0       0       0       0       0       0
0       0
N12     0       0       0       0       0       0       0
0       0       0       0       0.06    0.06    0.12    0.06
0.06    0.06    0.09    0       0       0       0       0
0       0       0       0       0       0       0       0
0       0
N13     0       0       0       0       0       0       0
0       0       0       0       0       0.06    0.12    0.06
0.06    0.06    0.09    0       0       0       0       0
0       0       0       0       0       0       0       0
0       0
N14     0       0       0       0       0       0       0
0       0       0       0       0       0       0.12    0.06
0.06    0.06    0.09    0       0       0       0       0
0       0       0       0       0       0       0       0
0       0
N15     0       0       0       0       0       0       0
0       0       0       0       0       0       0       0.06
0.06    0.06    0.09    0       0       0       0       0
0       0       0       0       0       0       0       0
0       0
N16     0       0       0       0       0       0       0
0       0       0       0       0       0       0       0
0.06    0.06    0.09    0       0       0       0       0
0       0       0       0       0       0       0       0
0       0
N17     0       0       0       0       0       0       0
0       0       0       0       0       0       0       0
0       0.06    0.09    0       0       0       0       0
0       0       0       0       0       0       0       0
0       0
N18     0       0       0       0       0       0       0
0       0       0       0       0       0       0       0
0       0       0.09    0       0       0       0       0
```

```
0       0       0       0       0       0       0       0
0       0
N19     0       0       0       0       0       0       0
0       0       0       0       0       0       0       0
0       0       0       0.09    0.09    0.09    0.09    0
0       0       0       0       0       0       0       0
0       0
N20     0       0       0       0       0       0       0
0       0       0       0       0       0       0       0
0       0       0       0       0.09    0.09    0.09    0
0       0       0       0       0       0       0       0
0       0
N21     0       0       0       0       0       0       0
0       0       0       0       0       0       0       0
0       0       0       0       0       0.09    0.09    0
0       0       0       0       0       0       0       0
0       0
N22     0       0       0       0       0       0       0
0       0       0       0       0       0       0       0
0       0       0       0       0       0       0.09    0
0       0       0       0       0       0       0       0
0       0
N23     0       0       0       0       0       0       0
0       0       0       0       0       0       0       0
0       0       0       0       0       0       0       0.09
0.42    0.42    0       0       0       0       0       0
0       0
N24     0       0       0       0       0       0       0
0       0       0       0       0       0       0       0
0       0       0       0       0       0       0       0
0.42    0.42    0       0       0       0       0       0
0       0
N25     0       0       0       0       0       0       0
0       0       0       0       0       0       0       0
0       0       0       0       0       0       0       0
0       0.42    0       0       0       0       0       0
0       0
N26     0       0       0       0       0       0       0
0       0       0       0       0       0       0       0
0       0       0       0       0       0       0       0
0       0       0.06    0.06    0.06    0.12    0.2     0.15
0.21    0.06
N27     0       0       0       0       0       0       0
0       0       0       0       0       0       0       0
0       0       0       0       0       0       0       0
```

```
0         0         0         0.06      0.06      0.12      0.2       0.15
0.21      0.06
N28    0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0.06      0.12      0.2       0.15
0.21      0.06
N29    0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0.12      0.2       0.15
0.21      0.06
N30    0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0.2       0.15
0.21      0.06
N31    0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0.15
0.21      0.06
N32    0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0.21      0.06
N33    0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0         0         0         0         0         0         0
0         0.06
;


TABLE Pgen(N,*)

         tmr   landa
N2        4   0.0002
N3        4   0.0002
N4        4   0.0002
N5        4   0.0002
N6        4   0.0002
N7        4   0.0002
```

```
N8        4   0.0002
N9        4   0.0002
N10       4   0.0002
N11       4   0.0002
N12       4   0.0002
N13       6   0.0002
N14       6   0.0002
N15       6   0.0002
N16       6   0.0002
N17       4   0.0002
N18       4   0.0002
N19       4   0.0002
N20       4   0.0002
N21       4   0.0002
N22       4   0.0002
N23       4   0.0002
N24       4   0.0002
N25       4   0.0002
N26       4   0.0002
N27       4   0.0002
N28       4   0.0002
N29       4   0.0002
N30       4   0.0002
N31       4   0.0002
N32       4   0.0002
N33       4   0.0002
;


ALIAS(N,NP) ;

VARIABLES
Profit
tap(DL)
PLOSS
QLOSS
PLOSS1(DL)
QLOSS1(DL)
delta(N,DL)
V(DL,N)
vp(DL,N)
Q(G,DL)
QDG(DGG,DL)
p(G,DL)
PDG(DGG,DL)
```

```
ppp(DL)
qqq
DGO
TOU(N,DL)
cre
reliab1(dl)
reliab2(dl)
*cre1(dl)
landaw(DL);

