Efficient Water-based Electricity Strategies to Reduce the Number of Switching Operations in a Smart Grid

Written by:

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Abstract

The increasing complexity of modern power systems, driven by the integration of renewable energy sources and the need for enhanced operational efficiency, has led to the widespread adoption of Transmission Switching (TS) as a cost-reduction strategy. TS optimizes the configuration of the transmission network by selectively switching transmission lines, thereby reducing the overall operational costs. However, this approach comes with significant drawbacks. The frequent switching operations required can degrade critical system components, particularly circuit breakers (CBs), leading to a shorter lifespan, higher maintenance and repair costs, increased likelihood of line outages, and a greater probability of load shedding. Moreover, these issues can collectively undermine the reliability of the entire power system.

To address these challenges, this thesis presents a novel congestion management framework integrated within the Security-Constrained Unit Commitment (SCUC) problem. The primary objective of the proposed framework is to minimize the number of TS operations necessary to manage congestion, thereby mitigating the adverse effects on CBs and enhancing the overall reliability of the power grid. The framework introduces a grid-connected water-power system that leverages a fuel cell-based renewable energy source, coupled with a hydrogen storage tank, to provide additional flexibility in managing grid congestion. By utilizing this water-power system, the framework reduces the need for frequent TS operations, thus alleviating the associated strain on the transmission network.

Additionally, the thesis addresses the inherent uncertainties in grid operations, particularly those related to fluctuating renewable energy output and unpredictable demand. To this end, an uncertainty-based Unscented Transform (UT) function is incorporated into the SCUC framework. This function enhances the robustness of the proposed methodology, ensuring that it remains effective under a wide range of operational scenarios and uncertainties.

The proposed framework is validated through comprehensive simulations conducted on two standard test systems: a 6-bus and a 118-bus IEEE grid. These simulations are performed using Bender's decomposition method in GAMS software, a widely recognized tool for large-scale optimization problems in power systems. The results from these simulations demonstrate that the proposed strategy significantly reduces line congestion and the number of TS operations required. Specifically, the framework achieves a 77% reduction in switching operations for the 6-bus system and a 45% reduction for the 118-bus system. These

reductions not only extend the lifespan of CBs but also lead to substantial decreases in operational costs, thereby offering a more sustainable and cost-effective solution for modern power systems.

The findings of this research contribute to the ongoing development of more resilient, efficient, and sustainable power systems, particularly in light of the increasing reliance on renewable energy sources. The proposed framework offers a viable path forward for grid operators seeking to balance cost efficiency with system reliability, all while integrating more renewable energy into the power grid.

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Finally, I dedicate this thesis to my family, whose love, patience, and unwavering belief in me have been my greatest source of strength. This work is a testament to their support and sacrifices.

Co-authorship Statement

I am the principal author of all the research papers used in the preparation of this thesis. My thesis supervisor, Dr. Mohsin Jamil is co-author. As the principal author, I conducted the majority of the research, performed literature reviews, carried out the designs, simulations, and result analysis for each manuscript. I also prepared the original manuscripts and revised them based on feedback from my supervisors and peer reviewers throughout the review process. Dr. Mohsin supervised the entire research project, reviewed and corrected each manuscript, provided research components, and contributed ideas throughout the research and manuscript preparation.

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List of Abbreviations

TS	Transmission Switching
CB	Circuit Breakers
SCUC	Security-Constrained Unit Commitment
SLR	Static Line Rating
GAMS	General Algebraic Modeling System
NCUC	Network-Constrained Unit Commitment
UT	Unscented Transform
IEEE	Institute of Electrical and Electronics Engineers
FACTS	Flexible AC Transmission Systems
SVC	Static VAR Compensator
STATCOM	Static Synchronous Compensator
AC	Alternating Current
DC	Direct Current
MG	Microgrid
CHP	Combined Heat and Power
LMP	Locational Marginal Pricing
ISO	Independent System Operator

GENCO	Generation Companies
TRANSCO	Transmission Companies
PSO	Particle Swarm Optimization
ADMM	Alternating Direction Method of Multipliers
DCOPF	Direct Current Optimal Power Flow
MILP	Mixed-Integer Linear Programming
PV	Photovoltaic
PLC	Power Line Carrier
MC	Monte Carlo
TMS	Time Multiplier Settings
DER	Distributed Energy Resource
DG	Distributed Generation
ANN	Artificial Neural Networks
TNEP	Transmission Network Expansion Planning
HPC	High-performance Computing
RoCoF	Rate of Change of Frequency
DR	Demand Response
FRP	Flexible Ramping Products

TBES	Portable Battery Energy Storage
DC-OTS	DC Optimal Transmission Switching
CTS	Corrective AC Transmission Switching
TVA	Tennessee Valley Authority
ERCOT	Electric Reliability Council of Texas
RTCA	Real-time Contingency Analysis
DRP	Demand Response Program
PEV	Plug-in Electric Vehicle
RTS	Reliability Test System
SDP	Semidefinite Program
VSC	Voltage Source Converter
TCR	Thyristor Controlled Reactor
TSR	Thyristor Switched Reactor
IGBT	Insulated-Gate Bipolar Transistor
CCGT	Combined Cycle Gas Turbine
SG	Smart Grid
SCADA	Supervisory Control and Data Acquisition

List of Symbols

t	Time
$(.)^s$	Scenario
$(.)^l$	Loss
J,r,m	Elements of a piecewise linearized model of radiation loss
g,b,k	Index of generators, buses, and lines, respectively
l	Number of piecewise linear blocks
R_g^+, SR_g^+	Maximum ramp up/ramp down rate [MW]
qs	Solar radiation heat losses [MW/m]
$P_g^{\max}, P_g^{\min}$	Active power limitation for generators [MW]
$Q_g^{\max}, Q_g^{\min}$	Reactive power limitation for generators [MW]
$P_k^{\max}, Q_k^{\min}$	Active/reactive power limitation for lines [MW]
$\Delta V^{\max}, \Delta V^{\min}$	Voltage limitation for busses [p.u]
$\delta_k^{\max}, \delta_k^{\min}$	Angle difference limitation for lines
M	A large positive
$Ibase$	Base current [A]
SUg,t,SDg,t	Start-up and shut-down cost for generators
zc_k^s, uc_g^s	Contingency state of (unit g)/(line k)

ajj, cjj	Failure probability of CB linearized coefficient
P_D	Real power of load
$P_g^{\max}, P_g^{\min}$	Active power limitation for generators [MW]
$Q_g^{\max}, Q_g^{\min}$	Reactive power limitation for generators [MW]
$\Delta V^{\max}, \Delta V^{\min}$	Voltage change limitation for busses [p.u]
$\delta_k^{\max}, \delta_k^{\min}$	Angle difference limitation for lines
M, VOLL	Large positive numbers
$P_t^{G_{chp}}, P_t^{G_{boi}}$	CHP and boiler input gas power during time slot *t,* respectively.
P_t^{ch} / P_t^{dch}	Charging/discharging power of the battery during time slot *t.*
Q_λ, Q_ς	Input and output covariance matrix, respectively.
S_t^{ES}	The EH battery remaining energy during time slot *t.*
$\underline{V}^{ST}, \bar{V}^{ST}$	Minimum/maximum volume of secondary tank
$\bar{V}^{DT}$	Maximum volume of desalination tank
$V_{w,t}^{ST}$	Secondary tank water volume during time slot *t* in scenario *w*
$V_{w,t}^{DT}$	Desalination unit water volume during time slot *t* in scenario *w*
$W_{w,t}^{OD}$	Desalination unit output water during time slot *t* in scenario *w*
$W_{w,t}^{Out}$	Secondary tank output water during time slot *t* in scenario *w*
$W_{w,t}^{ID}$	Desalination unit input water during time slot *t* in scenario *w*

$\underline{W}^{ID}, \bar{W}^{ID}$	Min/max input water of desalination tank
$\bar{W}^{OD}$	Maximum output water of desalination unit

Chapter 1: Introduction and Literature Review

Chapter 1 of the thesis sets the stage by providing a comprehensive overview of the evolving landscape of power systems, emphasizing the increasing integration of renewable energy sources and the challenges associated with maintaining system reliability and efficiency. It delves into the historical development of traditional power systems and contrasts them with modern grids, which are characterized by their high variability and reliance on renewable energy. The chapter discusses the concept of Transmission Switching (TS) as a strategy to enhance grid management by optimizing power flows, reducing operational costs, and alleviating congestion. It also introduces key challenges such as the wear and tear on infrastructure, particularly circuit breakers, due to frequent switching operations. A thorough literature review is presented, summarizing current research and methodologies in the areas of Security-Constrained Unit Commitment (SCUC) and congestion management. This review sets the foundation for the thesis by highlighting the gaps in existing research that the study aims to address, particularly in improving the efficiency and sustainability of power grids through innovative TS strategies integrated with a water-power system.

1-1 Background

The rapid industrialization process in the 20th century transformed transmission lines and networks into a crucial part of the economic infrastructure in industrialized countries. Typically, electricity is transmitted over long distances through a combination of overhead power transmission lines and underground cables. A transmission network is composed of power plants, substations, and transmission circuits. Usually, electricity is transmitted via a three-phase alternating current. In power plants, electricity is generated at a relatively low voltage level of about 10 to 15 kilovolts, then it is stepped up to a high alternating current voltage (220 to 440 kilovolts) by the power plant transformer to be transmitted to a substation, which is the exit point of the network and is located at distant locations [1]. Transmission lines can also be used for data transmission, known as Power Line Carrier (PLC). To reduce power loss percentage, it is necessary to transmit electricity at high voltages. The higher the voltage, the lower the current, which reduces the size of the required cable and the amount of energy lost. When it is necessary to transmit power over very long distances, using direct current for transmission is more effective (and thus more economical) than alternating current. Since this requires spending a lot of money on AC-DC power converters, this method is only used when transmitting very large amounts of power over very long distances or for special situations, such as an undersea cable [2].

The transmission network has been and remains a major obstacle to restructuring, and this issue is significant in two respects. First, due to technical issues, the transmission network cannot be separated and made competitive like generation and distribution. Second, for proper competition among producers in selling electrical energy and its optimal supply, free, fair, and problem-free communication at any point in the power network through transmission lines is necessary. Such communication ensures increased economic efficiency of the power network, which is the ultimate goal of restructuring. The combination of competitive generation and monopolistic transmission complicates congestion management. This difficulty will increase with the growing congestion due to increased electricity trade and the slow increase in transmission capacity [3].

For various reasons such as line outages, generator outages, and changes in power exchange contracts, parts of the transmission network may face overloads. For example, with the outage of one of the network lines, several power transmission paths from production sites to consumption sites, which are established in the normal state of the network based on the law of least impedance, are opened, and the transmitted power inevitably finds its way through other transmission equipment, which is longer and results in higher transmission losses. Generator outages also cause a similar situation in the system. Another major factor in transmission congestion is the formation and conclusion of contracts between market components. In a competitive market, consumers always prefer to purchase their required power from cheaper production units. The concentration of more efficient and cheaper units in a specific area of the network leads to an increase in the power density transmitted through the lines and transmission equipment of that area, intensifying transmission congestion in that area. From the transmission perspective, any overload in the network lines that occurs during the operation of the power system under conditions such as peak load or other emergency conditions like line and generator outages is referred to as congestion. The effects of congestion in transmission networks include preventing the conclusion of new contracts, the inability to fulfill existing and new contracts, additional outages, price monopolies in some areas, damage to electrical equipment in the system, and increased electricity prices in some areas [4,5].

The Security-Constrained Unit Commitment (SCUC) problem is one of the essential tools for system operators to create an operational and real-time performance plan. Internalizing the transmission network and security constraints (e.g., N-1 criterion) can lead to various decisions in production dispatching.

However, the load calculations of this problem are fundamentally challenging due to its large size [6]. Meanwhile, reducing operational costs in the SCUC problem has always been one of the main concerns. Congestion management is one of the significant efforts to reduce operational costs in an SCUC problem. Transmission Switching (TS) is a method for managing congestion. In TS, switching occurs in congested lines. An SCUC model with TS that considers wind power plants is presented in [7].

In [8], transmission switching is used to reduce problem probabilities. The authors in [9] provide an equation that obtains EENS based on the probability of CB failures, as failures or switching related to load-side CBs lead to unserved load. In [10], transmission switching is used to address contingencies. These efforts have been effective in reducing the cost function.

One of the main challenges of this issue is the high number of switching, which reduces the lifespan of CBs, causes CB failures, and decreases system stability. In addition to improving operational costs, this research proposes a method to reduce the number of transmission switching in TS. Congestion management here is used to reduce the number of switching and improve system reliability because it prevents lines from operating at their maximum limit and avoids additional switching. The hub system idea can also be a response to addressing energy management concerns aimed at compensating for the network's excess power during overload times [11].

Such a hub system, thanks to the use of Combined Heat and Power (CHP) systems, is capable of meeting thermal and electrical needs [12]. It is worth noting that the network operator must develop its data monitoring and communication to facilitate energy transactions with the hub system [13]. Depending on the type of energy, a hub system can create an interoperability structure between energy sources to facilitate the use of intervention policies in diverse energy demands, which can lead to better energy balance adjustments [14]. Overall, this idea brings many benefits, including reducing voltage fluctuations [15,16], reducing fossil fuel consumption [17-20], and more. Recently, researchers have tried to consider this type of system from various aspects due to its efficiency in multi-energy networks [21]. Therefore, many studies have proposed a multi-hub system for reliable energy management. However, another important point to consider is that the issue of uncertain parameters in the system makes energy scheduling more complex and unreliable, raising significant fundamental concerns. In response to these challenges, researchers have proposed different approaches to manage the uncertainty model. Among these, the Monte Carlo (MC) method is recognized as the safest model to cover uncertainty issues. This method has high accuracy close to real data, which is recognized as a reference for evaluating other models [22]. While it takes a long time to find a solution in electronic scale systems, recently, the Unscented Transform (UT) method has been proposed to address concerns related to the MC approach based on its specific characteristics [23].

1-2 Motivation

The landscape of electrical power systems is undergoing a profound transformation, driven by a multitude of factors that are reshaping the way energy is produced, distributed, and consumed. As global populations continue to grow and urbanize, the demand for reliable, uninterrupted electricity supply has escalated, necessitating significant expansions and upgrades to power grid infrastructures. This demand is further compounded by the global push towards sustainability, where the integration of renewable energy sources has become a central tenet of modern energy policies. However, these changes are not without their challenges, particularly in the realm of grid management, where maintaining operational efficiency, ensuring system reliability, and managing the complexities of a modern energy landscape have become increasingly difficult.

Historically, power systems were designed with a focus on centralized, predictable power generation. Large-scale power plants, primarily fueled by coal, natural gas, nuclear energy, and hydropower, formed the backbone of these traditional grids. The predictable nature of these energy sources allowed grid operators to easily balance supply and demand, ensuring a stable and reliable flow of electricity. However, the energy paradigm is shifting towards a more decentralized and sustainable model, characterized by the growing adoption of renewable energy sources such as wind, solar, and hydrokinetic power. These sources, while environmentally beneficial, are inherently variable and less predictable, posing significant challenges to the stability and reliability of power grids.

Renewable energy sources are subject to the whims of nature; wind speeds can fluctuate, and solar power is only available during daylight hours and is affected by weather conditions. This variability introduces uncertainty into the grid, making it more challenging to ensure that supply consistently meets demand. During periods of high renewable energy generation—such as when winds are strong or solar irradiation is intense—the grid may experience oversupply, leading to congestion in transmission lines. Conversely, during periods of low renewable output, the grid may face shortages, necessitating rapid responses from other generation sources to prevent blackouts [21].

The integration of renewable energy sources into the grid, while crucial for reducing carbon emissions and achieving sustainability goals, has thus introduced new operational complexities. The traditional approaches to grid management are often insufficient to cope with the increased variability and uncertainty, highlighting the need for more sophisticated strategies that can dynamically respond to these challenges. Transmission Switching (TS) has emerged as one such strategy, offering a means to enhance the economic efficiency and operational flexibility of power systems.

TS involves the selective switching of transmission lines to optimize power flows within the grid. By dynamically reconfiguring the network based on real-time conditions, TS can reduce operational costs, alleviate congestion, and improve overall system reliability. It allows grid operators to adjust the flow of electricity across the network, ensuring that power is delivered efficiently to where it is most needed while minimizing losses and avoiding bottlenecks. The strategic use of TS can also help integrate higher levels of renewable energy by smoothing out the variability in power supply, thus maintaining grid stability.

However, the benefits of TS are accompanied by several practical challenges. The frequent switching operations required to optimize grid performance can impose significant mechanical stress on critical infrastructure components, particularly circuit breakers (CBs). Circuit breakers are designed to protect electrical circuits by interrupting power flows in the event of a fault, but their frequent operation due to TS can accelerate wear and tear, reducing their operational lifespan. This leads to higher maintenance and replacement costs, and increases the risk of equipment failures, which can result in outages and reduced grid reliability.

Moreover, the increased reliance on TS can exacerbate congestion management issues, particularly in grids with high penetration of renewable energy sources. The variability of renewable generation can cause certain transmission lines to become overloaded during peak production periods, necessitating frequent TS operations to redistribute power and prevent bottlenecks. This creates a feedback loop where increased TS operations lead to more wear on CBs, which in turn increases the likelihood of failures and further complicates grid management.

These challenges underscore the need for innovative approaches that can enhance grid flexibility and reliability while minimizing the operational stresses on physical infrastructure. Effective congestion management strategies are crucial in this regard, as they can help mitigate the need for frequent TS operations by optimizing power flows more efficiently. Additionally, the integration of advanced technologies, such as smart grid solutions and real-time monitoring systems, can provide grid operators with the tools they need to better manage the complexities introduced by renewable energy sources.

The motivation for this thesis arises from the critical need to address these challenges. By developing and exploring new strategies for integrating TS with advanced congestion management techniques, this research aims to contribute to the evolution of more resilient and efficient power systems. The proposed solutions seek to strike a balance between leveraging the benefits of TS and mitigating its drawbacks, ultimately leading to power systems that are better equipped to handle the demands of modern energy grids. As the share of renewable energy in the global energy mix continues to grow, the findings of this research will be increasingly relevant, providing practical insights and tools for grid operators to ensure the reliability, efficiency, and sustainability of the power systems of the future.

1-3 Literature Review

Sheikh Mohammadi et al. [24] presented a bi-level optimization model for coordination between transmission and distribution systems interacting with local energy markets. This paper examines the coordination between transmission systems, distribution systems, and DER aggregators interacting in a local market model. The individual objectives of each of these systems are in conflict with each other. To this end, a bi-level optimization approach is proposed, where the operational problem of the Disco and the day-ahead market clearing managed by the wholesale market operator are considered as the upper and lower-level problems, respectively. Additionally, to model the uncertainties of the output power of renewable energy sources in the Disco problem, the information gap decision theory is used. The resulting model is a nonlinear bi-level problem that is converted into a single-level linear problem by exploiting the Karush-Kuhn-Tucker conditions and duality theory.

Chabanloo et al. [25] in their paper examined the comprehensive coordination of the resilience of radial distribution networks in the presence of distributed generation sources using fault current limiters. In this paper, a coordination algorithm is proposed to adjust the time multiplier settings (TMS) and current settings of protective devices, such as overcurrent relays, reclosers, and fuses, to overcome common problems of installing DGs, such as disturbance interruptions and fuse blowing.

Saviozzi et al. [26] implemented advanced features for distribution and transmission management systems for load forecasting and modeling through artificial neural network sets. This research designed and implemented two advanced functions in a real DMS: load forecasting and load modeling. These two algorithms are built based on artificial neural networks (ANN). The good performance obtained from the real distribution network encourages the use of the two proposed techniques to deal with uncertainties, to make effective use of controllable resources, and to cope with the stochastic behavior of RES.

Das et al. [27] in their research examined security-constrained AC transmission network expansion planning (TNEP) programs. The aim of this research is to develop an efficient two-stage optimization method for security-constrained AC TNEP. Using this method, in the first stage, a DC expansion planning problem is solved, providing an initial guess as well as some very smart strategies to reduce the number of power flow solutions required for the second stage of AC transmission and reactive expansion planning. The modified artificial bee colony (MABC) algorithm is used to solve the optimization problem. The static AC TNEP results for the Garver 6 bus, IEEE 24 bus, IEEE 118 bus, and IEEE 300 test systems were obtained using the proposed method.

Gan et al. [28] presented a security-constrained planning for transmission line expansion and energy storage with high wind power penetration. In this study, the Benders decomposition algorithm is introduced to divide the joint planning problem into a main problem and two sub-problems. In the main problem, the system operates under normal conditions, so security constraints are not considered. A two-stage technique is created to generate Benders cuts from mixed-integer linear programming subsets and return to the main problem. The results show that the joint planning model with security constraints in the real power system is profitable, with a 25% saving for newly constructed transmission lines and a 5.5% reduction in total cost.

Abreu et al. [29] focused on multi-modal load forecasting for distribution systems using fuzzy-ARTMAP neural networks. This study proposes a multi-modal forecasting system considering several points of an electrical network, such as substations, transformers, and feeders, based on the adaptive resonance theory family of neural networks. The advantages of this approach include: 1) the processing time is equivalent to the processing required for global forecasting (i.e., the additional processing time is very low); and 2) fuzzy-ARTMAP neural networks converge significantly faster than improved backpropagation neural networks. The preference for ART family neural networks is due to their stability and flexibility, which should provide fast and accurate results.