POSITIVE VARIABLE
X(bs,dl)
Pcharge(bs,dl)
Pdicharge(bs,dl)

Pload_DRP(N,DL);


binary variables
Ucharge(bs,dl)
Udicharge(bs,dl)
;

Parameters
DERO_lim
DERO_min
DERO_max
Profit_min
Profit_max
;

EQUATIONS
Profit_DMSO
totploss
totqloss
totploss1(DL)
totqloss1(DL)
pdgmax1(DGG,DL)

qdgmax1(DGG,DL)

pdgmin1(DGG,DL)

qdgmin1(DGG,DL)
```

```
pwmax(WG,DL)
Pwind(WG,dl)

pp(DL)
DGOwner
qq
VmaxLimit(DL,N)
VminLimit(DL,N)
VmaxLimit1(DL)
vper(DL,N)
PminLimit(G,DL)
PmaxLimit(G,DL)
QminLimit(G,DL)
QmaxLimit(G,DL)
PLOADFLOW(N,DL)
QLOADFLOW(N,DL)
maxlimit_delta(N,DL)
minlimit_delta(N,DL)
epsilon

e9(BS,DL)
e3(BS,Dl)
e4(BS,Dl)
e5(BS,Dl)
e6(BS,Dl)
e7(BS,Dl)
e8(BS,Dl)
ess8(bs)

E_DRP1(N,DL)
E_DRP2(N,DL)
E_DRP3(N,DL)
E_DRP4(N)

eq1(N,dl)
reliability1(dl)
reliability2(dl)
creliab

landacalc(DL);
parameter price_DG(DGG) /DGG1 80/
price_WG(WG) /WG1 80/ ;
scalar Fixed_sell_price /85/ ;

e3(BS,Dl)  .. X(BS,Dl)=l=0.8;
```

```
e4(BS,Dl) .. X(BS,Dl)=g=0.1;
e5(bs,dl)  ..Ucharge(bs,dl)+Udicharge(bs,dl)=l=1;
e6(bs,dl)  ..Pcharge(bs,dl)=l=0.5*Ucharge(bs,dl);
e7(bs,dl)  ..Pdicharge(bs,dl)=l=0.5*Udicharge(bs,dl);
e8(bs,dl) $ (ord(dl)>1) .. X(BS,Dl)=e=X(BS,Dl-1)+0.95*Pcharge(bs,dl)-
Pdicharge(bs,dl)/0.85;
ess8(bs) ..sum(dl,0.9*Pcharge(bs,dl))-sum(dl,Pdicharge(bs,dl))=e=0;
e9(BS,dl) $ (ord(dl)=1) .. X(BS,dl)=e=0.1;

E_DRP1(N,DL) .. Pload_DRP(N,DL)=e=Pload(N)*(df(DL)+TOU(N,DL)) ;
E_DRP2(N,DL) .. TOU(N,DL)=l=0.25*df(DL) ;
E_DRP3(N,DL) .. TOU(N,DL)=g=-0.25*df(DL) ;
E_DRP4(N)    .. sum(DL,TOU(N,DL))=e=0 ;

pwmax(WG,DL)..PW(WG,DL)=l=1*((speed(DL)-2)/12)$(speed(DL) le 14
$(speed(DL) gt 2))+4$(speed(DL) gt 14.1);
Pwind(WG,dl)..PW(WG,DL)=l=1 ;


**************************************************

pdgmax1(DGG,DL)..PDG("DGG1",DL)=l=1;
pdgmin1(DGG,DL)..PDG("DGG1",DL)=g=0;
qdgmax1(DGG,DL)..QDG("DGG1",DL)=l=PDG("DGG1",DL)*.4;
qdgmin1(DGG,DL)..QDG("DGG1",DL)=g=-0.4;


VmaxLimit(DL,N).. V(DL,N)=L=1.05*12.66;
VminLimit(DL,N).. V(DL,N)=G=0.95*12.66;
VmaxLimit1(DL).. V(DL,"N1")/12.66=e=1;
maxlimit_delta(N,DL)..delta(N,DL)=l=1;
minlimit_delta(N,DL)..delta(N,DL)=g=-1;
PmaxLimit(G,DL).. P(G,DL)=L=GDATA(G,"PMAX");
PminLimit(G,DL).. P(G,DL)=G=GDATA(G,"PMIN");
QmaxLimit(G,DL).. Q(G,DL)=L=GDATA(G,"QMAX");
QminLimit(G,DL).. Q(G,DL)=G=GDATA(G,"QMIN");
vper(DL,N)..vp(DL,N)=e=V(DL,N)/12.66 ;