Gong et al. [30] examined security in a distributable transmission network. This research proposes a fully parallel approach to achieve a quick and efficient solution while obtaining corrective actions after unforeseen events. In this study, the main optimization problem is sequentially decomposed into six main solution modules for unit commitment, optimal power flow, and transmission switching in base and contingency conditions. Additionally, each main module is decomposed by unit, period, flexible line, or contingency condition to optimize the proposed method in a fully parallel computing environment. Finally, the effectiveness and efficiency of the proposed fully parallel approach are justified using numerical cases on a high-performance computing (HPC) platform.

Khodaei and Shahidpour [31] investigated security-constrained transmission switching. In this study, transmission switching (TS) is introduced to reduce transmission violations and operational costs in security-constrained unit commitment (SCUC). The SCUC problem is decomposed into the main unit commitment (UC) problem and the TS sub-problem. The main UC problem finds the optimal hourly schedule of generating units. The TS sub-problem uses this solution for transmission switching to find the optimal dispatch of units while considering network constraints. The TS sub-problem also examines contingencies and identifies necessary changes in the main UC problem solution when contingencies cannot be mitigated under the given conditions. To propose a practical TS model, the standing phase angle difference constraint is considered, and the relevant constraints are added to the TS sub-problem. Case studies demonstrate the effectiveness of the proposed method.

Tou and Li [32] evaluated security-constrained unit commitment (SCUC) considering spatial frequency stability in low-inertia power grids. This paper first discusses the impact of inter-area oscillations on the security of the system's rate of change of frequency (RoCoF). Then, constraints related to accounting for spatial RoCoF for G-1 probabilistic stability are derived. To capture the highest spatial RoCoF during oscillations, several measurement windows are introduced. By applying these frequency-related constraints, a location-based RoCoF-constrained security unit commitment model (LRC-SCUC) is proposed. Additionally, an effective piecewise linearization (PWL) technique is used to formulate a linearization problem for RoCoF and linearize the nonlinear function representing location-based RoCoF constraints in SCUC. Case studies on the IEEE 24-bus system are conducted to demonstrate the effectiveness of the proposed LRC-SCUC model. The results show that employing virtual inertia techniques not only reduces total costs but also improves the market efficiency of the system.

Shoferpour and Karimi [33] improved the flexibility of power systems using portable batteries, transmission switching, demand response, and the flexible ramping product market in the presence of high wind power. This paper proposes a framework to enhance system flexibility by integrating emerging services for implementing day-ahead energy markets, spinning, and flexible ramping products (FRP) considering high wind power penetration. Given the uncertainty of wind power generation, this framework is presented as a stochastic network-constrained unit commitment (NCUC) problem. Services simultaneously implemented in the problem include transmission switching (TS), demand response (DR) programs, and portable battery energy storage (TBES). Additionally, two new indices are introduced to evaluate the effects of flexibility services. Another contribution of this paper is conducting comprehensive studies to compare various case studies under normal and worst-case network conditions. The IEEE 79-bus test system is used to validate the effectiveness of the proposed framework. The results of various case studies show that using emerging services together increases the flexibility of the power grid and reduces system operational costs.

Fisher et al. [34] addressed the economic dispatch problem along with transmission line switching to reduce system operating costs. In this paper, the problem of transmission line outages is formulated and solved based on the modified DC optimal transmission switching (DC-OTS) model. Given the DCOPF model used and the presence of a binary variable that determines the presence or absence of a transmission line in the network, the planning becomes a mixed-integer linear programming (MILP) problem.

Mahdavi et al. [35] studied relative transmission and expansion planning considering system reliability and line maintenance. This research examines the economic and reliability effects of line maintenance in transmission and generation planning, considering the reliability of transmission and generation systems. The goal of this paper is to improve system reliability and transmission line maintenance costs among the costs of developing transmission systems. To achieve this, the reliability of the transmission system and the reliability of the generation system are calculated using load loss criteria.

Lai et al. [36] evaluated the reliability of power systems with large-scale renewable energy sources. In this research, reliability evaluation models for wind farms and photovoltaic power plants are created and integrated with the load model for power system reliability evaluation based on sequential Monte Carlo simulation. The impact on power system reliability due to different power generation capacities, new energy access points to the power system, and complementary access methods of wind farms and photovoltaic power plants, both simultaneously and separately, is analyzed and compared in a case study calculated on the IEEE-RTS79 test system and programmed in MATLAB 7. The results demonstrate the efficiency and effectiveness of the proposed model and algorithm.

Sahoo et al. [37] investigated multi-objective planning of electrical distribution systems including sectional switches and tie lines using particle swarm optimization. This research presents a multi-objective planning method with the goals of minimizing investment and operating costs and maximizing reliability using the particle swarm optimization algorithm for distribution network planning. In this method, the number and route of feeders and the locations of sectionalizing switches are first determined, and then the optimal number and locations of tie lines are determined.

Lee et al. [38] conducted a probabilistic real-time analysis with corrective transmission switching. This paper addresses the challenges of the transmission network by developing a real-time contingency analysis (RTCA) tool based on corrective AC transmission switching (CTS) that can manage large-scale systems in a reasonable time. This tool quickly proposes several high-quality corrective switching actions for contingencies with potential violations. To reduce computational complexity, three heuristic algorithms are proposed to generate a small set of candidate switching actions. Parallel computations are implemented to speed up the solution time. Additionally, time-domain simulations are conducted to examine the dynamic stability of the proposed CTS solutions. Promising results tested on the Tennessee Valley Authority (TVA) system and real energy management system snapshots from PJM Interconnection (PJM) and the Electric Reliability Council of Texas (ERCOT) show that this tool effectively reduces post-contingency violations. It is concluded that CTS is ready for industry use for RTCA applications.

In [39], a model-based Security-Constrained Unit Commitment (SCUC) for the electricity market is presented. This paper summarizes the technical activities of the IEEE Task Force on Solving Large Scale Optimization Problems in Electricity Market and Power System Applications. Established by the IEEE Technology and Innovation Subcommittee, the Task Force initially reviewed the state-of-the-art SCUC business model, including its mathematical formulation and solution techniques for addressing electricity market clearing problems. The Task Force then explored emerging challenges in future market clearing problems and presented efforts to develop benchmark mathematical and business models.

Wu et al. [40] analyzed Security-Constrained Unit Commitment (SCUC) with uncertainties. This study reviews the latest modeling and solution methodologies for deterministic SCUC and extends these methodologies to address SCUC with uncertainties, aiming to effectively manage uncertainties and enhance the economics and security of power system operations. It includes numerical case studies demonstrating the effectiveness of the solution methodologies, which have substantial practical and computational requirements. The chapter reviews existing models and methodologies to handle uncertainties in the SCUC problem, focusing on short-term operations to improve power system economics and security. The SCUC solution provides an hourly generation schedule to meet power system demand and security margins, as well as an hourly generating reserve schedule to satisfy operating constraints during unexpected changes in power system demand. This reserve schedule ensures compliance with operating constraints in case of contingencies or unexpected demand fluctuations.

Rahmani and colleagues [41] introduced a stochastic, two-stage, reliability-focused Security Constrained Unit Commitment (SCUC) in the context of a smart grid. This study explores the integration of coordinated Plug-in Electric Vehicle (PEV) fleets and Demand Response Programs (DRPs) into power systems using the stochastic, reliability-based SCUC. The proposed SCUC aims to minimize network operation costs while identifying the optimal strategy for deploying PEVs and DRPs. Furthermore, the proposed method examines the impact of these resources on the power system's adequacy by taking into account reliability metrics. As mobile power storage devices, PEVs can supply their energy to the network when needed. In addition, DRPs can reduce power consumption during peak load periods or in emergency situations. The optimal integration of these resources could lower network operating costs and enhance security. A two-stage stochastic mixed-integer programming model is used for power system modeling in a smart grid environment. In this model, PEV fleets are depicted as virtual power plants capable of supplying electric power, while DRPs are assumed to only influence customer power consumption. The proposed approach is applied to the IEEE 6-bus and IEEE Reliability Test System (RTS) to demonstrate its effectiveness. Numerical analyses validate the effectiveness of the proposed strategy in reducing network operation costs, improving performance during emergencies, and enhancing reliability.

Bahrami and colleagues [42] put forward a model-based SCUC for AC-DC grids with generation and load uncertainty. This study delves into the SCUC problem in AC-DC grids, taking into account uncertainties in generation and load. The concept of conditional value-at-risk is introduced to manage the risk of deviations in load demand and renewable generation. The binary variables are relaxed, and an l_1-norm regularization term is added to the objective function. Convex relaxation techniques are then employed to convert the problem into a semidefinite program (SDP). An algorithm is developed based on the iterative reweighted l_1-norm approximation, which involves solving a series of SDPs. Simulations are carried out on an IEEE 30-bus test system. The results indicate that the proposed algorithm delivers a solution within a 2% gap from the global optimal solution for the test system under consideration. When compared with the multi-stage algorithm in existing literature, the proposed algorithm demonstrates a shorter running time and yields a solution with a smaller gap from the global optimal solution.

He et al., [43] examined how to enhance power grid flexibility using battery energy storage transportation (BEST) and transmission switching (TS). To improve the flexibility of the transmission system and alleviate transmission congestion, they proposed a network-constraint unit commitment (NCUC) model that takes into account BEST and TS. This model integrates a novel indicator-based BEST model and a TS model to minimize the total operating cost. The benefits of BEST mobility and TS flexibility are quantitatively assessed and compared with the traditional NCUC model. The flexibility provided by BEST and TS is evaluated quantitatively based on the reduction in the overall operating cost compared to the unit commitment (UC) and NCUC. A case study on a modified IEEE RTS-79 system is conducted to validate the effectiveness of the proposed model. The results indicate that BEST and TS synergistically enhance power grid flexibility, which is reflected in this study as an improvement in the economics of power grid operation and a reduction in renewable energy curtailment. Although BEST and TS increase transmission system losses, their application to the system can alleviate transmission congestion, making them valuable technologies for enhancing power system security.

1-4 Research Objectives

The primary objective of this research is to develop a comprehensive strategy to reduce the number of switching operations in a smart grid, thereby addressing the practical challenges associated with TS while maintaining or improving system reliability. The research aims to achieve this objective by integrating congestion management techniques with an innovative water-based electricity generation strategy that leverages hydrogen production and storage.

The specific research objectives are as follows:

1. **Optimizing Transmission Switching Operations**:

Develop a methodology to reduce the number of TS operations required to manage congestion in the grid. This includes exploring the trade-offs between the benefits of TS in reducing operational costs and the drawbacks associated with frequent switching, such as increased wear and tear on CBs and other grid components.

2. **Incorporating a Water-Power System for Grid Support**:

Propose and evaluate a grid-connected water-power system that generates hydrogen through electrolysis and uses fuel cells for power generation. This system is designed to provide additional flexibility in managing grid congestion, particularly during periods of high renewable energy generation or unexpected demand spikes.

3. **Addressing Uncertainty in Grid Operations**:

Develop an uncertainty-based Unscented Transform (UT) function to model and manage the impact of uncertain parameters, such as fluctuating renewable energy output and unpredictable load demand. This approach will help ensure that the proposed strategies remain effective under a wide range of operating conditions.

4. **Simulation and Validation**:

Implement the proposed strategies in simulation models of power systems (e.g., 6-bus and 118-bus grids) and validate their effectiveness using Bender's decomposition method in GAMS software. The simulations will test the ability of the strategies to reduce switching operations, alleviate congestion, and improve overall system reliability under different scenarios.

5. **Evaluating Economic and Reliability Impacts**:

Assess the economic benefits of the proposed strategies in terms of reduced operational costs and the extended lifespan of grid components. Additionally, evaluate the impact on system reliability, ensuring that the strategies do not compromise the grid's ability to meet demand and maintain stable operations.

Through these objectives, the research aims to contribute to the development of more efficient and reliable smart grids capable of integrating higher levels of renewable energy while minimizing the negative impacts associated with frequent TS operations. The findings from this research will provide valuable insights for grid operators and policymakers seeking to enhance the performance and sustainability of modern power systems.

Chapter 2: Security Constrained Unit Commitment (SCUC)

Chapter 2 delves deeply into the Security Constrained Unit Commitment (SCUC), a critical framework for ensuring the operational security and economic efficiency of power systems. This chapter begins by outlining the fundamental concepts of unit commitment (UC) and the additional complexities introduced when security constraints are incorporated. It discusses the optimization challenges involved in SCUC, including the need to balance cost-efficiency with reliability and compliance with regulatory standards. The chapter elaborates on the various mathematical models and algorithms used to solve the SCUC problem, with a particular focus on linear and nonlinear programming techniques. It also examines the role of transmission switching (TS) within the SCUC framework, illustrating how TS can be utilized to alleviate congestion and reduce operational costs without compromising the security of the power system. Through a detailed analysis, the chapter illustrates the integration of renewable energy sources into the SCUC problem, addressing the variability and uncertainty these sources introduce. Finally, the chapter reviews several case studies and past research efforts to highlight the effectiveness and challenges of implementing SCUC in real-world scenarios, setting the stage for the innovative approaches proposed in later chapters of the thesis.

2-1 Introduction

Looking at the history of the electricity industry in various countries around the world and examining the planning, management, and operation methods of power networks, it becomes clear that the electricity industry has been managed monopolistically and unipolarly for many years. This means that governments or the owners and operators of this industry were solely responsible for the production, transmission, and distribution of electrical energy in a geographical area. In this structure, the ownership of various sectors such as power plants, transmission networks, and even distribution networks could be in the hands of government entities or even private companies. If ownership is in the hands of the private sector, the existence of a government-affiliated entity responsible for controlling electricity prices is inevitable. Therefore, with specific regulations in place for the purchase and sale of electrical energy, power plants can determine their level of participation based on production costs. However, the experience of various countries, including the United States, indicates that the development and advancement of technology motivated the owners of production industries to combine with each other to increase efficiency and revenues. As a result, regulatory bodies faced large economic companies. For example, in the United States in 1935, more than half of the electricity production was controlled by three large power companies. In such conditions, trusting the proper performance of the price regulatory network was difficult.

In the past two decades, especially during the 1990s, extensive efforts have been made worldwide to reform the governing laws of the electricity industry, particularly in the production sector. Countries whose electric energy markets were managed unipolarly or where the responsibility for supplying electric energy was in the hands of a government-affiliated entity sought to maximize the participation of various companies in the production of this type of energy by creating a competitive market. Multiple factors have played a role in this decision-making. Among the most important factors are the technical, economic, and political issues in each country.

The advancement of high-voltage equipment technology in the 1960s and 1970s made it possible to transmit electrical energy from the place of production to distant consumption locations. Additionally, the technology for constructing thermal power plants was such that they could easily produce between 600 to 1000 megawatts. On the other hand, constructing each power plant took between four to five years, which doubled in the case of nuclear power plants. Therefore, the decision-making regarding the development of power plants was in the hands of a limited number of companies or government entities that had the financial capability to do so.

Restructuring leads to the separation of the three elements of the electricity industry, namely production, distribution, and transmission. In a restructured industry, independent control of transmission network operations facilitates a competitive market for production and direct retail access. However, independence in network operation is not possible without the existence of an independent entity such as an Independent System Operator (ISO) [44].

In general, the expansion of networks and the increasing demand for electrical energy consumption, as well as the maximum utilization of electrical energy transmission systems, have caused power systems to often operate near their security limits. Today, power system security is a serious challenge for planners and operators. Power system security can be at risk from both internal and external threats. External factors such as lightning and ecological effects, and internal factors related to the physical nature of power system operation, each pose a threat to system security. Operating the power system near limits such as thermal limits for transmission lines and transformers usually causes many problems for the system. Quick fault clearance and rapid system response during faults are important factors in maintaining power system security. By using security indices and comparing them, the power system is classified into three categories: secure, alert, or insecure. Given the increasing demand in the electricity industry, load supply and network development are of great importance. One method that can be used for this purpose is the optimal switching of transmission lines, considering the security of the transmission network, which maximizes the network's capacity utilization.

Security in power systems means the system's ability to maintain its stability during sudden disturbances, so that the minimum level of blackout remains in the system. These disturbances can include events such as short circuits on lines or buses, or the loss of a major element in the network, such as a large power plant or a heavily loaded line. A power system must be operated in such a way that after a fault occurs, it can meet the following conditions:

1. Successful transition from transient conditions without any generation loss in the system and reaching acceptable steady-state conditions after the fault.

2. In the new steady-state conditions, all system operating parameters must be within permissible limits.

Network security encompasses two broad concepts: performing the necessary tasks to satisfy the consumer with the delivered energy and the reliability of the power network. To describe these two concepts from the network perspective, certain characteristics must exist in the power supply network for a system to be evaluated as secure according to the above parameters. These characteristics include:

1. In the generation sector, the ability to produce energy to meet the total demand must be available.

2. In the transmission and distribution sectors, the necessary tools and equipment to transmit the generated power to the consumer are required.

3. From an upstream perspective, the entire generation, transmission, and distribution ensemble must be able to maintain its stability in the face of unexpected faults through good interaction with each other and continue to supply power to consumers without interruption.

Today, network security assessment is one of the important issues in the planning, design, and operation phases of power networks.

The lack of information is one of the fundamental issues in decision-making. The problem of data scarcity is prevalent in various fields such as engineering, economics, business, and more. This scarcity is also evident in issues related to the electricity market. In fact, participants in the electricity market face many uncertainties in their matters. For example, the amount of consumption load and the price of electricity are not predetermined, so sellers cannot correctly present their price offers to the market. Since all these uncertainties must be considered in the electricity market, there is a motivation to use stochastic planning for decision-making in the electricity market and the operation of the power network under various uncertainties. On the other hand, the analysis of power networks, considering the network in a steady state or assuming small changes in network elements, is called deterministic analysis. In this type of analysis, the existing uncertainties in the power network are ignored. However, ignoring uncertainties can lead to incorrect answers. Many data in an optimization problem are uncertain data that can be represented using random variables. The uncertainty of random variables is modeled using the Monte Carlo method and sampling from the distribution function of these variables and generating a scenario tree.

In this chapter, the unit commitment problem is initially presented, then the unit commitment problem considering the security constraint is analyzed and examined. Finally, an appropriate modeling of the SCUC problem will be presented.

2-2 Unit Commitment Problem

One of the most important issues in optimizing energy production resources is determining the arrangement of power plants to produce the consumption load in a short-term period, known as the unit commitment problem. Bringing power plants online is a critical issue in the operation of power networks, which, given the constraints and parameters involved, is highly complex. This problem is considered difficult due to the large volume of calculations and the vast dimensions involved.

The goal of unit commitment is to determine how power plant units participate in production based on the network's required load. The unit commitment problem plays a significant role in the economic operation of power networks. Identifying the appropriate times for power plants to enter or exit the network among possible states can result in substantial economic savings. It is assumed that the network's required load curve is predicted based on past consumption and load growth patterns, and this curve is available as one of the problem's inputs. Another important input is the characteristics of the existing power plant units in the network, including the cost function of production, minimum and maximum production based on the existing facilities in the power plant, minimum allowable on-time and off-time, startup costs, and more. The solution to this problem indicates the presence or absence of each power plant in producing the desired load and determines the share of each participating power plant.

2-3 Security-Constrained Unit Commitment (SCUC)

The goal of security-constrained unit commitment (SCUC) planning is to achieve unit commitment planning with the lowest production cost without adversely affecting the reliability of a network. The reliability of a network is interpreted as satisfying two functions: adequacy and security. Adequacy is defined as providing capacity corresponding to the network's maximum demand, and security is defined as the network's ability to plan daily and hourly to overcome changes and unexpected events [44].

The traditional unit commitment planning algorithm aims to minimize operating costs and meet prevailing constraints such as load balance, spinning reserve, ramp rates, minimum downtime, and uptime over a set of time periods. The planned unit meets the load demand and maintains bus voltages within permissible limits as much as possible.

With changes in network load, network security can only be maintained by limiting the active power flow on certain branches. These constraints restrict the production capacity of generators connected to these branches and prevent them from producing at maximum capacity. Therefore, the limitation on active power flow is the most critical constraint in ensuring security [45].

Given these points, when most units in the network are located in one area, meeting network constraints across the entire network becomes more challenging. The denser the network, the more the ISO considers transmission constraints in the SCUC formulation to minimize deviations and costs associated with normal network operation [44].

2-4 Modeling the Security-Constrained Unit Commitment (SCUC) Problem

SCUC is formulated as an optimization problem where the operating costs are minimized based on the incremental costs from the generating units [44]:

The modeling of the SCUC problem consists of two parts:

1. Objective Function: This is usually determined based on the amount of fuel consumed.

2. Planning Constraints

The modeling and equations related to each part will be presented below.

2-4-1 Objective Function

In the unit commitment problem, the objective function includes factors such as fuel cost, startup cost, and shutdown cost. Consequently, the objective function over the time horizon of the problem is as follows.

$$\min CF = min\sum_{i=1}^{NG}\sum_{t=1}^{NT}\left[F_{c,i}.\left(P_{i,t},I_{i,t}\right) + SU_{i,t} + SD_{i,t}\right] \quad (2\text{-}1)$$

In the above equation, $P_{i,t}$ represents the power output of unit i at time t, $I_{i,t}$indicates the on/off status of unit I at time t, $SU_{i,t}$ and $SD_{i,t}$ are the startup and shutdown costs of unit i at time t, respectively. $F_{c,t}$ is the fuel cost of unit i, as shown in equation (2-2).

$$F_{c,i}\left(P_{i,t}\right) = a_i + b_i.P_{i,t} + c_i.P_{i,t}^2 \quad (2\text{-}2)$$

Linearization of the Objective Function

The SCUC problem is a Mixed Integer Programming (MIP) optimization problem. Due to the considerable complexity of the current problem and to enable solving it using the GAMS optimization software, the objective function and all nonlinear constraints of the problem must be linearized and converted into a form suitable for the MIP solver in GAMS.

Given that the cost functions of the power output of various units are nonlinear and usually represented by a quadratic function, using these nonlinear functions in the optimization problem results in a nonlinear mixed-integer problem with real numbers, which is impossible to solve on a large scale. Therefore, the existing solution is to model these cost functions as piecewise linear functions, as shown in Figure 2-1.

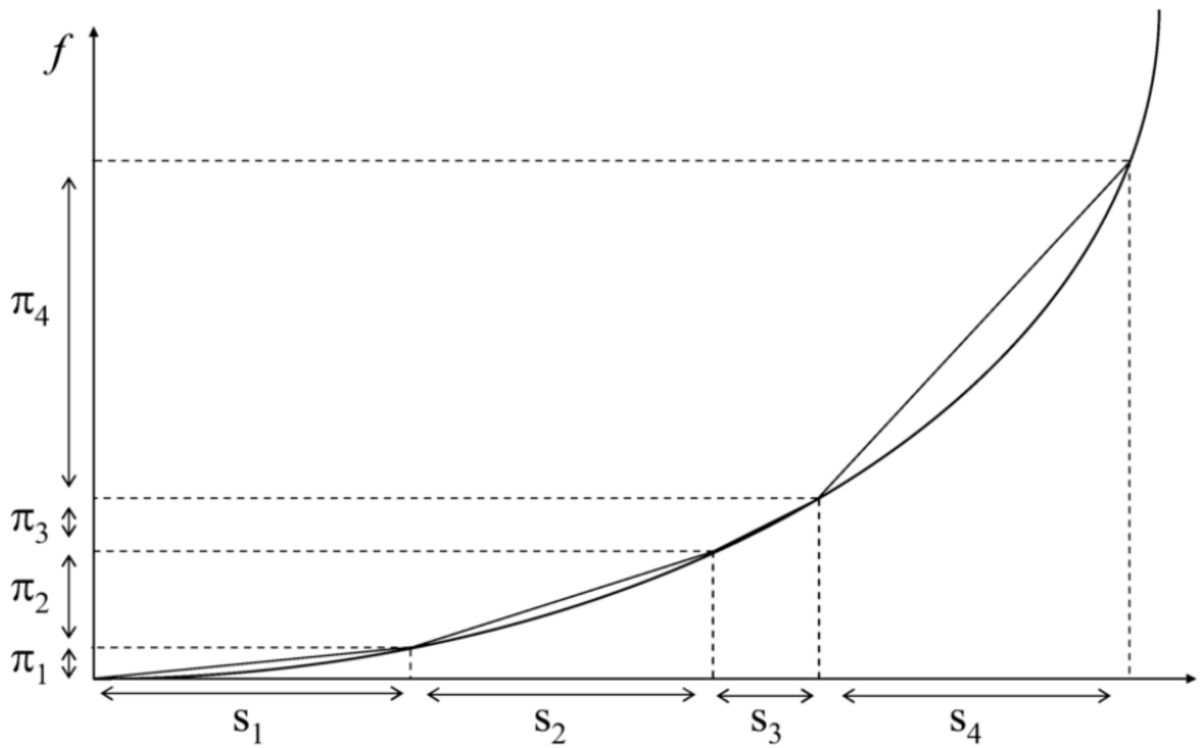

Figure 2-1: Piecewise linearized fuel cost function

The fuel cost function is usually an increasing convex quadratic function. To linearize the cost function equation, piecewise linear approximation is used. This involves dividing the cost function into (k) segments, and each segment is approximated by a line. These lines are then summed together to form an approximation of the cost function.

$$F_{c,i}\left(P_{i,t}, I_{i,t}\right) = MC_i I_{i,t} + \sum_{k=1}^{kk} \rho_{i,t}^{k} P_{i,t}^{k} \tag{2-3}$$

so that:

$$MC_i = F_{c,i}(P_i^{min}) \tag{2-4}$$

As following constraints:

$$0 \leq P_{i,t}^{k} \leq P_i^{k,max} \quad \forall k, \forall i, \forall t \tag{2-5}$$

$$P_{i,t} = P_{i,t}^{min} I_{i,t} + \sum_{k=1}^{kk} i,t\,\mathrm{k} \quad \forall i, \forall t \tag{2-6}$$

Which:

MC_i : minimum cost

$P_i^{k,max}$: The maximum linear piecewise power in the k'th part

P_i^{min} : The minimum power of the i'th unit

$P_{i,t}^k$ and $\rho_{i,t}^k$: The piecewise linearized power in the k'th part and the slope of the piecewise linearized cost in the k'th part, respectively.

In Figure 2-1, the higher the k value, the higher the accuracy of this approximation

Given the monotonic nature of the cost function, the slope of the graph is always increasing. Therefore, in the new cost function, the power output of each segment of the cost function reaches its maximum limit before the next segment starts to fill.

The startup and shutdown costs are as follows:

$$SU_{i,t} = I_{i,t}(1 - I_{i,(t-1)})C_i^{SU} \tag{2-7}$$

$$SD_{i,t} = I_{i,(t-1)}(1 - I_{i,t})C_i^{SD} \tag{2-8}$$

In the above equations, C_i^{SU} and S_i^{SD} are the startup and shutdown costs of unit i.

Given the nonlinear nature of the startup and shutdown costs of thermal units, a method presented in various references is used to address this issue.

In this method, new variables $\gamma_{i,t}$ and $\delta_{i,t}$ are defined. In this definition, $\gamma_{i,t}$ represents the on status and $\delta_{i,t}$ represents the off status. If a unit changes from off to on, then $\gamma_{i,t}$ becomes one, and if an on unit turns off, becomes one. For example, the relationship of $I_{i,t}$' with these variables is shown in a sample table [45].

Table 2-1: Relationship between Unit States and On/Off Status

Time(H)	0	1	2	3	4
$I_{i,t}$	0	1	1	0	0
$\gamma_{i,t}$	-	1	0	0	0
$\delta_{i,t}$	-	1	0	1	0
Time(H)	5	6	7	8	9
$I_{i,t}$	0	0	1	1	0
$\gamma_{i,t}$	0	0	1	0	0
$\delta_{i,t}$	0	0	0	0	1

By using the introduced binary variables, as described below, the limits of the problem will be linear. But by adding these variables, we must add the following conditions:

$$\gamma_{i,t} + \delta_{i,t} \leq 1 \quad (2\text{-}9)$$

$$\gamma_{i,t} - \delta_{i,t} \leq I_{i,t} - I_{i,(t-1)} \quad (2\text{-}10)$$

Equation (2-9) essentially shows that a unit either turns off or on at any given moment, and both events do not occur simultaneously. In equation (2-10), by considering each of the on and off statuses as zero, the relationship between the unit status and the other variable is shown.

Given the linearization performed on the objective function, the final objective function will be as shown in equation (2-11):

$$\sum_{t=1}^{NT}\sum_{i=1}^{NG}\left[MC_i I_{i,t} + \sum_{k=1}^{Nk}\rho_{ri,t}^{k} P_{i,t}^{k} + \gamma_{i,t} c_i^{SU} + \delta_{i,t} c_i^{SD}\right] \tag{2-11}$$

2-4-2 Constraints

There are many constraints in unit commitment planning considering security constraints [39]. Naturally, these constraints vary across different power networks. Increasing the number of constraints in the problem reduces the number of possible states and shrinks the problem space, but it also decreases the likelihood of finding a feasible solution, making the problem unsolvable.

Constraints are generally divided into two categories:

- Network Constraints
- Unit Constraints

Network Constraints

Network constraints are those imposed by the power network on the problem. Generally, these constraints include:

1. **Power Balance**

In each time period, the total production of the units must be able to meet the load in that time period. As a result, in the power balance equation, transmission line losses are neglected.

$$\sum_{i=1}^{NG} P_{i,t} = D_t \tag{2-12}$$

In equation (2-12), D_t represents the consumption load at time t.

2. **Spinning Reserve**

Spinning reserve refers to the difference between the total active capacity of the network and the total load. Spinning reserve must be available in the network to prevent a severe frequency drop in case one or more units are lost. In other words, if a unit is lost, there must be sufficient reserve in the units to compensate for the shortage within a specified time. Spinning reserve is allocated according to specific rules, which determine the amount of spinning reserve for different units. To determine the amount of spinning reserve, both probabilistic and deterministic methods are used.

In the deterministic method, the reserve can be considered as a percentage of the total network load, equal to the largest generating unit, or arbitrarily for an hour, which is formulated as follows.

$$\sum_{i=1}^{NG} P_i^{max} I_{i,t} - D_t \geq R_t \quad \forall t \tag{2-13}$$

where R_t is the required reserve at hour t.

3. Transmission Line Flow Limitations

In a network, for all buses, the sum of the power entering each bus must be zero. This means that the sum of the load power, the generated power, and the power entering from the connected transmission lines to the bus is zero. This constraint, which essentially represents the network structure, is expressed for a network with NB buses and NL lines as follows:

$$\sum_{i=1}^{NG_b} P_{i,t} - P_{bt}^D = \sum_{l=1}^{NL_b} PL_{lt} \quad \forall b, \forall t \tag{2-14}$$

$$PL_{l,t} = \frac{1}{X}(\theta_{ls} - \theta_{lr}) \quad \forall b, \forall t \tag{2-15}$$

Equation (2-15) represents the DC power flow equations. According to the power flow convention, one bus is arbitrarily chosen as the reference bus, and its voltage angle is set to zero. Therefore, the voltage angle difference for this bus is considered zero. In DC power flow, it is assumed that the voltage magnitude at all buses is the same, the line resistances are negligible, and the voltage angle differences between buses are sufficiently small. Given these simplifying assumptions, the power flow through line (l) at hour (t) is modeled in equation (2-15).

The transmission line flow limit constraint is as follows:

$$-PL_l^{max} \leq PL_{l,t} \leq PL_l^{max} \quad \forall l, \forall t \tag{2-16}$$

In the above constraints, $PL_{l,t}$ is the power flow through line l at time t, P_{bt}^D is the load demand at bus b at time t, and PL_l^{max} is the maximum power flow through line l.

Unit Constraints

Unit constraints are those related to the units themselves and are applied to the problem.

1. **Maximum Ramp-Up and Ramp-Down Rates**

The process of bringing a unit online involves starting it up, increasing its speed, and synchronizing it with the network. Since power plant units are electromechanical systems, inertia is an integral part of them. Therefore, the power output of a unit, no matter how small, cannot be changed suddenly. This limitation is known as the ramp rate constraint, which indicates the maximum allowable change in the power output of each unit.

$$P_{i,t} - P_{i,(t-1)} \leq \left(1 - \gamma_{i,t}\right)RU_i + \gamma_{i,t}p_i^{min} \quad \forall i, \forall t \tag{2-17}$$

$$P_{i,(t-1)} - P_{i,t} \leq \left(1 - \delta_{i,t}\right)RD_i + \delta_{i,t}p_i^{ini} \tag{2-18}$$

In the above equations, RU_i represents the maximum ramp-up rate and RD_i represents the maximum ramp-down rate of unit i. For (t-1), the value of $P_{i,0}$ in the above equations is equal to the initial power output of the units, denoted as p_i^{ini}.

2. **Maximum and Minimum Production Limits**

In all time periods, the power output of the units must not exceed their permissible limits. In other words, equation (2-19) must be satisfied.

$$P_i^{min} I_{i,t} \leq P_{i,t} \leq P_i^{max} I_{i,t} \tag{2-19}$$

where P_l^{max} is the maximum power output and P_l^{min} is the minimum power output of unit i.

3. **Minimum On and Off Times**

Each unit, after being brought online, must remain in operation for a minimum duration (T_i^{on}). This constraint represents the minimum on-time. The unit cannot be taken offline again before this time has elapsed.

Similarly, if a unit is turned off, it must remain off for at least T_i^{off}, which is referred to as the minimum thermal off-time.

The formulation of the above constraints is as follows:

$$\sum_{\tau=1}^{t=1} I_{i,\tau} \min\left(T_i^{on} - t + 1, T_i^{ini}\right) I_i^{ini} \geq T_i^{on} \delta_{i,t} \quad \forall i, t \in \{1,2, \dots, T_i^{on}\} \tag{2-20}$$

$$\sum_{\tau=t-T_i^{on}}^{t=1} I_{i,\tau} \geq T_i^{on} \delta_{i,t} \quad \forall i, t \in \{T_i^{on} + 1, \dots, NT\} \tag{2-21}$$

$$\sum_{\tau=1}^{t=1} (1 - I_{i,\tau}) + \min\left(T_i^{off} - t + 1, T_i^{ini}\right)(1 - T_i^{ini}) \geq T_i^{off} \gamma_{i,t} \quad \forall i, t \in \left\{1,2, \dots, T_i^{off}\right\} \tag{2-22}$$

$$\sum_{\tau=t-T_i^{off}}^{t=1} (1 - I_{i,\tau}) \geq T_i^{off} \gamma_{i,t} \quad \forall i, t \in \left\{T_i^{off} + 1, \dots, NT\right\} \tag{2-23}$$

In the above formulas, T_i^{ini} indicates the duration of being on or off and I_i^{ini} is the state of the i-th unit at the first moment.

2-5 Locational Marginal Pricing (LMP)

Locational Marginal Pricing (LMP) is a method used in wholesale electricity markets to determine the cost of electricity at specific points on the power grid. It reflects the cost of supplying electricity at a particular location, considering the cost of generation, transmission losses, and grid congestion. This pricing mechanism ensures that the price of electricity accurately represents its value at different locations, taking into account the load, generation patterns, and the physical constraints of the transmission system. LMP consists of three main components: the energy component, the congestion component, and the losses component[2]. The energy component represents the cost of generating electricity, the congestion component accounts for the cost associated with transmission constraints that prevent the cheapest electricity from reaching all locations, and the losses component covers the energy lost during transmission. These components are calculated every five minutes to provide real-time pricing that reflects the current state of the grid[2]. This dynamic pricing helps manage the grid efficiently by signaling where and when to generate or consume electricity. The use of LMP promotes economic efficiency by encouraging electricity generation and consumption in locations where it is most cost-effective[3]. It also enhances grid reliability by providing financial incentives to alleviate congestion and reduce transmission losses. By reflecting the true cost of delivering electricity, LMP aids in making informed decisions about infrastructure investments and operational strategies. This pricing mechanism is widely used by Independent System Operators (ISOs) in various regions, including PJM, ISO New England, and MISO, to manage and optimize the electricity market.

LMP is the marginal cost of supplying the next increment of electrical energy at a specific bus, considering the marginal cost of generation and the physical characteristics of the transmission network. LMP is defined as follows:

LMP = marginal production cost + congestion cost + marginal loss cost

Mathematically, LMP at each node in the network is the dual variable (sometimes referred to as the shadow price) for the equality constraint at that node (the sum of injections and withdrawals equals zero). LMP represents the additional cost of supplying one more megawatt at a specific node. Using LMP, buyers and sellers experience the true cost of delivering energy to points within the transmission network. Differences in LMPs occur when lines are constrained. If transmission line constraints are not considered in the optimization problem, or if it is assumed that the transmission limits are very large, LMPs will be the same for all buses, which is the marginal cost of the most expensive generating unit in operation. In this case, no congestion cost is applied. However, if a line is constrained, LMPs will vary from bus to bus or region to region, potentially leading to congestion costs [44].

Chapter 3: Congestion Management

Chapter 3 explores the complexities and methodologies of congestion management within power systems, crucial for maintaining reliability and efficiency as the grid adapts to increasing inputs from variable renewable energy sources. This chapter provides a detailed analysis of the causes and impacts of congestion in transmission networks, particularly under high renewable penetration scenarios that introduce greater variability and unpredictability into the system. The chapter discusses traditional and modern approaches to congestion management, including reconfiguration, demand response, and the use of advanced technologies like Flexible AC Transmission Systems (FACTS). It thoroughly examines different strategies for managing congestion, such as locational marginal pricing (LMP) and capacity allocation, which help in optimizing power flows and minimizing costs while ensuring network safety and reliability. The chapter also delves into the integration of Transmission Switching (TS) as a dynamic tool for congestion management, showcasing its ability to enhance grid flexibility by altering physical network topology in response to real-time demand and supply conditions. Through simulations and case study evaluations, the chapter demonstrates the potential improvements in grid performance through the application of strategic TS, particularly in systems heavily laden with intermittent renewable energy resources. This analysis sets a robust foundation for the innovative congestion management techniques introduced in the thesis, aimed at addressing both the operational challenges and the economic impacts of grid congestion.

3-1 Introduction to Congestion

The restructuring of distribution networks updates the network structure based on location and different load levels. In network reconfiguration, simply by opening and closing existing switches and changing the network graph structure, losses, voltage drops, and load and current imbalances can be improved. In the reconfiguration problem, the objective function is first determined, which can be network losses, total voltage deviation of buses, inverse average voltage of buses, load imbalance, current imbalance of lines, and network security. Then, considering the network constraints, such as the minimum and maximum voltage limits of buses and the maximum current passing through each line, the appropriate switches to achieve the objective function are selected. The first step in solving the reconfiguration problem is to represent the network structure with a comprehensive code for the software. To represent the (N) switch states in a distribution feeder, a string of (N) bits can be used. For each switch, 1 indicates the closed state and 0 indicates the open state. The optimal code for the network is obtained from the minimum value of the objective function. For a distribution network with (N) switches, there are (N^2) possible codes, but not all of them are feasible. One advantage of the reconfiguration problem is that its undesirable responses are predictable, allowing the search space to be reduced [46].

Key principles in the discussion of restructuring include:

- Maintaining the radial structure of the network
- Ensuring electricity reaches all loads and consumers
- Adhering to the voltage limits of buses and current limits of lines without exceeding their permissible ranges

Generally, most methods for reducing losses in power networks require the installation and commissioning of new equipment in the network. Installing this new equipment not only imposes financial burdens on companies (which sometimes may outweigh the potential benefits), but it may also introduce new faults in the network, disrupting service to customers. The network reconfiguration method does not require the installation and commissioning of new equipment in the network and reduces losses simply and cost-effectively using the existing equipment and switches [47].

The transmission network has been and remains a fundamental challenge to restructuring, and this issue is significant for two reasons. First, due to technical issues, the transmission network cannot be separated and made competitive like generation or distribution. Second, proper competition among producers in selling electrical energy and its optimal delivery requires free, fair, and problem-free communication at any point in the power network through transmission lines. Such communication ensures increased economic efficiency of the power network, which is the ultimate goal of restructuring. The combination of the competitive generation sector and the monopolistic transmission sector complicates congestion management. This difficulty will increase with the growing congestion due to increased electricity trade and the slow growth of transmission capacity [48].

For various reasons, such as line outages, generator outages, and changes in power exchange contracts, parts of the transmission network may become overloaded. For example, with the outage of one of the network lines, several power transfer paths from production sites to consumption sites, which were established based on the least impedance path rule in the normal network state, will be disrupted. The transferred power will inevitably find its way through other transmission equipment, resulting in longer paths and higher transmission losses. Generator outages also cause a similar situation in the system. Another fundamental factor in transmission congestion is the formation and conclusion of contracts between market participants. In a competitive market, consumers always prefer to purchase their required power from cheaper production units. The concentration of more efficient and cheaper units in a specific area of the network leads to increased power density in the lines and transmission equipment of that area, intensifying transmission congestion. From a transmission perspective, any overload in network lines during power system operation under conditions such as peak load or other emergency conditions like line and generator outages is referred to as congestion [2, 3]. The effects of congestion in transmission networks include:

- Preventing the conclusion of new contracts
- Inability to fulfill existing and new contracts
- Additional outages
- Price monopolies in certain areas
- Damage to electrical equipment in the system
- Increased electricity prices in certain areas [48].