PLOADFLOW(N,DL)..SUM(MAP1(G,N),P(G,DL))+SUM(MAP3(DGG,N),PDG(DGG,DL))+SUM(M
AP4(WG,N),PW(WG,DL))-Pload_DRP(N,DL)-
SUM(MAP6(BS,N),Pcharge(bs,dl))+SUM(MAP6(BS,N),Pdicharge(bs,dl))-
Ybase*SUM((NP),V(DL,N)*V(DL,NP)*YLDATA(N,NP)*cos(0.017453292519943*(TETALD
ATA(N,NP))+delta(NP,DL)-delta(N,DL)))=e=0;
```

```
QLOADFLOW(N,DL)..SUM(MAP1(G,N),Q(G,DL))+SUM(MAP3(DGG,N),QDG(DGG,DL))-
QLOAD(N)*df(DL)+Ybase*SUM((NP),V(DL,N)*V(DL,NP)*YLDATA(N,NP)*sin(0.0174532
92519943*(TETALDATA(N,NP))+delta(NP,DL)-delta(N,DL)))=e=0;

eq1(N,dl)..SUM(MAP3(DGG,N),PDG(DGG,DL))+SUM(MAP4(WG,N),PW(WG,DL))=l=SUM((N
P),Pl(N,NP)*(df(DL)+TOU(N,DL)));

********************************
********************************
********************************
********************************

totploss..PLOSS=e=sum((G,DL),P(G,DL)*time(DL))+sum((WG,DL),PW(WG,DL)*time(
DL))+sum((DGG,DL),PDG(DGG,DL))-sum((N,DL),PLOAD(N)*df(DL)*time(DL));
totqloss..QLOSS=e=sum((G,DL),Q(G,DL)*time(DL))+sum((DGG,DL),QDG(DGG,DL))-
sum((N,DL),QLOAD(N)*df(DL)*time(DL));
totploss1(DL)..PLOSS1(DL)=e=sum((G),P(G,DL))+sum((WG),PW(WG,DL))+sum((DGG)
,PDG(DGG,DL))-sum((N),PLOAD(N)*df(DL));
totqloss1(DL)..QLOSS1(DL)=e=sum((G),Q(G,DL))+sum((DGG),QDG(DGG,DL))-
sum((N),QLOAD(N)*df(DL));


MSO_OF ..
Profit=e=SUM((N,DL),(Fixed_sell_price)*time(DL)*PLOAD(N))+SUM((N,DL),.5*Fi
xed_sell_price*time(DL)*QLOAD(N))
                 -SUM((G,DL),price(DL)*time(DL)*P(G,DL))-
SUM((G,DL),price(DL)*.5*time(DL)*Q(G,DL))-EENS.C
                 -SUM((WG,DL),PW(WG,DL)*time(DL)*price_WG(WG))-
SUM((DGG,DL),(price_DG(DGG)+reprice(DL))*time(DL)*PDG(DGG,DL))
            -SUM((DGG,DL),price_DG(DGG)*.5*time(DL)*QDG(DGG,DL))-******   ;

DERO_OF ..
DGO=e=SUM((DGG,DL),(price_DG(DGG)+reprice(DL))*time(DL)*PDG(DGG,DL))+****
            +SUM((WG,DL),PW(WG,DL)*time(DL)*price_WG(WG))-***
            -SUM((bs,DL),2.7*(0.9*Pcharge(bs,dl)-
Pdicharge(bs,dl)/0.9)*time(DL))-***
           -
SUM((DL),(A1*PDG("DGG1",DL)*PDG("DGG1",DL)+B1*PDG("DGG1",DL)+C1)*time(DL))
          -***

epsilon .. DERO=g=DERO_lim ;

**** ;
**** ;
```

```
MODEL opf /all /;

MODEL opf1 /e3,e4,e5,e6,e7,e8,e9,E_DRP1,E_DRP2,E_DRP3,E_DRP4
Profit_DERO
totploss
totqloss
totploss1
totqloss1
pdgmax1

qdgmax1

pdgmin1

qdgmin1

pwmax
Pwind
pp
DGOwner
qq
VmaxLimit
VminLimit
VmaxLimit1
vper
PminLimit
PmaxLimit
QminLimit
QmaxLimit
PLOADFLOW
QLOADFLOW
maxlimit_delta
minlimit_delta
eq1
reliability1
reliability2
landacalc/;

option minlp=sbb;
SOLVE opf1 USING minlp MAXIMIZING Profit;

Profit_max=Profit.l;
DGO_min=DGO.l;

SOLVE opf1 USING minlp MAXIMIZING DGO;
```

```
Profit_min=Profit.l;
DGO_max=DGO.l;

parameter
dataout(it,*)
dataout1(it,N,DL,*)
dataout2(it,G,DL,*)
dataout3(it,DL,N,*)
dataout4(it,DGG,DL,*)
dataout5(it,WG,DL,*)
dataout6(it,BS,DL,*)
dataout7(it,DL,*)
;