3-1-1 Characteristics and Features of the Electricity Market

The development and creation of the electricity market are based on the assumption that electrical energy can be considered a commodity. However, there are fundamental differences between electrical energy and other commodities, which have a profound impact on the organization and regulations of the electricity market. The most significant difference is that electrical energy is inseparably connected to a physical system (the power system) that operates faster than any market. In this physical system, supply and demand must be balanced instantaneously. If there is an imbalance between supply and demand, the power system can face catastrophic consequences [49]. Such an event is intolerable because it would leave not only commercial transactions but also entire regions or countries without power for a considerable time. Recovering a completely collapsed power system takes at least 24 hours. Therefore, the consequences of such an incident are extensive, and no government would allow market mechanisms to cause such widespread disruption. The demand for electrical energy exhibits predictable daily and weekly cyclical variations. During some hours, electricity consumption is low, and only high-efficiency generating units remain online, while during other hours, consumption is high, and less efficient units are also brought online. Additionally, electrical energy must be produced at the exact moment it is consumed. Given the variability of marginal production costs at different hours, it is expected that prices will change with the load. Such rapid changes in the prices and costs of commodities are unusual [50].

3-1-2 Entities Related to the Electricity Market

Some of the entities active in the market include:

1. **Consumers**

These are the end-users of electrical energy. They can obtain their required electricity from the real-time market, futures markets, or retail companies. Consumers can be residential, commercial, industrial, etc., and naturally, the consumption profiles of these groups differ.

2. **Retail Companies**

Retail companies provide electrical energy to consumers who, according to market regulations, cannot participate in the wholesale electricity market. These companies may also have their own generation facilities but primarily meet their consumers' energy needs by purchasing from the spot market or futures market [51].

3. **Market Operator**

The market operator manages the electricity market. This entity is responsible for legislating and overseeing the proper functioning of the market, ensuring legal and social health, and drafting executive and operational regulations.

4. **Independent System Operator (ISO)**

The ISO is responsible for controlling the network. Its duties include transmission tariffs, system security, maintenance, and more. The ISO operates independently of market participants. Market settlements are handled by the market operator, while system security is maintained by the ISO [52].

5. **Generation Companies (GENCOs)**

These companies are responsible for the operation and maintenance of generating units. They may own power plants or only operate them. The relationship between generation companies and consumers is through short-term markets and long-term contracts [53].

6. **Transmission Companies (TRANSCOs)**

Transmission companies transport electrical energy between generation companies and distribution companies at high voltage levels. The use of transmission facilities is controlled by the ISO, but ownership remains with the transmission company. Construction, ownership, maintenance, and repair in each area are the responsibilities of a transmission company.

7. **Distribution Companies**

Distribution companies use their equipment and facilities to distribute electrical energy within a specific geographical area. They are responsible for the creation, maintenance, operation, and reliability of the distribution network. Consumers typically contract with distribution companies to supply their electrical energy [53].

3-1-3 Market Participants in the Electricity Market

1. **Aggregators**

An aggregator is an entity or company that combines customers into a single buying group. This group purchases electrical power and other services in bulk at a lower price. An aggregator may act as a broker between customers and retailers. When an aggregator buys power and resells it to customers, it acts as a retailer and must first qualify as a retailer [51].

2. **Brokers**

A broker of electrical energy services is an entity or company that acts as an intermediary in the market where these services are priced, purchased, and traded. A broker does not directly participate in existing exchanges and does not produce, purchase, or sell electrical energy but facilitates transactions between buyers and sellers. If a broker is interested in acquiring a stake in electrical energy exchanges, it is considered a producer or marketer. A broker may act as an intermediary between GENCOs or a group of production companies and marketers.

3. **Marketers**

A marketer is an entity or company that lacks production facilities and purchases electrical power to resell it. A marketer operates as a wholesaler and acquires transmission services. A marketer may engage in both marketing and retail activities [53].

4. **Customers**

Customers are the end-users of electricity. Small customers connect to the distribution system with specific facilities, while large customers connect to the transmission system. In a vertically integrated structure, consumers receive electrical energy from a company authorized to provide services in that area. In a restructured environment, customers are no longer required to purchase services from local companies. They have direct access to producers and can contract with other power suppliers, purchasing a range of services (with the desired level of reliability) that best meet their needs [50].

3-2 Congestion Management

Any activity undertaken to resolve congestion issues is referred to as congestion management. Managing transmission line congestion is one of the key responsibilities of the Independent System Operator (ISO). It is a process that ensures the use of the transmission network within permissible operational limits.

In restructured power systems, the primary goal of congestion management is to develop a set of rules that ensure sufficient control over producers and consumers to maintain an acceptable level of power system safety and reliability while achieving the highest economic efficiency during transmission network constraints. These rules must have three characteristics: decisiveness, fairness, and transparency. Decisive rules prevent opportunistic exploitation during network congestion by some profit-seeking entities, thereby preserving market efficiency. Fairness and transparency are essential for the general satisfaction of transmission network users [55].

The importance of transmission line congestion is such that entities like ETSOY in Europe and RTI in the United States have been established to address transmission network congestion issues.

3-3 Methods for Addressing Congestion

Generally, three methods for congestion management have been used depending on the restructuring form in different countries: a) Using optimal load sector programs centrally and controlling congestion by the network operator. b) Using price signals based on pre-established markets to prevent congestion, which may also involve central congestion control and adjustments. c) Accepting or rejecting power exchanges to alleviate congestion [56-58].

Two main mechanisms are generally used to address transmission network congestion:

- Preventive methods
- Corrective methods

In preventive methods, congestion can be avoided using solutions like reserving, acquiring ownership rights, and congestion pricing.

In corrective methods, congestion can be improved and corrected by applying controls such as phase shifters, tap-changing transformers, reactive power control, redispatching contracts, violating some contracts, and canceling certain loads.

From a cost perspective, congestion management methods include:

- Cost-free methods (line outage, using FACTS devices, and installing active and reactive power sources)
- Costly methods (redispatching generators contrary to market agreements, shedding permissible loads, etc.)

From a temporal perspective, congestion management methods can be categorized as:

- Short-term congestion management
- Medium-term congestion management
- Long-term congestion management

Short-term methods are generally used in short-term exchange markets and are essentially corrective methods applied after congestion occurs in the network.

Medium-term methods are mainly preventive methods, with the most famous being monthly markets for selling rights in various forms.

Long-term methods are based on development, transmission, and generation planning with a multi-year horizon.

In another classification, congestion management methods can be divided into two sections:

- Market-based congestion management methods (redispatching, counter-trading, etc.)
- Market-independent congestion management methods (based on contract type and priority methods, etc.)

Different congestion management methods are implemented through instructions from the system operator to various electricity market participants to readjust contracts, shift production, and even shed loads in critical situations. These actions are costly and disrupt market conditions, leading to increased electricity prices. In some cases, free and low-cost methods are available to alleviate congestion. For example, the operation of various control devices such as tap-changing transformers, phase shifters, and other FACTS devices can play a role in reducing congestion [58].

Transmission network limitations due to environmental issues, right-of-way, and costs are fundamental problems in power systems. Additionally, certain generation patterns impose high losses due to heavy currents, threatening system stability and reliability, thus excluding specific generation patterns from competition. This creates a motivation to employ tools like FACTS devices to better utilize transmission system capacities. By adjusting the control parameters of these devices, power distribution in transmission lines can be controlled to achieve various objectives [59].

3-3-1 Load Flow

Among the challenges faced by the power industry for operators are high network losses, especially in distribution networks, uneven load curves, severe peak loads, environmental issues from burning fossil fuels, and the waste of primary resources and capital due to high and unmanaged consumption. In the past, high consumption was addressed by constructing power plants, mainly thermal, which incurred high costs and caused environmental pollution. An alternative solution in developed countries is known as negative power. This concept suggests that to meet the load, especially the part that only enters the circuit for a short period each year and imposes high costs on the system, there is no need to build and operate expensive power plants. Instead, demand-side management programs can reduce the very costly part of the load, saving costs and reducing environmental pollution.

The restructuring of the power industry has intensified competition, transforming many aspects of the industry. In this changing scenario, the scarcity of renewable resources, rising production costs, air pollution, and most importantly, the continuous increase in electricity demand have made the need for optimal economic dispatch more critical. Economic operation of a power system is crucial for the return on investment and fuel savings, with power companies striving to maximize efficiency and reduce costs. Economic dispatch determines the output power of each power plant and each generating unit within a plant for any predicted load condition, minimizing the total fuel cost required to meet the system load [60].

In other words, with rising fuel costs and power network reconstruction, economic dispatch has become increasingly important. Economic dispatch is a nonlinear optimization problem where the optimal generation of each unit is determined to minimize total costs. This problem is subject to many constraints, including equality constraints for power balance and inequality constraints for output power and rate of change of output power. From the system operators' perspective, the objective is to minimize the fuel cost function while satisfying various constraints such as generation unit limits, prohibited zones, steam valve effects, and transmission losses. Adding a sinusoidal term to the quadratic cost function and considering the steam valve effect results in a non-smooth cost function for generating units. New generators, considering the steam valve effect, will have prohibited zones, making the search space non-convex and discontinuous. Considering different types of fuel units further complicates the objective function. With these constraints, the number of local minima increases significantly, requiring highly accurate optimization methods to solve the problem. Proper scheduling of existing generating units can lead to significant savings in production costs [61].

Considering all physical and operational constraints and environmental challenges, classical economic dispatch becomes a multi-objective problem that simultaneously minimizes fuel cost and emissions, clearly a nonlinear and non-convex optimization problem with a discontinuous domain [62].

As a result, economic dispatch in the electricity market is one of the key factors in controlling the stable and orderly operation of this market. To ensure fair competition and real-time economic distribution by various power generation companies, establishing principles and power distribution programs is essential. The study of economic dispatch mainly focuses on the following two aspects [63]:

1. **Economic Dispatch through Unit Start-Stop:** This involves traditional solutions such as unit prioritization, dynamic programming, integer programming, etc. In recent years, some new methods like genetic algorithms have been used for the unit start problem.

2. **Economic Dispatch through Daily Power Generation Scheduling in the Market:** Given the current conditions of the electricity market, economic dispatch not only requires the lowest cost of electricity production but also includes various aspects such as the cost of purchasing electricity, greenhouse gas emissions, active power losses [54], etc. Therefore, the daily energy production scheduling model in the current market conditions should be a multi-objective planning model [63].

In today's world and in production centers, economic dispatch has been the most important goal of energy distribution and plays a significant role in the economic performance of the power system. In the industry, when generators with different loads are interconnected, their production capacity becomes much larger than the loads. Therefore, assigning loads to generators can be diversified, and since reducing electricity production costs is important, economic load distribution is considered. Fuel costs account for most of the production costs in power plants. Other costs, such as labor, maintenance, and economic factors, are secondary. As a result, energy distribution specialists must control power plant production to reduce costs, making economic dispatch an optimization problem that includes an objective function and constraints [64].

The economic dispatch problem is essentially an optimization problem with an objective function and constraints. The objective function in the economic dispatch problem is the production cost function of power plant units, considered as a quadratic function derived from the sum of the cost functions of all power plant units. However, it is not just a quadratic function but a non-convex curve. The second part defines the constraints of the optimization problem. In the economic dispatch problem, there are many constraints, including the balance of production and consumption in the system, prohibited zones, production limits, and the increasing and decreasing rates of generators [65,66].

Importance of Economic Dispatch

As the electricity industry steps into increasingly fierce competition, the importance and necessity of load dispatch software to maximize the use of the transmission system and power plants are becoming more apparent. On the other hand, traditional fossil energy consumption has led to rapid economic progress and effects such as global warming and environmental degradation. Therefore, considering the possibility of selecting various objective functions for system optimization and applying multiple and different constraints on system components and operating conditions, there are various applications for load dispatch, which are briefly presented below, highlighting the importance of studying and examining economic dispatch [67]:

- Determining the generation capacity of generators to optimize production costs and the final price of produced electricity, considering system constraints and limitations.
- Economic dispatch plays a significant role in calculating the final subscription fees and determining tariffs.
- Economic load dispatch is a method that determines the most efficient and lowest operating cost of a power system by appropriately distributing energy production resources to meet the system load.
- Load dispatch can play a role in reducing costs and losses, thereby reducing pollution.

Simultaneous Development Planning for Load Dispatch

The total practical capacity of installed power plants in an electricity network must equal the total power required by all consumers, plus total power losses, internal power consumption of substations and power plants, and a percentage as spinning reserve within the study period. If the total practical capacity of installed power plants is less than the required amount, a combination of new power plants with minimum cost must be added to the network. In development planning, the goal is to determine the type, capacity, location, and timing of new power plant units to maintain the balance of production and consumption in the network at the lowest possible cost. To determine the location of power plants, the load distribution in the study area must be considered from both economic and technical aspects, along with environmental constraints for power plant construction, transmission line constraints for power transfer, and fuel supply constraints. Due to the large dimensions of the generation system development planning problem, it is usually divided into two separate issues.

In the first issue, known as generation system development planning in the network, the location of power plants is disregarded, and only the type, timing, and capacity of power plants are determined. The second issue assumes the first issue is solved, and thus the type, timing, and capacity of power plants are known. Now, considering factors such as geographical load distribution, environmental and fuel supply constraints, transmission network structure, etc., the power plant location issue is addressed [68].

Even for identical power plants, environmental conditions such as water resources, land prices, and fuel supply costs result in different development and operational costs. On the other hand, the distance of power plants from consumption centers may increase transmission line development costs, or the long distance from fuel centers may increase production costs. Considering these factors, it cannot be said that generation development planning in a single-bus network is optimal, but due to the difficulty of planning with simultaneous consideration of power plant locations, the power plant location issue is usually examined separately. The development and economic operation costs of power plants in a power system depend on the location of power plants and the load distribution in the network [69].

3-3-2 FACTS Devices

FACTS devices like SVC and STATCOM are suitable reactive power compensators in the network used to improve the reactive power level. Since the voltage parameter is significantly influenced by the reactive power level in the network, SVC and STATCOM can be used to regulate reactive power and adjust the output voltage of wind turbines and wind farms against environmental changes such as wind speed variations. Static voltage instability caused by reactive power imbalance in the network can be countered by properly adjusting the capacity of devices like SVC and STATCOM and optimally placing them in the power system. Another function of FACTS devices in systems with high wind turbine penetration is minimizing and reducing power losses in the network caused by the presence of wind turbines and their power fluctuations. Optimal placement and capacity adjustment of FACTS devices reduce power losses in the network and increase network efficiency. However, since FACTS devices like SVC and STATCOM are expensive, their capacity in the network must be accurately determined to ensure static voltage stability. Overcapacity in the network would result in economic losses. Therefore, this thesis studies the economic evaluation of using SVC and STATCOM to improve static voltage stability and reduce power losses in the network [70,71].

Two different generations of FACTS devices are used in power systems. The first generation, or the older generation, is based on thyristor switching, while the second generation, or the newer generation, is based on Voltage Source Converter (VSC) technology. Both generations provide the same services. The main difference between these two generations is that VSC-based technologies are faster and control a wider range. Figure (3-1) shows the classification of different types of FACTS devices [72].

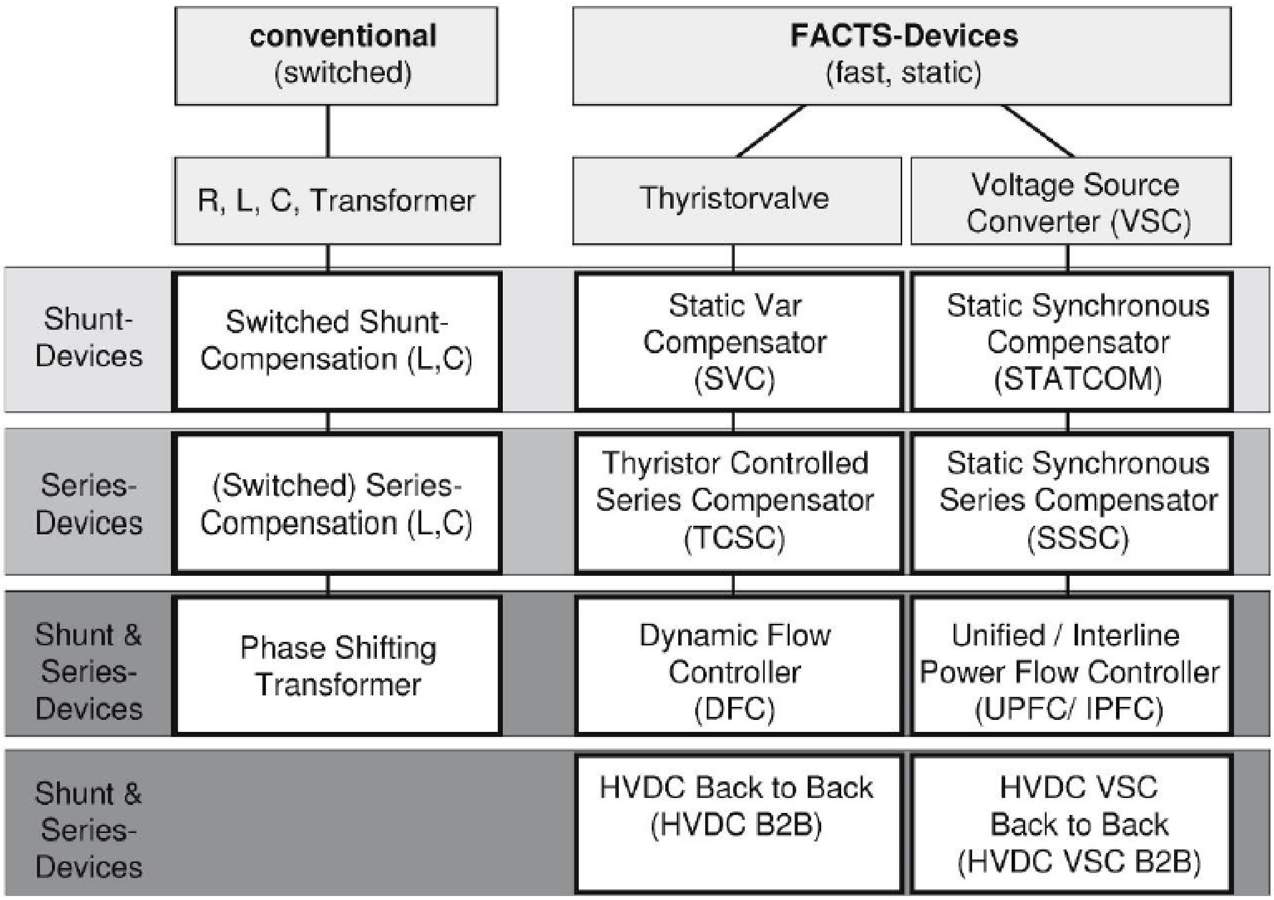

Figure 3-1: Classification of different types of FACTS tools

Static VAR Compensator (SVC)

The Static VAR Compensator (SVC) is the first generation of FACTS devices that can control the voltage at the required bus and thus improve the system voltage profile. The main function of the SVC is to maintain the voltage at a steady value at a specific bus by compensating reactive power, which is done by changing the thyristor firing angle. Additionally, the SVC can help damp power oscillations, improve transient stability, and reduce system losses by optimally controlling reactive power.

Static Synchronous Compensator (STATCOM)

The Static Synchronous Compensator (STATCOM), based on Voltage Source Converter (VSC) technology, belongs to the second generation of FACTS devices and can improve power quality against voltage sags and flicker. The biggest advantage of STATCOM compared to SVC is its ability to maintain the reactive output current at its nominal value over a wide range of voltages, whereas the SVC's capability to limit current is reduced when the voltage drops [73].

Static VAR Compensator (SVC)

Since the 1970s, Static VAR Compensators have had the largest share of FACTS devices. These devices include traditional thyristors, which can control bus voltage faster than mechanical switches and have more complex control compared to mechanical switches. SVCs are connected in parallel to the bus and can absorb or generate reactive power. By having controlled capacitive or inductive current at their output, they can stabilize the voltage at the connected bus.

Three common structures of SVCs are shown below, including Thyristor Controlled Reactor (TCR), Thyristor Switched Reactor (TSR), and Thyristor Switched Capacitor (TSC), or a combination of these three structures in parallel. TCR is used for continuous control of the firing angle to increase or decrease inductive current, while TSR, where the reactor is connected to the switch, cannot continuously control the firing angle. SVCs are usually connected to high-voltage power transmission lines. Therefore, SVCs must have a modular design. The figure below shows the types of SVC structures along with their voltage-current characteristics [74].

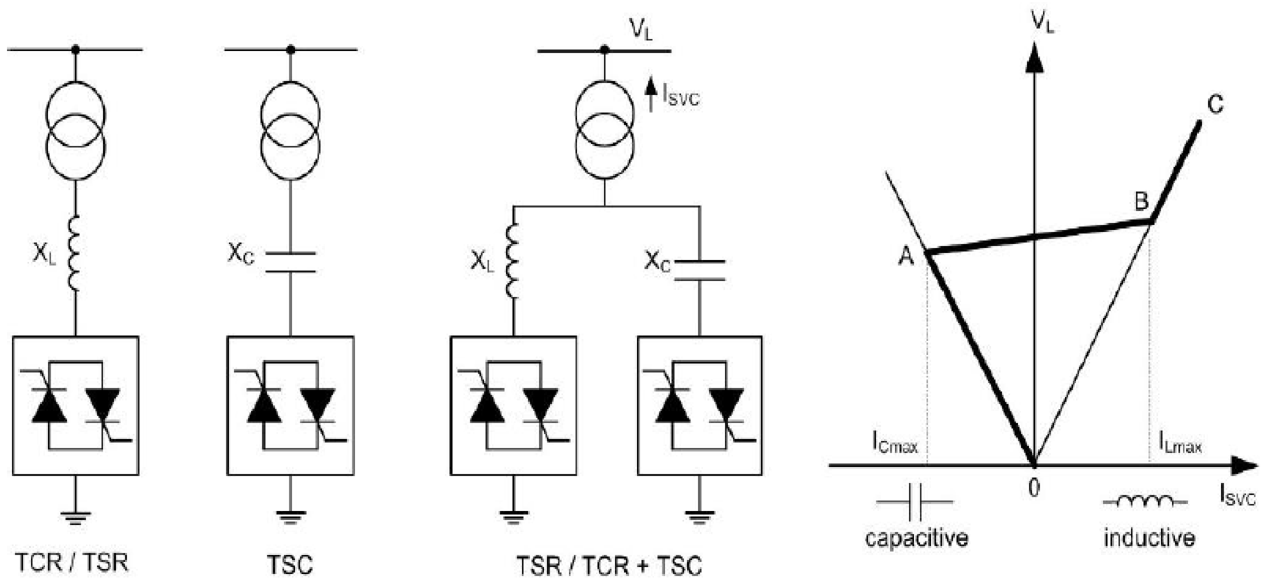

Figure 3-2: Basic structures of SVC and its characteristic curve

Static synchronous compensator (STATCOM)

Static synchronous compensator (STATCOM) is actually a solid-state synchronous condenser connected in parallel to the power grid. The output current of this controller is adapted to control the range of node voltage or reactive power injected into the bus. STATCOM is a relatively new reactive power compensator based on voltage source converters (VSC). The characteristic of STATCOM is similar to synchronous condenser, but its performance and output is better than synchronous condenser. Because STATCOM is an electrical equipment and has no moment of inertia or rotating part. The advantage of this technology is lower investment cost, lower maintenance cost and better dynamics.

The circuit structure of STATCOM is shown in the figure below. This equipment includes a voltage source converter and a capacitor on the DC side of the converter and a transformer connected in parallel. The voltage source converter is usually made of switches such as thyristor or GTO or IGBT [75].

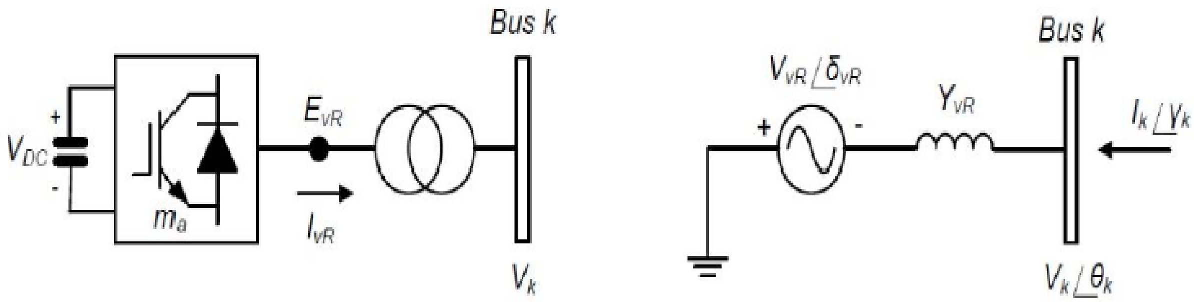

Figure 3-3: STATCOM circuit structure

STATCOM actually acts like a synchronous voltage source whose output voltage can be controlled in a desired way. Assume that no active power is transferred between the STATCOM and the network (lossless operation), as a result, the controller voltage is in phase with the network voltage. In this case, if the voltage range of the compensator is smaller than the connection point voltage, the current will flow from the network to the STATCOM. In this case, reactive power will be consumed. These principles of STATCOM operation are shown in the figure below.

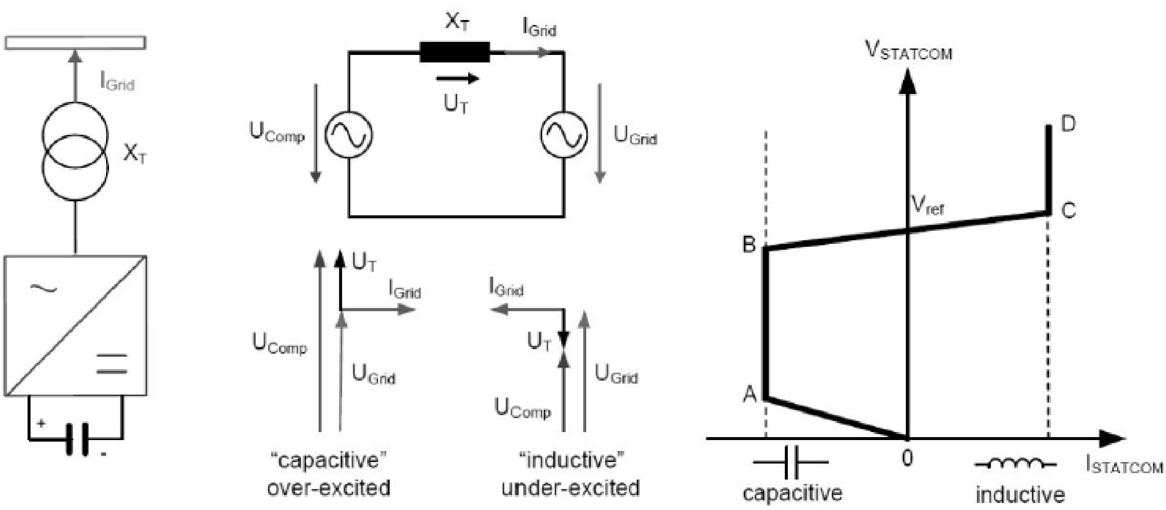

Figure 3-4: Principles of STATCOM operation

When the STATCOM injects reactive current into the network, it increases the network voltage. Also, when the STATCOM absorbs the reactive current, it reduces the network voltage. In the first case, this controller acts like an over-excited generator or capacitor, and in the second case, it acts like an under-excited generator or inductor.

Differences between SVC and STATCOM

The difference between SVC and STATCOM is in the way they work. STATCOM behaves like a controllable voltage source while SVC acts like a dynamically controllable parallel reactance. STATCOM, unlike SVC, can provide the possibility of feeding the network with the maximum available reactive current even at low voltage levels. SVC is very sensitive to the condition of harmonic resonances with transmission lines, while this problem does not exist for STATCOM.

The Table 3-1 compares the technical specifications of SVC and STATCOM.

Table 3-1: Comparison of SVC and STATCOM technical specifications

STATCOM	SVC		
	TSR(+TCR)	TCR	The name of the parameter
Excellent	Good	Good	Compensation accuracy
Continuous	(very good with TCR)	Continuous	Control type
Very Fast	discrete	quick	Response time
(less than half a cycle)	(continuous with TCR)	(0.5 to 2 cycles)	Harmonics
Good	quick	medium	Losses
(Depending on the keying pattern)	(0.5 to 2 cycles)	(Large filters are required)	Phase balance capability

Table 3-2 deals with the economic comparison of different types of compensating devices.

Table 3-2: Economic comparison of different types of compensating devices

cost ($)	Controller type
8 dollars per KVAR	shunt capacitor
40 dollars per KVAR	SVC
50 dollars per KVAR	STATCOM

Table 3-1 shows that in terms of technical characteristics, STATCOM is superior to SVC, while according to Table 3-2, SVC is cheaper and more cost-effective in terms of compensation cost per kilovar.

3-3-3 Congestion Management in FACTS Devices

FACTS devices provide suitable control tools for both steady-state load flow control and dynamic and transient stability control. The ability to control load flow in a power system without the need to adjust generation or change network topology significantly increases efficiency. Using these devices, power flows through lines can be altered so that thermal limits are not violated, losses are minimized, stability margins are increased, and contract requirements are met without changing a specific generation and consumption pattern, thus reducing or eliminating congestion [8]. The increasing trend towards these devices is due to two reasons [76]. First, recent advances in high-power device manufacturing have made these devices cost-effective. Second, increased power system loading and deregulation in the electricity industry have provided sufficient motivation to use load flow controllers as very cost-effective means for power transactions.

As mentioned, congestion in the transmission system or limiting power transfer causes the power system to be divided into local electricity markets. With the localization of electricity markets and the reduction in the number of competitors, the market becomes less competitive and more semi-monopolistic, which contradicts the main goals of restructuring and deregulation in the electricity industry. Therefore, installing FACTS devices and controlling their drawbacks to alleviate congestion is of high importance. Since power transfer limitations in the network can essentially be resolved or reduced by controlling power flow, using

FACTS devices for congestion management seems very beneficial. The advantages of using these elements, compared to constructing new transmission lines, are faster. Therefore, using these devices to alleviate or reduce congestion in the short term is justifiable.

3-4 Congestion Background

The increase in industrialization and standard of living has led to increased dependence on electrical energy. Therefore, increased transmission line congestion and frequency deviation are major problems that today's power system network faces. Thus, operating a power system effectively under these conditions is a challenging task. In the early 1990s, power industries worldwide began to undergo extensive changes. Electricity markets moved from a vertically integrated monopoly system towards open structures by creating separate generation, distribution, and transmission networks. One reason for restructuring was that making the market competitive could lead to lower electricity prices and faster emergence of new technologies. The liberalization process was implemented for several reasons. The introduction of Combined Cycle Gas Turbine (CCGT) technology provided a technological justification for competition in the electricity market. Combined cycle gas turbine technology was allowed in small power plants, provided they were as economically and efficiently viable as large-scale thermal power plants. Therefore, it was believed that new programs could easily enter the electricity market and make it competitive. However, transmission networks were still considered natural monopolies. Fixed costs are high, while variable costs are low. Being a monopoly, energy is transmitted at a significantly lower final cost compared to a competitive market. Large-scale power networks show economies of scale and must be physically interconnected to maximize commercial efficiency and be installed in specific locations. Under these conditions, it is usually suggested that government regulations should be added to competitive markets to regulate contract behavior. Re-regulating transmission networks would not be appropriate.

Although pricing mechanisms from competitive markets do not provide effective results for natural monopolies, and therefore, transmission access and tariffs are subject to regulations, there is a growing need for market-based pricing concepts in transmission networks. Ideally, these pricing concepts do not provide the correct economic incentives but will facilitate the physical operation of the network. In this regard, congestion management and pricing methods were specifically considered because these methods are crucial for improving the performance of electricity markets [77].

Chapter 4: Transmission Switching

Chapter 4 provides a comprehensive exploration of Transmission Switching (TS) and its application as a strategic tool to improve the operational flexibility and efficiency of power grids. The chapter begins with a detailed introduction to the concept of TS, explaining how selective switching of transmission lines can optimize power flows, reduce operational costs, and mitigate congestion. It outlines the technical mechanisms and processes involved in TS, including the criteria for selecting lines to switch and the impact of these decisions on grid stability and reliability. The chapter reviews various algorithms and methodologies used to implement TS, emphasizing optimization techniques that account for the variability introduced by renewable energy sources. Additionally, it discusses the regulatory and safety challenges associated with TS, particularly the concerns about the wear and tear on equipment such as circuit breakers due to frequent switching operations. The chapter then presents several case studies and simulation results to illustrate the efficacy and complexities of implementing TS in real-world scenarios. Through these studies, it highlights the significant benefits of TS in enhancing grid resilience and adaptability, particularly in systems with high levels of renewable integration. This chapter sets the stage for the novel approaches proposed in the thesis, which aim to integrate TS more effectively within the broader framework of grid management strategies to tackle emerging challenges in modern power systems.

4-1 Smart Grids

Over the past decade, the global population has gradually become familiar with digital concepts, and this trend will intensify in the coming years. The global market has also increased and developed networks and monitoring systems to replace energy sources. The power system network we currently use was developed in the 1890s and has been strengthened with engineering advancements over the decades. According to the U.S. Department of Energy, there are nearly a thousand power generation units capable of supplying close to one million megawatts of electricity, with a total of 300,000 miles of transmission lines considered for power systems. Therefore, there is a need for an incredibly organized system with noise-free, efficient, secure, open, and reliable communications to compellingly manage advanced power system mechanisms, including electricity generation, transmission, and distribution. This system is called the Smart Grid (SG).

The structure of the smart grid has changed compared to the traditional power grid so that all entities can play the role of both producer and consumer, meaning entities can both generate and consume energy. This change is made for several reasons, such as reducing pressure during peak consumption times for producers and lowering the final cost for consumers. This energy production can make them independent of purchasing energy from the main distribution network or even allow customers to sell their excess energy to neighbors and other consumers willing to buy energy [77]. Table 4-1 provides a brief comparison between the features of smart grids and existing conventional grids to easily understand the characteristics of smart grids.

Table 4-1: A comparison between smart grid features and existing networks

Property	**Existing network**	**Smart network**
Function	electromechanical	Digital
connections	One-way communication	Two-way communication
Production	centralized production	Distributed production
Assessment	manual	Automatically
Number of sensors	little	All over
Type of crash recovery	manual	Automatically
Type	Has failure and blackout	Adaptive and insular
Control	limited	Wide
Number of customers	Limited number of customers	A large number of customers

More specifically, a smart grid can be considered an electrical system that integrates information, two-way communication technologies, cybersecurity, and computational intelligence across the generation, transmission, substations, distribution, and consumption of electricity to achieve a unified system. This system results in features such as cleanliness, safety, reliability, flexibility, efficiency, and sustainability.

This description encompasses the entire spectrum of the energy system from generation to the endpoints of electricity consumption. The ultimate smart grid is a future vision that involves the seamless integration of complementary components, subsystems, functions, and services under the pervasive control of highly intelligent management and control systems. Given the broad scope of smart grid research, different researchers may present varying perspectives on these networks due to differing focuses and viewpoints [78].

Smart grids were proposed to address the problems of current power networks and to manage the power system more effectively and efficiently. These networks enable complete monitoring and real-time control of equipment for power companies. It is expected that the creation of these networks will improve power system control and operation and facilitate the widespread use of distributed generation. A smart grid should be capable of self-healing and quickly returning to optimal conditions despite any faults that occur.

In the context of the reliability of generation, transmission, and distribution systems, each of these systems is studied in several subsystems. The generation system includes the generation unit and the generation substation, the transmission system includes transmission lines, switching stations, transmission substations, and sub-transmission systems, and the distribution system includes high-voltage to medium-voltage substations, medium-voltage distribution systems, medium-voltage to low-voltage substations, and finally, low-voltage distribution systems. The final stage in supplying electrical power is delivering power from feeders to consumers, which is the main goal of the distribution system. The reliability of the service delivered to consumers can be affected by faults occurring inside and outside the operational area of the electrical distribution system. These faults are called internal and external faults. Regardless of the fault location, the effects on consumers due to voltage changes include blackouts, voltage drops, and minor voltage fluctuations. The effects of external faults mainly appear as voltage drops, which is the primary reason for the networked configuration of the transmission and sub-transmission systems that supply the distribution system. As a result, power disturbances experienced by consumers due to external factors are less than those caused by internal factors. In contrast, internal faults lead to interruptions and voltage drops. Therefore, the share of internal faults in total interruptions and voltage drops is greater than that of external faults.

Smart grids are often seen as a fundamental change in the power system and a framework for communication systems. This change increases the efficiency, stability, and financial management relationships, leading to the effective and efficient use of power systems. Another significant advancement in the distribution network system is the innovation that combines centralized home control, which is a smart home controlled by a central device, with a computer. The new network connection, advanced communications, and better system control simplify the advanced tracking of the digital infrastructure and the future SG distribution network. The most thought-provoking aspect of SG's responsive innovation is the integration of advanced measurement, monitoring, metering, communication, and control capabilities into one electrical system. According to Dileep, some of its technologies include smart metering systems, automatic meter reading with communication systems and smart billing, plug-in hybrid electric vehicle technology, smart sensing technology, and real-time network monitoring [79].

In other words, to systematically meet energy requirements in different areas, a strategic energy distribution plan is necessary. Although SCADA and other continuous monitoring systems are very common, an intelligent system is needed to efficiently, effectively, and quickly meet energy distribution needs. This system can consider the energy requirements of areas and the availability of energy from different regions without human intervention. Regardless of distance, smart distribution networks enhance connectivity, automation, and coordination between suppliers, consumers, and networks. A smart grid is a term that considers the modernization of transmission and distribution networks. The concept of a smart grid involves the "digital upgrade" of remote distribution and transmission networks to optimize operation by reducing losses and establishing a new competitive market for alternative forms of energy production [80].

According to the DOE, a smart grid includes digital technologies that enhance the reliability, security, and efficiency of the electrical system from generation to delivery to electrical consumers. The widespread installation and operation of numerous distributed generation sources and energy storage resources are other achievements of the smart grid [81].

Some of the standards and protocols needed for smart grid implementation are not yet commercially available. The need to achieve smart grid goals, along with billions of dollars in financial incentives, has generated significant interest in academic environments, equipment manufacturers, software vendors, venture capitalists, energy companies, and government agencies to develop and implement smart grid capabilities and technologies. Achieving this outcome requires investment and the development of construction standards [81].

In the development of smart grids, designers, system operators, and equipment manufacturers must ensure a similar or even higher level of reliability while considering the expectations of smart grid electricity consumers. Some of the benefits of this modernized network include the ability to reduce power consumption on the load side during peak hours, known as demand-side management, enabling distributed generation sources (such as photovoltaic cells, small wind turbines, micro-hydro systems, or even combined heat and power generation in buildings) to connect to the grid, utilizing energy storage systems to balance the load of distributed generation sources, and eliminating faults such as cascading and widespread failures in the power network. It is expected that the increased efficiency and reliability of the smart grid will save consumer costs and reduce carbon dioxide emissions. Due to the increasing focus of governments on energy security, investing in smart grids can help reduce dependence on non-domestic energy sources [82].

Any network that possesses the seven characteristics of self-healing, energy storage, demand response, electricity markets, power quality, energy efficiency, and cybersecurity is considered a smart grid. In general, the term smart grid refers to an electrical power system equipped with specific technologies to achieve goals such as improved reliability, ease of control and management, integration of distributed energy resources, and electricity market functions [82]. These technologies can be categorized into five essential areas:

1. **High-Speed Integrated Communications**

This technology makes the smart grid dynamic and foundational for information and power exchange with high-speed, fully integrated, two-way communication technologies. The open network design provides an environment where network components can interact securely.

2. **Sensing and Measurement**

These technologies facilitate power system measurements and the conversion of data into necessary information. They help monitor equipment health and provide the best possible network support and protection.

3. **Advanced Equipment**

Advanced equipment plays a crucial role in determining system behavior. The new generation of power system equipment will benefit from the latest research in materials, superconductivity, energy storage, power electronics, and microelectronics, enabling higher power density production, improved reliability and power quality, higher electrical efficiency, and real-time diagnostics [83].

4. Smart Meters

Smart meters that measure customer electricity consumption are essential devices in a smart grid. A smart meter can be considered an electronic meter with a communication link. Smart meters must continuously send their measurement data to a nearby server, typically every 15 minutes, hour, or day. Customer electricity bills are based on this data. This information can also be used to predict the electrical energy needed in a specific area for better power distribution. Therefore, protecting the data generated and transmitted by each meter is crucial for the security of a smart grid [83].

5. Improved Interfaces and Decision Support

In most cases, operators must make necessary decisions within seconds. The smart grid, with its integrated, extensive, and simultaneous functions and capabilities, allows operators and network managers to make necessary decisions in the shortest possible time. Advanced interfaces and decision support enhance human decision-making at every network level.

6. Advanced Control Methods

These methods include equipment and algorithms that analyze, diagnose, and predict smart grid conditions to determine appropriate corrective actions to eliminate, reduce, and prevent outages and power quality disturbances. These technologies largely rely on the four previously mentioned technologies. For example, they monitor various components (sensing and measurement), provide timely and appropriate responses (integrated communications, advanced equipment), and have rapid diagnostic capabilities (improved interfaces and decision support) for any event [84].

Smart grid technologies are used to perform specific sets of applications and functions in electrical power systems. For each function, several smart grid technologies can be used, categorized into five key areas. This study focuses on smart grid technologies used to improve the reliability of electrical power delivered to consumers in the electrical distribution system. Today, many smart grid technologies are in use, and many are still under study and review [85].

Given the structure of smart distribution networks, ensuring network security and protection is one of the most critical challenges. Security in a power network means the network's ability to avoid unnecessary operations. Generally, security is defined as the electrical system's ability to respond to sudden disturbances without interruption in supply. Security assessment in the distribution network, considering the protection system, has been limited. Protection systems may affect the stable operation and reliability of smart distribution networks. Therefore, a comprehensive reliability assessment of smart distribution networks is mainly conducted through primary distribution networks and a protection system. Protection system factors affecting the reliability of smart distribution networks include relay protection, fault location, and reconfiguration. Given the complex configuration of protection systems, especially when the quality of the power supply is directly affected by the performance characteristics of protection systems, using protection systems is a key aspect of reliability assessment in smart distribution networks [86].