Loop(it,

DGO_lim=DGO_max+(DGO_min-DGO_max)*(card(it)-ord(it)+1)/card(it);

SOLVE opf USING minlp MAXIMIZING Profit;

dataout(it,'MSO-Profit')=Profit.l;
dataout(it,'DERO-Profit')=DGO.l;
dataout(it,'EENS.C')=cre.l;
dataout(it,'PLOSS')=PLOSS.l;
dataout(it,'QLOSS')=QLOSS.l;

dataout(it,'Profit_pu')=(Profit.l-Profit_min)/(Profit_max-Profit_min);
dataout(it,'DERO_pu')=(DERO.l-DERO_min)/(DERO_max-DERO_min);

dataout1(it,N,DL,'Pload_DRP')=Pload_DRP.l(N,DL);
dataout1(it,N,DL,'TOU')=TOU.l(N,DL);

dataout2(it,G,DL,'P')=P.l(G,DL);
dataout2(it,G,DL,'Q')=Q.l(G,DL);

dataout3(it,DL,N,'Vp')=Vp.l(DL,N);
dataout3(it,DL,N,'V')=V.l(DL,N);

dataout4(it,DGG,DL,'PDG')=PDG.l(DGG,DL) ;
dataout4(it,DGG,DL,'QDG')=QDG.l(DGG,DL) ;

dataout5(it,WG,DL,'PW')=PW.l(WG,DL) ;

dataout6(it,BS,DL,'X')=X.l(BS,Dl) ;
dataout6(it,BS,DL,'Pcharge')=Pcharge.l(BS,Dl) ;
```

```
dataout6(it,BS,DL,'Pdicharge')=Pdicharge.l(BS,Dl) ;


dataout7(it,DL,'reliab2')=reliab2.l(dl);
dataout7(it,DL,'reliab1')=reliab1.l(dl);
dataout7(it,DL,'landaw')=landaw.l(dl);
) ;

display
dataout,dataout1,dataout2,dataout3,dataout4,dataout5,dataout6,dataout7;

****************  for sending data to Excel *************************
**********************************************************************
******
execute_unload "Proposed.gdx" dataout
execute 'gdxxrw.exe Proposed.gdx par=dataout  rng=Profit-cre!a1'
**********************************************************************
******
**********************************************************************
******
execute_unload "Proposed.gdx" dataout1
execute 'gdxxrw.exe Proposed.gdx par=dataout1  rng=load!a1'
**********************************************************************
******
**********************************************************************
******
execute_unload "Proposed.gdx" dataout2
execute 'gdxxrw.exe Proposed.gdx par=dataout2  rng=upstream!a1'
**********************************************************************
******
**********************************************************************
******
execute_unload "Proposed.gdx" dataout3
execute 'gdxxrw.exe Proposed.gdx par=dataout3  rng=voltage!a1'
**********************************************************************
******
execute_unload "Proposed.gdx" dataout4
execute 'gdxxrw.exe Proposed.gdx par=dataout4  rng=DG!a1'
**********************************************************************
******
execute_unload "Proposed.gdx" dataout5
execute 'gdxxrw.exe Proposed.gdx par=dataout5  rng=wind!a1'
**********************************************************************
******
```

```
  execute_unload "Proposed.gdx" dataout7
execute 'gdxxrw.exe Proposed.gdx par=dataout7  rng=relib!a1'
**************************************************************************
******
  execute_unload "Proposed.gdx" dataout6
execute 'gdxxrw.exe Proposed.gdx par=dataout6  rng=ESS!a1'
**************************************************************************
******
```

Curriculum Vitae

Candidate's Full Name: Mohammadreza Shafiee

Universities Attended:

- Bachelor of Science in Engineering, Electrical Engineering, Power Systems, Semnan University, Iran, Sep. 2005-Sep. 2009.
- Master of Science in Engineering, Electrical Engineering, Control Systems, IAU, Iran, Sep. 2011-Feb. 2014.

Journal Publications:

- Wu, Minrong, Li, Shanshan, Chen, Hongyan, Duan, Wenqi, Shafiee, Mohammadreza. "Parameters Estimation of the Mathematical Model of Solid Oxide Fuel Cell Stacks based on a Fractional-order Water Strider Algorithm", Journal of Electrical Engineering & Technology. 17, 73–84 (2022). https://doi.org/10.1007/s42835-021-00862-x, 2022.
- Mohammadreza Shafiee, Meysam Amirahmadi, Mehdi Farzinfar, and Andrew Lapthorn, "Voltage Stability Improvement in Optimal Placement of Voltage Regulators and Capacitor Banks Based on FSM and MMOPSO Approach", International Journal of Engineering (IJE) Transactions A: Basics Vol. 34, No. 04, (April 2021) 881-890. https://dx.doi.org/10.5829/ije.2021.34.04a.14, 2021.
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