4-1-1 Benefits of Operating Smart Grids

The economic and environmental benefits of implementing smart grids can be significant for both power companies and consumers. These benefits are summarized as follows:

- Profits for power supply companies
- Improved reliability
- Delayed network capacity expansion and reduced investment in generation, transmission, and distribution
- Improved power quality
- Reduced outages and widespread blackouts
- Environmental compatibility
- Empowered energy markets
- Enhanced economic and financial performance
- Operational and maintenance cost savings
- Increased efficiency of delivered power
- Integration of distributed generation and renewable energy sources
- Enhanced system security [85].

4-1-2 Benefits of Smart Grids for Consumers

- Consumption management
- Cost savings by reducing peak load
- Facilitation of distributed generation resources
- Cost savings through increased energy efficiency
- Advanced metering facilities
- Reduced consumer costs [86].

4-1-3 Smart Grid Technologies

The tools and programs introduced by industry owners and investors in traditional networks affect various aspects. For example, distributed generation resources in a distribution network have many positive aspects in terms of reducing losses, improving power quality, and enhancing consumer reliability. To avoid examining the numerous devices used in smart grids, some of the most important factors and technologies added to traditional networks to improve reliability indicators in the distribution network will be discussed.

Smart grid generation technologies include governor response, real-time energy balancing, increased reserve capacity, shifting production throughout the 24-hour day, and more. Smart grid generation technologies include various types of distributed generation, microgrids, and electrical energy storage systems. Traditional demand-side programs, such as energy efficiency, demand response, and related technologies, are an important part of the smart grid concept. These programs have created effective processes in recent years [86].

4-1-4 Microgrid

Micro-grid is a new concept that is introduced with the introduction of smart grids. The micro-grid configuration is island-like in distribution systems and near local loads, which includes a set of loads. Micro-grids are active low or medium voltage distribution networks in various sizes and shapes, which include renewable energy sources such as PV[1], wind turbines, batteries, loads and control devices. Micro-grids can be connected to or disconnected from the main network and continue to operate independently,

[1] Photovoltaic

and when connected to the network can create two-way power exchange. The main purpose of these networks is to raise technical issues related to increasing the reliability and quality of power delivered to consumers [87]. A schematic of micro-grids is represented in Figure 4-1.

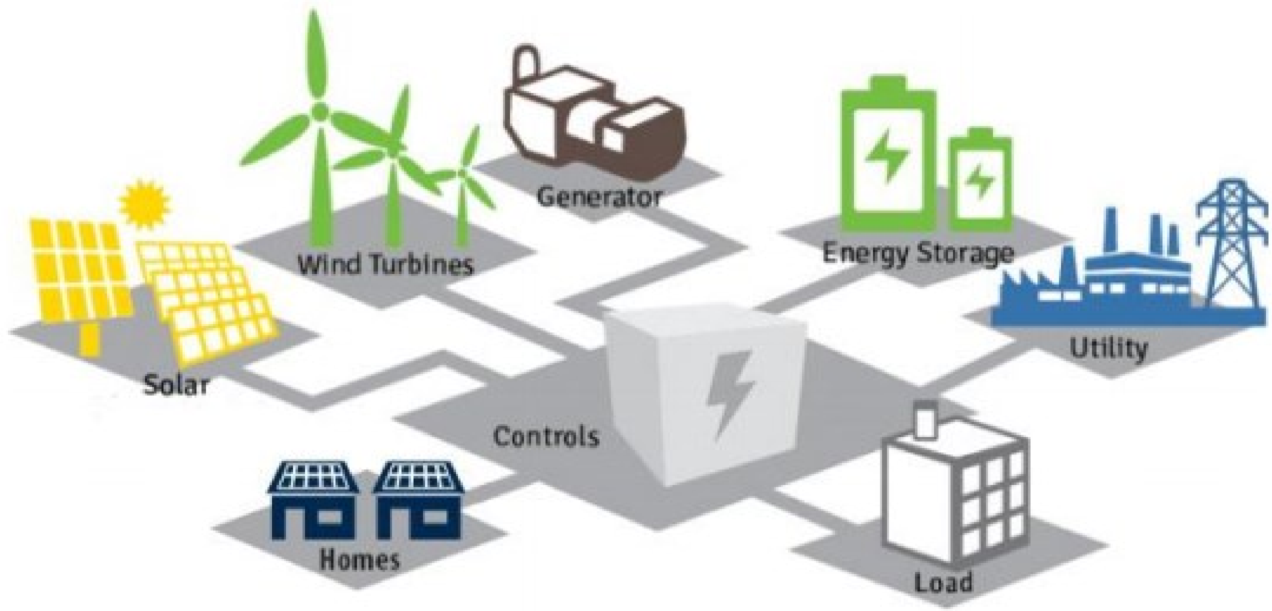

Figure 4-1: The schematic of a micro-grid

Micro-grids have important benefits for consumers, including improved reliability and power supply under stress in independent operation and improved power quality. Micro-grids also shorten the gap between production and consumption, thereby reducing losses and managing the shutdown, and facilitate the maintenance process. In addition, the widespread use of renewable resources in micro-grids will prevent the excessive emission of greenhouse gases, which is a human concern today [88]. Important benefit of own production for a consumer is to avoid paying distribution grid fees and taxes. Roughly one third of grid supplied energy cost is from energy itself, one third about grid fee and the last one third about taxes. The consumer save a lot, if has cheap enough production on his/her own premises. PV has received grid parity in many countries already.

Ccomponents of a Micro-Grid

1) Distributed Generation (DG) Resources

Distributed generation, or DG, is the generation of electricity at the point of consumption but is sometimes referred to as technologies that use renewable sources to generate electricity. The IEEE defines power generation by devices that are smaller enough than a central power plant and can be installed on site as a DG. The IEA identifies power generation units at the point of consumption or within the distribution network that inject power directly into the local distribution network as the DG. Distributed power plants are limited in size to about 10 megawatts or less and are used interconnected at distribution feeders or consumer load substations. These power plants also have different technologies such as wind power plants, fuel cells, micro turbines, Stirling engines (a type of internal combustion engine) and internal combustion generators [89].

2) Storages (Batteries)

Batteries, as one of the most widely used storage devices in the network, are one of the most important components of micro-grids that are able to store energy at low load times and deliver it to the grid at peak load times. Therefore, they are very important in increasing the reliability and flexibility of micro-grids. The amount of discharge of the storage devices per hour will depend on the amount of charge in the previous hours. Due to the high cost of construction and maintenance of storage facilities, the use of storage facilities for micro-grid activity is not well developed [90]. It's necessary to say that all new microgrids are very much based on batteries. The cost of batteries is reducing very fast due to automotive industry involvement.

3) Controllers

Micro-grid control system is designed in such a way that with very high security, it manages the system activities in two modes of work independently of the network and work as a part of the network. When each micro-grid is disconnected from the mains, the control system must control the local voltage level and output frequency and calculate the difference between the output and the active and reactive power consumption in the micro-grid. By taking the necessary measures for stability, the controllers have the task of protecting the micro-grids against accidents, errors, and blackouts, and they must maintain and ensure the consumption of the subscribers in the most optimal way possible [91].

Types of Micro-Grids

1) DC Micro-Grids

The twentieth century, in turn, has witnessed a powerful war over how to power transmission and use electricity. This war, known as the War of the Currents, was waged by Westinghouse and Tesla on the AC side, and Edison as the DC's biggest arguer. Naturally, this controversy ended with the further implementation of AC distribution in most power networks, for reasons that were more logical at the time. One of the most important factors and reasons for this superiority was the invention of the transformer, which provided a simple and excellent tool for increasing the amount of voltage, and as a result, wider areas were covered by the distribution system. While changing the DC voltage levels was an obstacle. In addition, the invention of AC multiphase machines helped people find an alternative to DC machines that was only available at the time. However, DC systems have not disappeared from distribution. For instance, there is an old system in which gas and electricity are used in San Francisco to power DC elevator motors in several historic buildings. Advances in power electronics that make DC voltage regulation a simple task, as well as increasing the penetration of DC loads and resources, encourage researchers to consider the DC distribution in at least parts of today's power system to increase their overall efficiency [92].

Many of today's consumer electronics, such as many electronics-based home and office appliances such as computers, laptops, tablets, cell phones, printers, televisions, microwave ovens, and lighting, are DC-powered appliances. Also, more efficient and newer lighting technologies such as compact fluorescent lamps and solid-state lamps are involved in a single DC phase, making it more economical to use a DC distribution system to power them. DC power is also used in variable speed drives for pumps, heating, purification and ventilation systems, fans, elevators, traction systems and mills. In addition, for industrial applications, the steel industry uses DC electric furnaces because they consume less energy than the AC type and cause less light flicker. In the electrochemical industry, there is always a demand for pure DC. Therefore, feeding these loads through AC distribution systems often adds conversion steps, resulting in inefficiencies in the delivery cycle. Approximately 30% of the AC power generated passes through the electronic power converter before being used. In this system, the amount of energy loss varies but is usually in the range between 10-25%. Other research has shown that power conversion efficiency can be increased by 80% using the DC system and about 25% by removing the converter. Since the majority of renewable sources generate DC power, the need for a DC bus to connect to the grid seems essential. Modern DC loads in distribution systems have also grown significantly in recent years. DC micro-grids have better protection against short circuits and lower voltage levels, which significantly improve performance and reduce the size and cost of the distribution network. DC micro-grids have emerged because of the advantages such as efficiency, cost, and system that can eliminate the AC-DC and DC-AC power conversion steps as well as the energy losses caused by them [93,94]. In another paper, the focus is on smart DC direct current micro-grids based on the most advanced distributed generation and modern electrical loads. An example of this network is shown in Figure , according to which a number of AC and DC sources are connected to the DC low voltage network after the required conversions and connection to the common PCC connection point.

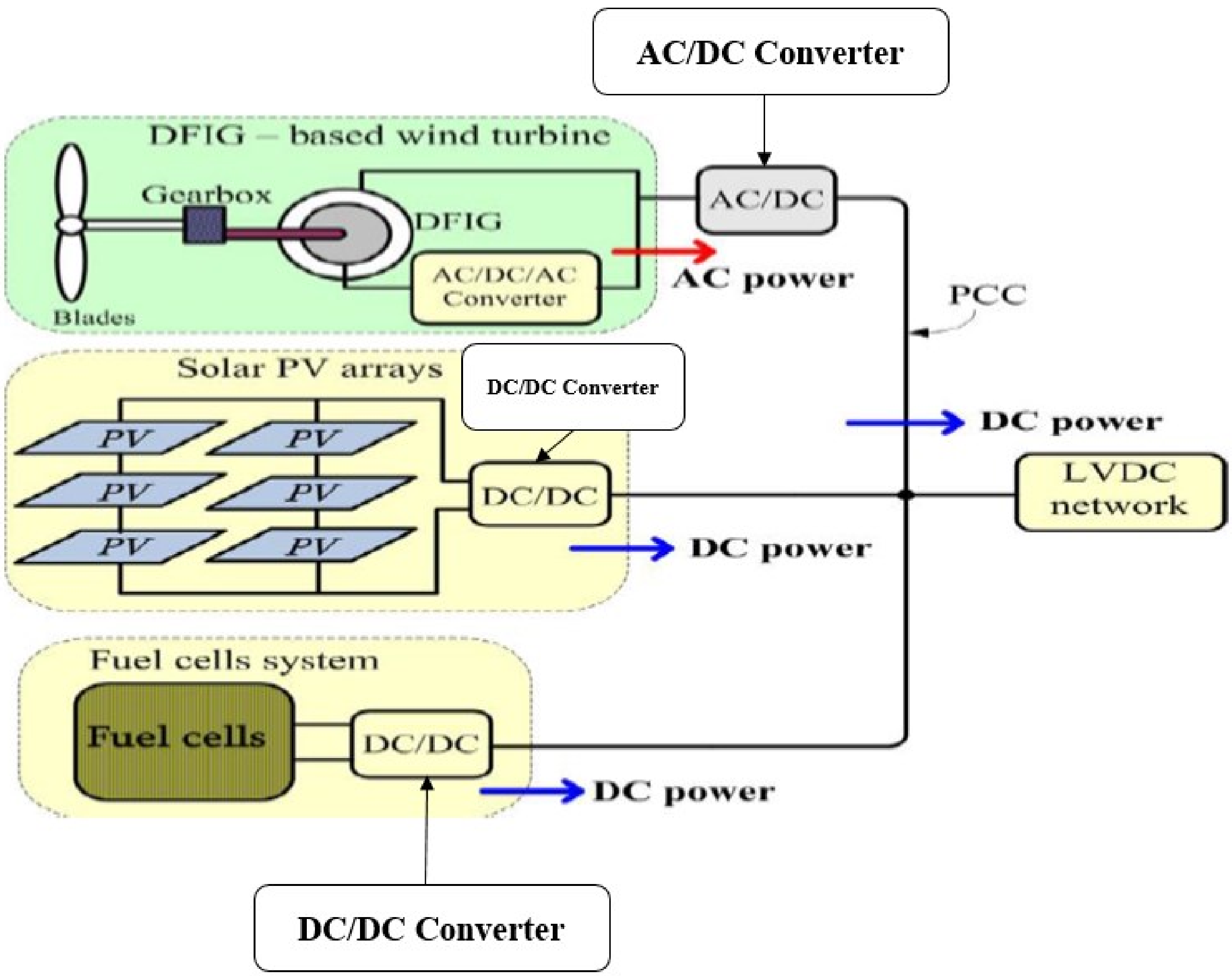

Figure 4-2: A DC micro-grid

Some US states have invested millions of dollars in promoting micro-grids as part of regional disaster response programs. Because micro-grids generally include renewable resources and batteries, DC micro-grids will have a high capacity to improve the efficiency of the entire system. There are several articles that suggest that DC micro-grids can be a more effective way to solve some operational problems on the main network. Solar cells and batteries should also be used to reduce the severe effects of nonlinear charges. As a result, these factors have led to much research to raise the question of whether DC distribution is the most efficient way to distribute electrical energy, or whether it is time to consider the development of DC distribution as an alternative. Research has shown that DC power systems are no longer obsolete. Figure shows a real and laboratory-sized DC micro-grid which is used at the University of Aalborg [93-95]. It is examples from real-life as well.

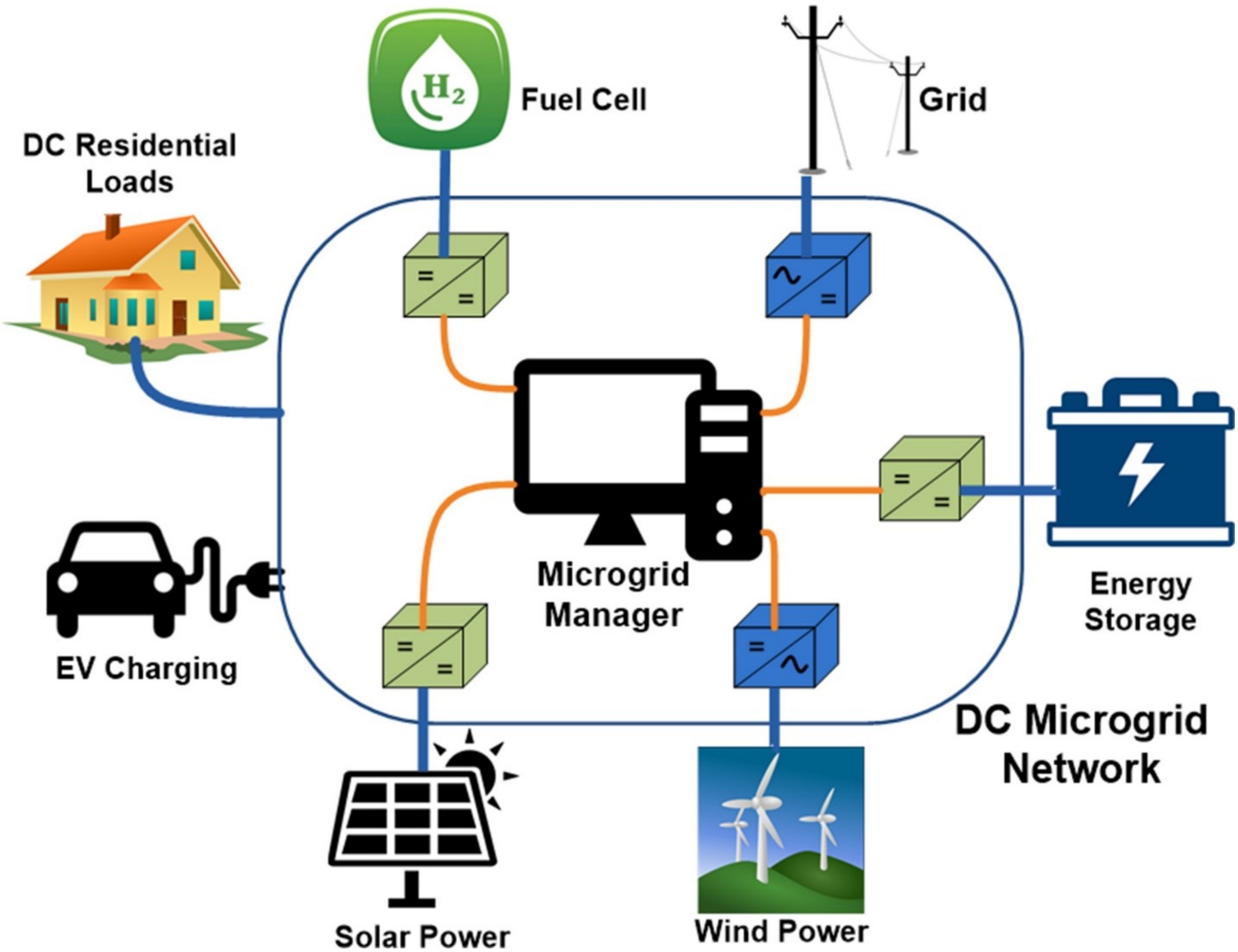

Figure 4-3: A typical DC micro-grid

2) AC Micro-Grid

The AC micro-grids were generally the common denominator of all micro-grids. Considering that all the infrastructures of production, connection and distribution networks all over the world are AC power networks, so connecting this type of sub-network to the global network and using the previous structure to transfer power will be a great advantage. Figure 3-4 shows an example of an AC micro-grid.

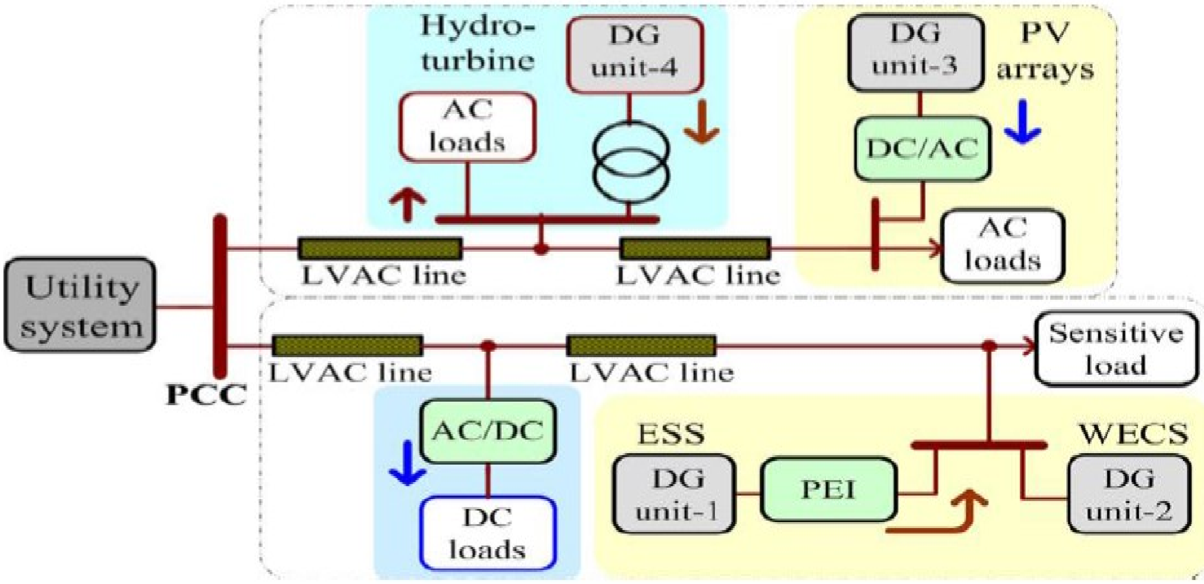

Figure 4-4: An AC micro-grid

As mentioned, due to the fact that a large part of power networks are currently AC, so AC micro-grids have a large part and format of power networks. DC micro-grids are expected to be used exclusively in the power grid in the coming years. In many micro-grids, AC generating units with AC output power are connected directly to a bus. They are then connected to the main system for a stable building through power converters. Examples of DC units that produce AC output power include biogas turbines, wave turbines, and tidal turbines. These micro-grids are usually either directly connected to the network or may require AC / DC / AC converters that enable them to connect to LVAC networks. In this regard, the LVAC network can be connected to the global network through a power transformer. In addition, AC loads are connected directly to the mains. DC loads, on the other hand, require DC-AC power converters to connect to LVAC networks. In other words, DG units that generate DC power are connected to LVAC networks with DC / AC converters. One of the biggest problems and complexities associated with AC micro-grids is the complex control strategies for the synchronization process and the maintenance of system stability. Perhaps the general meaning and concept of micro-grid is AC micro-grid, a network in which different sources, both AC and DC, are responsible for feeding different AC loads [96].

In this type of micro-grid, DC sources are provided by AC / DC converters and the use of appropriate amounts of filters provides a suitable value with the least distortion for AC loads. A concept in which loads and sub-sources, including AC and DC sources and, of course, loads that are all AC, act as a single control system and in many cases provide heat and power for local loads. These micro-grids can be considered as a controlled cell of the power system, for example, this cell must be able to be sent as a load that can meet the needs of the transmission system in a fraction of a second. From the consumer point of view, the micro-grid should be able to meet the following needs:

- Increasing the local reliability

- Reducing feeder losses, supplying local voltages

- Increasing productivity through the use of wasted heat

- Correction of voltage drop or supply of emergency power supply functions [96].

Micro resources that are of particular interest to micro-grids and units with a power of less than 100 kV with electronic power interfaces. These resources are located at customer locations. Low cost, low voltage and high reliability are low emissions. Electronics provide the power and flexibility needed for the concept of micro-grids. With the correct design of control and fine power electronics, the network can meet the needs of the consumer, such as the needs of the network. The above features can be provided by an architectural system with the following three main components:

- Fine control of local resources
- System optimizer
- Distributed protection

In general, the difference between AC and DC micro-grids is as follows:

1- AC micro-grids are more compatible with existing AC systems. However, synchronization methods must be followed before connection. In contrast, it is easier to connect a DC micro-grid to AC systems. DC micro-grids are more compatible with the nature of today's DC loads. (Home appliances, lighting systems and motor drives)
2- Most renewable energy sources such as PV solar cells, fuel cells, and DC energy storage units are. Protecting DC systems is more challenging due to the lack of zero current flow, which is a feature of self-extinguishing fault current in AC systems. AC systems are associated with the skin effects of transmission lines. Due to the above issues, hybrid AC / DC systems have emerged to take advantage of both networks. Also, the losses will be significantly reduced as the conversion steps of the power electronics go down, and the reliability of the system will significantly increase.

3) AC / DC Hybrid Micro-Grids

Various hybrid system structures have recently been used to connect AC and DC subsystems using a three-phase voltage source converter or back-to-back converters. Given the aforementioned advantages of both AC and DC micro-grids and the challenges ahead, AC / DC hybrid micro-grids are well-known as an attractive idea with very unique features, and there is a lot of research day by day to apply and Optimal use of this type of micro-grid is underway. In fact, this type of micro-grid, as shown in Figure 2-5, will be a combination of the ideas of Westinghouse and Tesla on the AC side, and Edison as the biggest DC arguer [97].

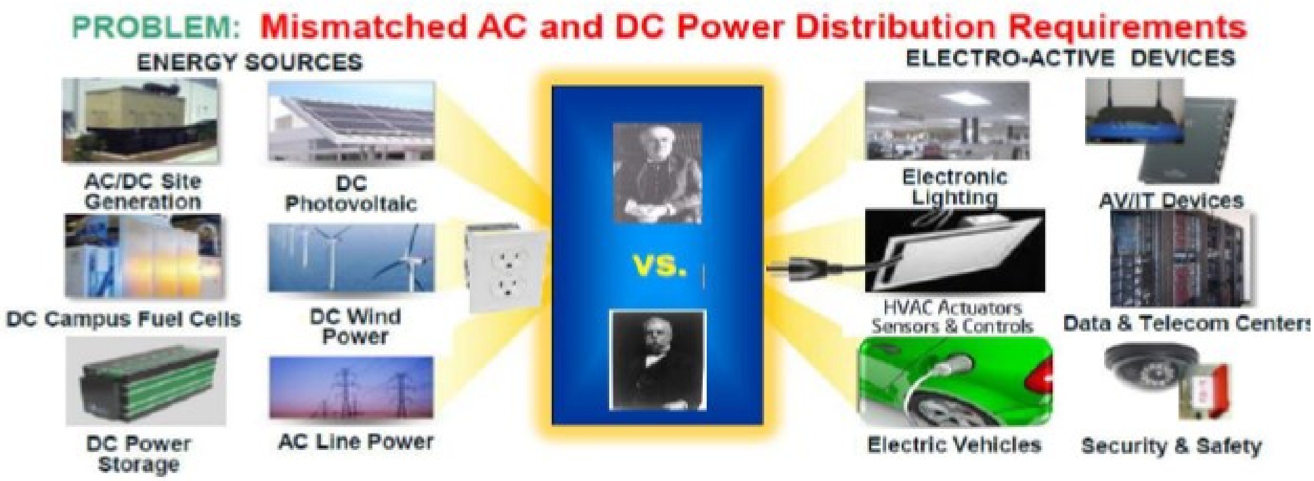

Figure 4-5: A hybrid micro-grid

As mentioned earlier, a micro-grid will be an efficient way to integrate micro source resources without any interruption. Power generation through micro-sources and renewable resources such as solar energy and wind farms will have a significant momentum. Therefore, hybrid AC / DC micro-grids are the best solution to reduce high AC-DC-AC conversions in a proprietary AC network. Accordingly, AC loads are a separate AC network and DC loads and sources are interconnected. In addition, energy storage systems can be connected to AC or DC bus. Today, most renewable power conversion systems are connected to AC distribution systems at low voltage levels as distribution and micro-grid generators. Due to environmental issues created by conventional fossil fuel power plants, on the other hand, the use of DC loads such as light emitting diodes (LEDs) and electric vehicles are now connected to AC power systems. It will not be necessary to use high voltage lines over long distances when it is possible to supply power from local renewable sources. Micro-grids are provided to facilitate the connection of renewable energy sources to the conventional AC system. However, photovoltaic panels or fuel cells must be converted to AC / DC inverters using AC / DC amplifiers to connect to the AC mains. In AC network, AC / DC and DC / DC converters are required for various home and office facilities to supply DC voltage. AC / DC / AC converters are commonly used as drives to control the speed of AC motors in industrial plants. Recently, DC networks have been revitalized to develop and utilize DC renewable energy sources and the inherent advantage of DC loads in residential and industrial applications. DC micro-grids are provided for the integration of different distributed generators. Multiple reverse conversions on DC or AC networks only add additional operational losses to the system, further complicating office and home appliances [98].

Therefore, to meet these goals, electrical power technology plays a very important role in connecting different resources and loads to the network and smartening. Therefore, with the studies performed to reduce multiple reverse conversion processes in a single AC network or DC network and to facilitate the connection of AC and DC sources, renewable and AC / DC hybrid micro-grids power have been introduced many times [97,98].

Operation of Microgrid

One of the most important and required feature of a microgrid is the ability to operate in both grid-connected and island mode. This capability makes them appropriate in providing emergency power to the connected loads during a contingency hence improving power delivery within the island. In grid-connected operating mode the Distributed Energy Resources (DER) is connected with the main grid. In islanding or autonomous mode, local loads can be feed without using the distribution network [99].

The two microgrid operational modes are described below:

1) Grid-connected Mode

In the grid-connected mode, the microgrid (MG) connects to the upstream network. A microgrid may receive energy from the whole or part of the main grid, which depends on the power distribution. Conversely, when production exceeds consumption, the excess power is returned to the main power grid.

2) Island mode

Sometimes an upstream network can encounter an error or deliberate action, such as performing network maintenance, so in such cases, the microgrid operates in an island mode. Therefore, when a microgrid operates autonomously it is called an island operation mode.

In other word, island mode refers to the situation when it is separated from the main grid and operates independently with micro sources and load.

The islanding process can be done by opening the upstream switches on the substation, which connect the main power grid and the microgrid. This change can occur due to any type of disorder or intentional reasons. There is a difference between intentional and unintentional islanding. Intentional islanding means a managed and controlled operation transition mode, while unintentional islanding refers to unintended islanding due to a fault in the utility grid [100].

In intentional islanding, the active and reactive power flow between the microgrid and the main network is managed at almost zero before transition in order to reach power balance inside the microgrid. The microgrid management system constantly monitor the transition process [100].

If the unbalance power inside the microgrid is smaller than the existing control capacity, transition to island operation is possible. This capacity consists of the control feedback of locally controlled DER units, strong enough energy storage for fast response, and controllable microgrid loads, which can be separated from the main grid very quickly. Therefore, the transition is very easy because of fast communication between components and management system [101].

4-1-5 Methods of Controlling Energy Sources of Smart Grids (SG)

In recent years, the analysis and design of large-scale systems, such as power systems in which a large number of renewable energy generators are located, has attracted the attention of many researchers. Uncertainty in the output of renewable energy causes frequency deviation in the entire power system. To realize a reliable supply-demand system, developed design and control methods are needed in order to stabilize the voltage power in these systems [102]. Recent advances in computer networking technology have enabled systems equipped with DER resources to operate in a spatially distributed manner. For example, in power systems control, a system operator manages distributed power plants with distributed metering units to meet the demands of a number of consumers. In order to systematically control such networked systems, decentralized and distributed control techniques have been studied in the last half century [103].

Recently, researchers' efforts have been focused on designing suitable controllers for systems equipped with DER resources and also expanding these controllers to more general examples. In the following, some control methods of these networks will be examined.

Decentralized Control

Among the existing structures against the centralized structure, the initial research has been in the field of decentralized controls. Research on decentralized control dates back to the seminal work of Davison Wang in 1973, and interest in this topic has grown significantly since then. The articles published by Fu (1992), Jain and Khorrami (1997), Tang et al. (2000), and Jiang (2000) are among the first researches on decentralized control of nonlinear systems.

Decentralized control plays an essential role for the design and control of systems with DER resources. In this method, each of several controllers uses only local measurements to control the entire system. Figure 4-6 shows an example of decentralized control that includes system inputs and outputs. Controllers are implemented in a decentralized manner as shown in Figure 4-6(a). The entire controlled system is represented by an iterative feedback system in which structured subsystems are also connected to a base system. This problem is shown in Figure 4-6(b). In practice, not only the implementation but also the design of the controller should be decentralized so that each controller is designed independently from other controllers. The most important point in the design of decentralized controllers is to achieve stability and proper performance in the entire controlled system [104].

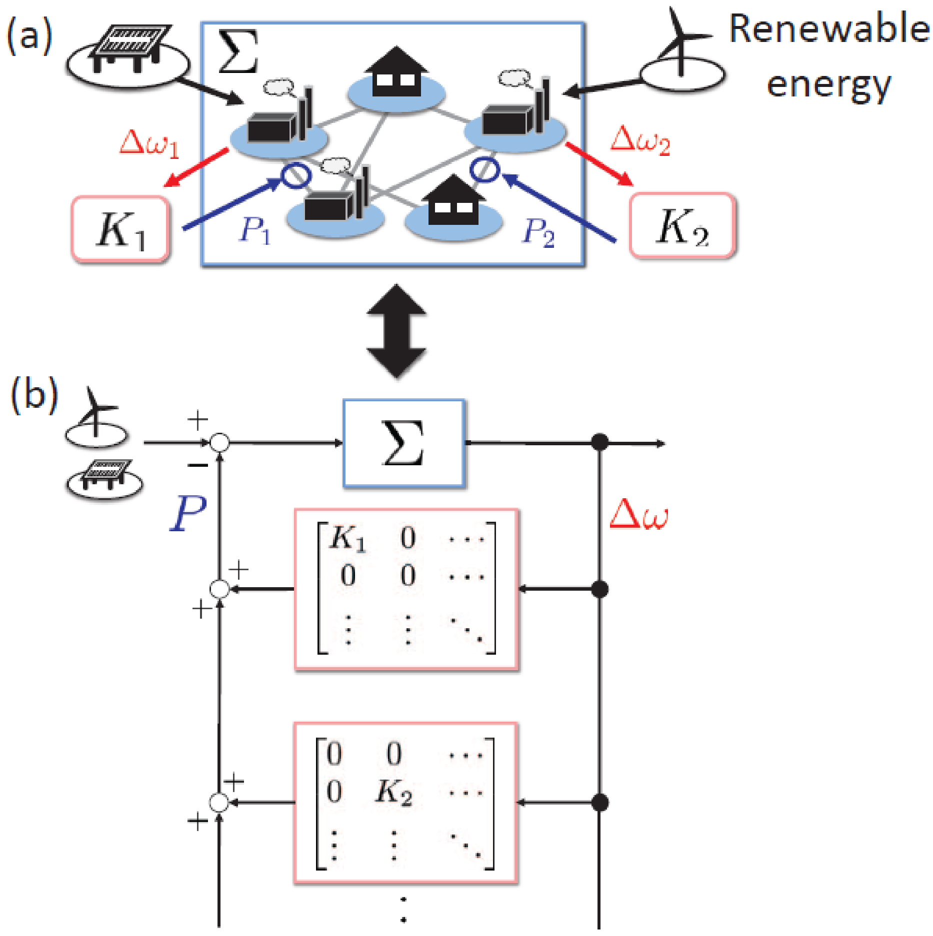

Figure 4-6: Decentralized control schematic of a power system consisting of a large number of renewable energy generators [114].

Passivity theory has contributed to the development of decentralized control schemes for systems with DER resources. Because based on this theory, it has been proven that the design of feedback controllers is useful for linear and non-linear systems. Such controllers have been used in many applications such as robotics and energy systems. Various efforts have also been made to develop robust and adaptive controllers based on passives. Also, so far, many passive continuous-time based control schemes have been designed. However, it is well known that the passive properties of continuous-time systems are lost under discretization due to the energy leakage resulting from zero-order retention. Hence, various methods have been developed such as the use of small sampling where passivity is preserved under discretization [105].

A control system design approach based on passivity, or more generally, looseness, is related to the modular design of network systems. This approach has an advantage that the input-output behavior of the entire grid system can be analyzed using only the subsystems, to which the corresponding energy supply rates are associated. However, supply rate-based analysis is only valid when an acceptable supply rate is found for the common variable, i.e., the stack vector, disturbance and interaction inputs, and the evaluation common variable and interaction outputs [106].

Decentralized control in power systems with DER sources has advantages such as flexibility in system structure, because a separate controller is considered for each subsystem. By changing the structure of a part of the controller system of the same part, it is updated according to the new structure, and there is no need to redesign a global controller, which is a very difficult task in power systems with DER sources.

Other advantages of decentralized control are resistance to errors, less calculations and no need for information from the entire system. As described, each local controller uses local signals and a small amount of information from other subsystems to issue commands.

Many industrial systems are still controlled by a decentralized architecture, in which the control variable (input u) and the controlled variable (output y) are grouped into separate sets. These sets join together to form "non-overlapping" pairs for which local regulators are designed to operate completely independently. These local regulators can be single-input-single-output (SISO) or multi-variable, depending on the selected input and output category. An example of decentralized control structure can be seen in Figure 2-9 that the system under control consists of two subsystems S1 and S2, which have state variables and input and output variables (x1, u1, y1) and (x2,u2,y2) respectively and the relationship between these subsystems is shown by the effects of two state variables [107].

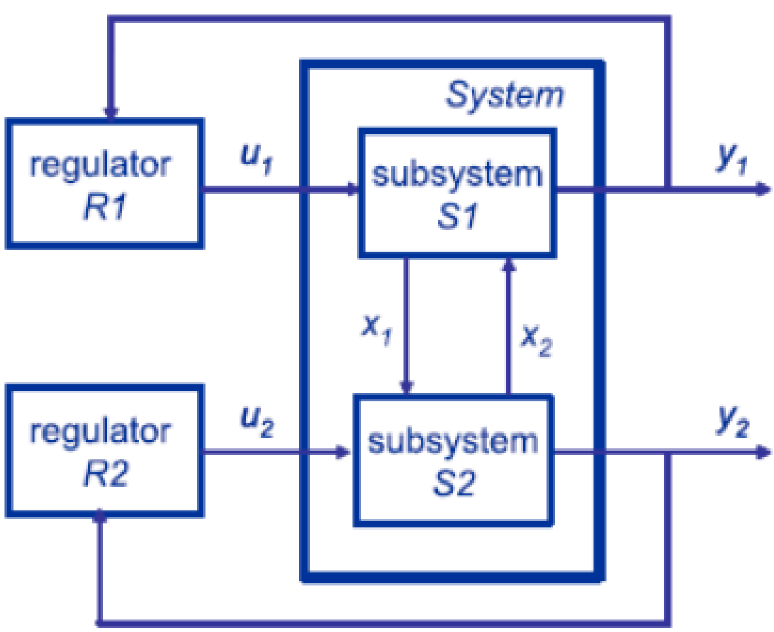

Figure 4-7: Decentralized control structure for two input two output system

When the decentralized regulatory structure is determined, when the internal interactions between inputs and outputs of different pairs are weak, the design of local regulators (R1 and R2 in Figure (4-6)) is obvious. These internal interactions can be direct (input coupling) or caused by the bilateral effects of the internal states of the subsystems under control, as shown in Figure (4-6). On the contrary, it should be noted that strong internal interactions can prevent decentralized control from achieving stability or proper implementation.

As stated in the [108] which examines different structures from the point of view of communication networks, more than two decades have passed since the application of this structure in power systems.

Centralized Control

In contrast to decentralized control, to coordinate the control actions of the whole system, a centralized scheme is usually used, assuming that general information is available from the entire system. Centralized control means that information from the entire system is sent to a single center, where all control components are located in that unit, and that part is responsible for performing all calculations and estimates and generating control input for the entire system.

There are important reasons for replacing other structures instead of the centralized control structure, the most important of which are mentioned below. As it is clear from the above definition, centralized control for geographically distributed power systems is usually not the answer and the implementation of this control structure for this category of systems is very difficult for technical and economic reasons. Because sending information from the entire system to a control unit and providing high computing power is practically impossible and expensive.

In addition, the design of centralized controllers is highly dependent on the structure of the system, and these controllers cannot deal with the structural changes of the systems and perform their actions optimally. It is also possible that the system consists of separate and independent subsystems that have unique control tools. Therefore, the best way to control such systems is to use local computing and control resources. As stated, power systems are usually composed of a large number of interconnected and interconnected subsystems, and therefore control by a centralized control structure, due to the inherent computational complexity required, due to resistance and capability problems. Reliability can also be very difficult due to communication bandwidth limitations. In addition, when the central control in the centralized structure is lost, the whole system is out of control, and the correctness of the control is not guaranteed when the control components are lost. In some cases, the global information of the system is not available for the central controller [109].

For all the reasons mentioned above, a large number of decentralized control structures have been developed and applied to systems in the last forty years. In this way, instead of designing a general and general controller of the decentralized control scheme, it is possible to design separate controllers for each subsystem. Subsystem controllers need only local signals and a small amount of information from other subsystems. Among the proposed structures, completely decentralized structures, distributed control systems with information exchange between local controllers and hierarchical structures are of special importance.

It should be noted that the centralized control has the best performance in terms of performance, because fewer restrictions are applied to the system. Therefore, usually in the articles, the result of simulation seeks to approach the function of distributed and decentralized control to the function of centralized control.

Hierarchical Control

The point that appears after decomposing a power system with DER resources into smaller subsystems is the interconnection and communication between these subsystems. Each of these subsystems that have internal interaction with other subsystems through their inputs or states are "adjacent subsystems". Decentralized control will not provide useful performance if the connection and continuity between subsystems is strong and cannot be ignored. In this way, the presence of a coordinator whose task is to provide the information needed by each local controller is helpful.

Hierarchical control scheme includes primary controllers. The secondary control level is a central controller that first receives the instantaneous output currents of all DG units through a low bandwidth communication link (LBC). After that, the secondary control level calculates the instantaneous eddy currents corresponding to the main components and dominant harmonics and sends them to the primary controllers of all DG units in order to achieve accurate harmonic current and reactive power sharing and also to reduce the eddy current between the units.

Figure 4-8 shows the application of the hierarchical control plan for a three-phase island microgrid where N three-phase DG units are connected to the PCC bus through LCL filters and ZF feeder impedances with inverter interface. It is worth mentioning that as long as they operate in parallel, the LCL filter is mainly preferred over several VSI LC filters. It should be noted that for DG voltage control units with capacitor voltage control, filter inductances of the network side filter are considered as part of the impedances of the feeder. In addition, as it is clear from Figure 4-8, the microgrid system includes both linear and non-linear loads that are considered jointly in the AC bus (PCC) and locally in the DG output terminal for each unit. DG power requirements are provided by power generators and/or energy storage systems. In the microgrid system, it is assumed that the DC links of the DG units are separately controlled and kept constant [110].

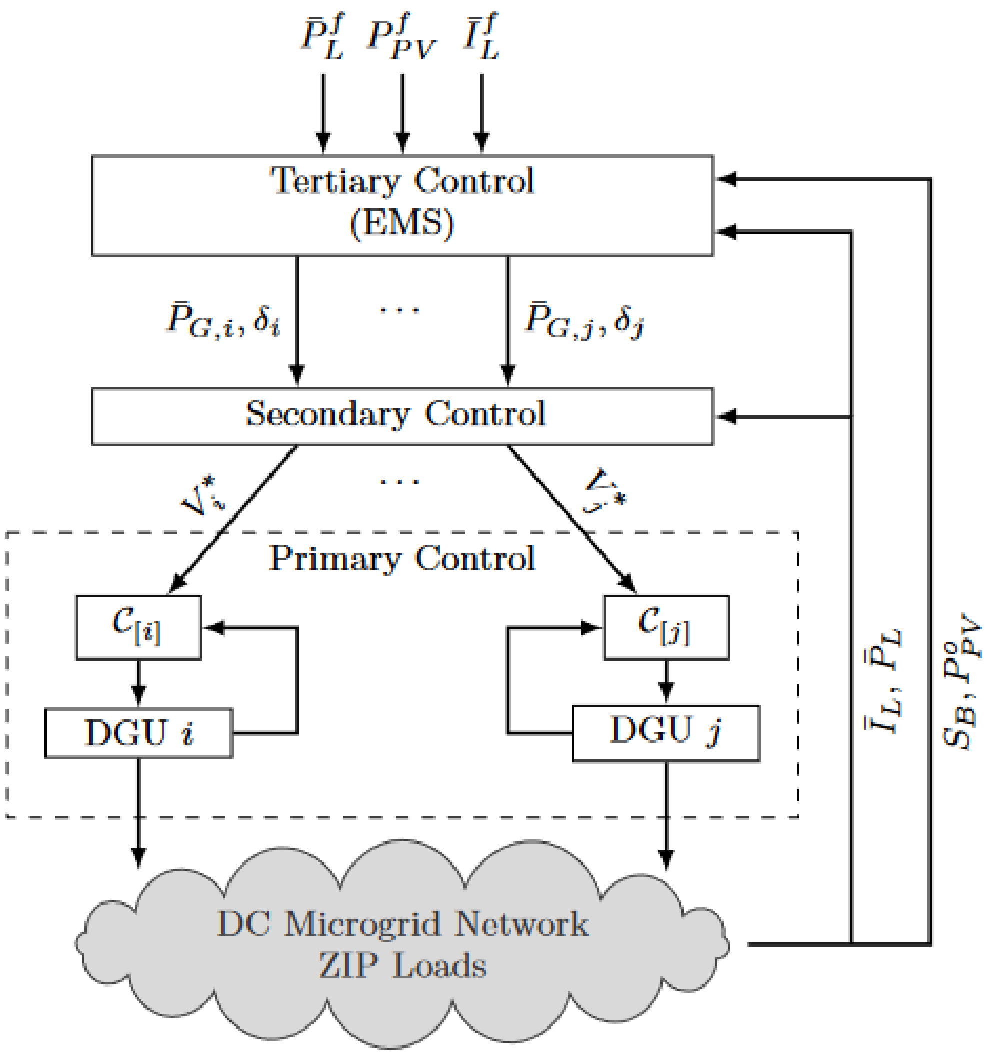

Figure 4-8: An example of a hierarchical control plan for a microgrid

Distributed Control

With the introduction of new communication structures, architecture and control structures also change. Hierarchical communication networks with physical subsystems at the lower layer and coordinators at the higher layer are replaced by distributed control structures. This structure will take advantage of graph theory, in such a way that the communication configuration is described by a directed graph, in which each node represents physical subsystems with its corresponding control units, and each edge is a communication link. The most important issue is to find a communication topology for a desired purpose.

Distributed control systems (DCS) have three main characteristics. The first is the distribution of various control functions in a relatively small set of subsystems that are semi-automatic and interconnected through a high-speed communication bus. Some of these functions include data acquisition, data presentation, process control, process monitoring, information reporting, and information storage and retrieval. The second feature of the distributed control system is the automation of the production process by integrating advanced control strategies, and the third feature is the arrangement of everything as a system. DCS organizes the entire control structure as a single automation system in which the various subsystems are unified through a proper command structure and information flow. These features of DCS can be shown in its architecture as shown in the diagram below. The main elements formed in DCS include engineering workstation, operator station or HMI, process control unit or local control unit, intelligent devices and communication system.

In the distributed control structure, the local controllers themselves decide which controllers to send information to and from which controller to receive the information they need, and there is no longer a coordinating unit for this purpose. In the distributed control structure, as shown in the example of Figure 4-9, it is assumed that part of the information is transferred between the local regulators (R1 and R2), so each of the regulators or the controller have some information about the behavior and actions of other controllers. Figure 4-9 shows a simple system where controllers R1 and R2 are designed to control subsystems S1 and S2, respectively [111]

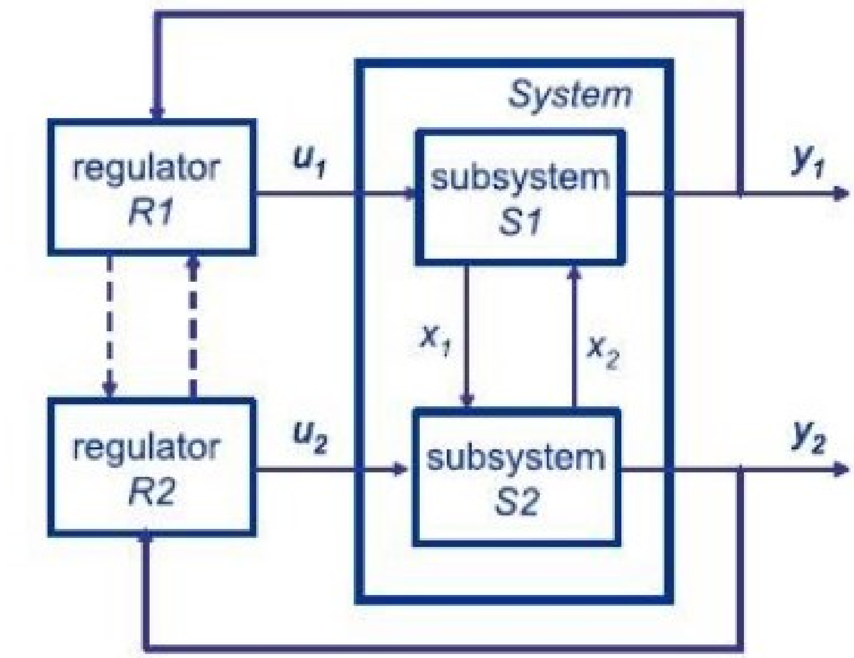

Figure 4-9: Distributed control structure for two-input-two-output system [111]

In geographically distributed systems such as transportation and power networks that include hundreds or thousands of nodes, it is not possible to collect all sensor information in one place for control. In this case, there is a need for distributed methods that rely only on information available locally or sent from nearby nodes, where some communication between nearby nodes is allowed [112]. In order to understand the distributed control system, a system is considered in which a basic system is involved with the gradual connection of several subsystems in a step-by-step manner (Figure 4-10). Then, multiple subsystems are implemented in a decentralized manner in a base system. Furthermore, the implementation continues as a modular connection. For practical reasons, not only the implementation but also the design process should be modularized. This type of design is called distributed design, in which each subsystem is designed independently of the others except for their brief specifications. Despite the difficulty of modularized design, it is also essential to achieve stability and good control performance for the entire control system [113].

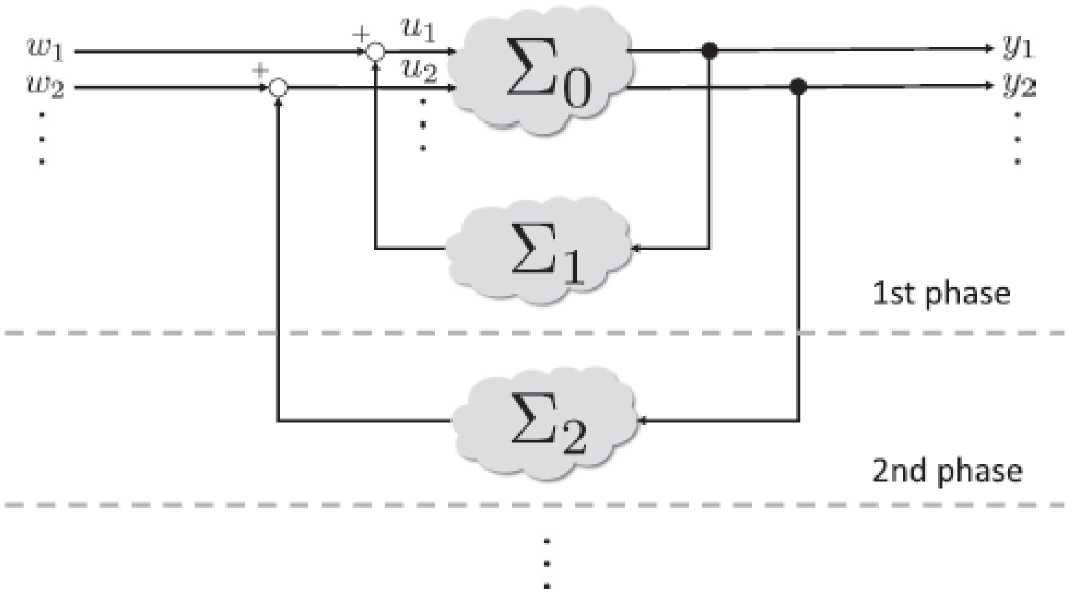

Figure 4-10: Evolution of a base system Σ0 with gradual connection of several subsystems Σi [31]

Retrofit control is an effective method for designing a distributed controller. In the framework of this method, the network system to be controlled is considered as an interconnected system consisting of the desired subsystem and its environment consisting of other unknown subsystems with their interaction. Resilience controllers are defined as controllers that can guarantee the internal stability of the network system for any environment as long as the initial stability of the network system under control is maintained. By designing a retrofit controller as a sub-controller, each sub-controller can implement its control policy independently from other controllers. All retrofit controllers can be specified through the Yola parameter with a linear constraint on the Yola parameter. Unfortunately, since it is difficult to control the finite parameters analytically, the synthesis of the most general retrofit controller cannot be done in a simple way [114]. In Figure 4-11, a schematic of a retrofit control is shown. Accordingly, the Σ2 in Figure 4-11 can be considered as a network system consisting of existing sub-controllers and sub-systems, because its dimensions and structure are not limited. In general, the assumption that a complete system model is available for network systems is not realistic. In addition, the simultaneous design of all sub-controllers is generally difficult to control DER-equipped grid systems. Even if Σ2 is considered as model uncertainty, it is usually assumed to be normative in resistive control. The robustness control problem, the search for a controller that guarantees the stability of the closed-loop system for all possible Σ2, so that the pre-existing system Σ is stable, is different from the usual robust control problems [115].

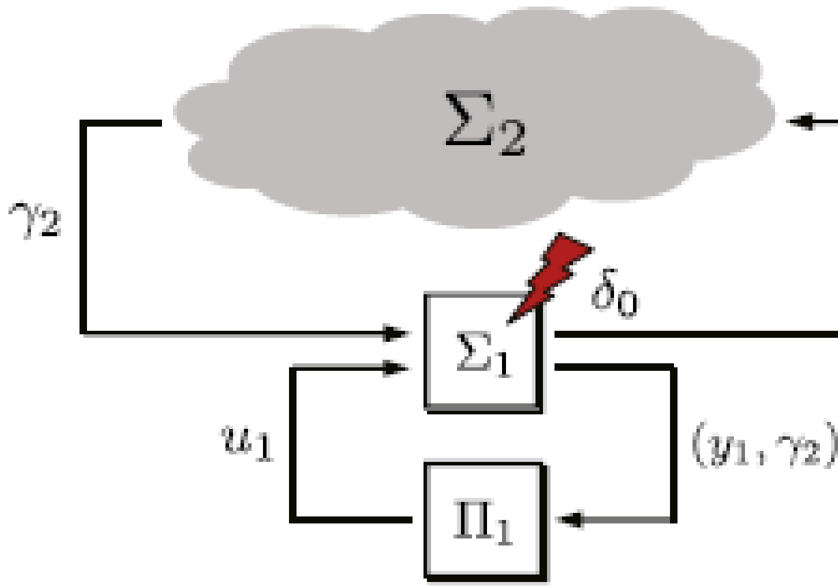

Figure 4-11: Schematic of signal flow in retrofit control [115].

Owing to the extensive use of communication networks, which makes the centralized control operation complex, costly, and unreliable, the research interest has been shifted towards the distributed control paradigms. Figure 4-12 shows the classification of secondary control architecture, which includes centralized, decentralized, and distributed control structures. It is evident from Figure 4-12 that the information-sharing links in a distributed control scheme reduce dramatically with the increasing number of DG units in a MG network [116]

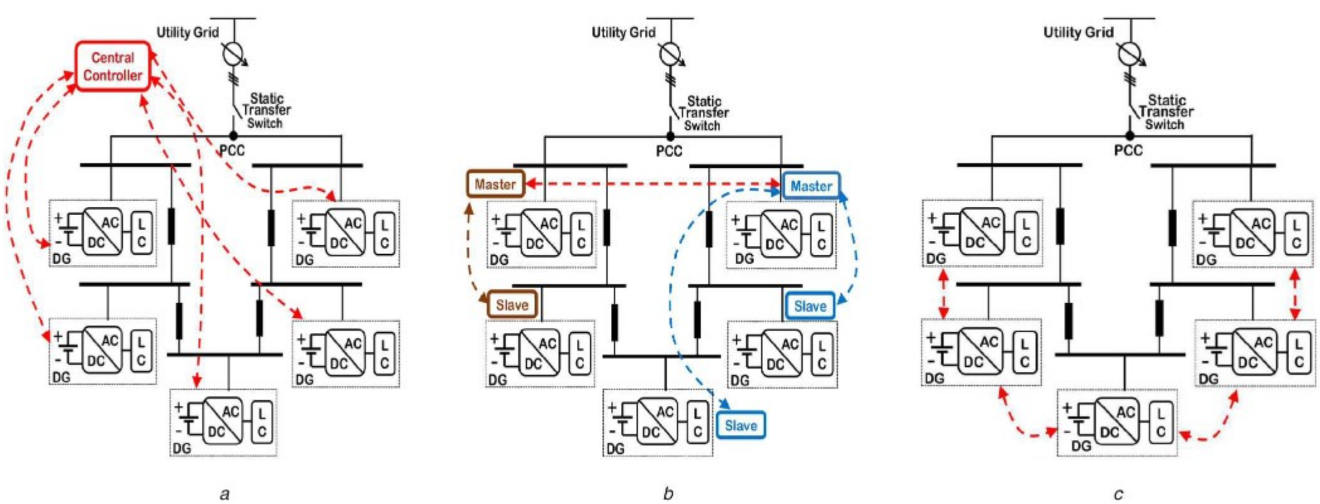

Figure 4-12: Classification of secondary control architecture in AC MG. LC: local controller (a) Centralized control structure, (b) Decentralized control structure, (c) Distributed control structure

4-2 Switching

Given the rapid growth of the electricity industry and its importance in economic, social, and political matters, the proper functioning of this industry is very significant. A closer look at the history of this industry reveals its importance. In 1890, the electricity industry in the United States and Europe was growing rapidly, with power companies building thousands of power systems (both direct current and alternating current). These networks were effectively dedicated to electric lighting. At this time, a hostile competition known as the “War of Currents” broke out between Edison and Nikola Tesla, who was employed by Westinghouse. The war was over the method of transmission and which of the two methods, direct current or alternating current, was better. In 1891, Westinghouse launched the first large power system designed by Tesla, which aimed not only at lighting but also at driving an electric motor. Although high-voltage direct current is used to transmit large amounts of electricity over long distances, most power generation, electric power transmission, electricity distribution, and electric power trading are achieved using alternating current. In many countries, electric power companies own all the infrastructure from power plants to transmission and distribution infrastructure. Therefore, in those countries, electric power is considered a natural monopoly. The electricity industry is generally heavily regulated with price controls, and its ownership and operation are usually in the hands of the government. In some countries with large electricity markets, electricity producers and sellers trade electricity like cash and stocks. Electric power transmission is the second process of delivering electricity after its generation. The electric power transmission network allows the delivery of generated electricity to consumers.

As power networks expanded in cities and the continuous supply of electricity to consumers became necessary, the importance of a critical issue called security emerged. Power system security includes actions that must be taken to keep the system in optimal operating condition. Therefore, a security plan must protect the integrity of the system. Security assessment is an essential, key, and challenging issue for power system operators. Operators must operate the system in an economic state while avoiding security risks and ensuring a minimum security margin. In power system security, it is essential to evaluate and identify lines and equipment with high importance. By ranking lines and equipment from a security perspective, high-importance equipment can be identified, and by reducing their importance and preventing their outage as much as possible, power system security can be increased. After identifying high-importance lines and equipment, appropriate solutions should be provided to reduce their importance. This is very helpful for planners in planning for periodic maintenance and servicing of equipment. Another way to improve network security is to use distributed generation resources in the distribution network [108].

The expansion of networks and the increasing demand for electrical energy, as well as the maximum utilization of electric power transmission systems, have caused power systems to often operate near their security limits. Today, power system security is a serious challenge for planners and operators. Power system security can be at risk from internal and external threats. External factors such as lightning, ecological effects, and internal factors related to the physical nature of power system operation each pose a threat to system security. Operating the power system near limits such as thermal limits for transmission lines and transformers usually causes many problems for the system. Quickly resolving faults and the rapid operation of the system when encountering faults are important factors in maintaining power system security. By using security indices and comparing them, the power system is classified into three categories: secure, warning, or insecure. Given the increasing demand in the electricity industry, load supply and network development are of great importance. One method that can be used for this purpose is the optimal switching of transmission lines, considering the security of the transmission network, which maximizes the utilization of network capacity.

Considering the minimum and maximum reactive power requirements of the distribution system and the economic justification for installing variable capacitors, the minimum and maximum required reactive power can be supplied at the optimal location by placing the necessary taps in the capacitor bank, thus enabling the change of capacitor capacity. For variable capacitors, it must be determined how the switching schedule of capacitors should be planned according to the load changes in the system. For variable capacitors, in addition to the costs mentioned for fixed capacitors, fixed costs such as the cost of the regulator, contactors, and measuring devices should also be added. Variable capacitors can only be installed in ground substations, and capacitor switching may be mechanical or use power electronics devices. The use of variable capacitors causes harmonics in the network. Since the capacitor shows low impedance against high-order harmonics, the current amplitude will be significant. The location of the installed capacitor in the system can determine the amplitude of the generated harmonics. If the harmonic level is such that it causes defects in sensitive electronic equipment or errors in protective equipment, the current passing through the capacitor should be reduced by some means, such as using a reactor. Capacitor placement in the distribution system and its control should be done in such a way that the resulting benefit is maximized. Negative costs include the cost of capacitor installation and positive costs such as energy losses, line construction, and power plant production costs during peak network load [20]. In past research, switching has been done for various purposes. The first application of switching was to take corrective actions in cases of line overload, voltage deviation, etc. Switching has also been used to reduce line losses and congestion in the system. In optimal transmission line switching, by managing congestion in the system, generator production changes, thereby reducing system costs.

4-2-1 Switching and Line Losses

If in a transmission network, one of the two parallel lines connected to a bus is taken out of service, it causes an increase in losses. This is because more power flows through one line, and the equivalent resistance of two parallel lines is less than the resistance of each of those two lines. As a result, it seems that in a large network, if any line is taken out of service, losses increase. However, in a large network, system operators optimize the network structure by taking some lines out of service, which changes the combination and production power of the units compared to the previous state. Therefore, switching lines does not necessarily increase losses. Although losses may increase on some lines, overall, losses may decrease. In optimal line switching in the network, since both the network configuration and the power generation of the generators are optimized together, it cannot be definitively stated that taking a line out of service increases or decreases losses [109]. If in a transmission network, one of the two parallel lines connected to a bus is taken out of service, it causes an increase in losses. This is because more power flows through one line, and the equivalent resistance of two parallel lines is less than the resistance of each of those two lines. As a result, it can be said that in a large network, if any line is taken out of service, losses increase. However, in a large network, system operators optimize the network structure by taking some lines out of service, which changes the combination and production power of the units compared to the previous state, and this does not necessarily increase losses [117].

4-2-2 Switching for Congestion Management

The issue of congestion in the system must be addressed and controlled using congestion management schemes. These schemes are often based on optimal load flow with the following objective functions:

- Minimizing the number of control actions
- Minimizing the cost of redispatch
- Minimizing the difference between the distribution before and after switching [111]

One of the most important and appropriate ways to manage congestion is the optimal change of network structure, which operators use to improve operating conditions. Generally, two types of switches are used for this purpose:

- Disconnect switches
- Tie switches, which are normally closed and open, respectively.

4-2-3 Using Switching as a Preventive and Corrective Action

A key criterion in operating a system is maintaining system reliability. Reliability includes steps that must be taken during the interruption of the operation of system components to maintain system operation. For example, a unit may need to be taken out of service due to the interruption of its auxiliary equipment. By maintaining an appropriate amount of spinning reserve, the remaining units in the system can compensate for the shortage without significant frequency drop or load shedding. Additionally, a transmission line may be damaged by a storm or taken out of service by automatic relays. If sufficient attention is paid to the amount of power transferred from the lines when units are brought online and load is distributed, other transmission lines can handle the resulting overload and remain within permissible operating limits. Since it is impossible to predict the interruption of system components, the system must always be operated in such a way that it does not enter a dangerous state in the event of an incident. Since power system equipment is designed to operate within specific limits, most of them are protected by automatic equipment so that they are automatically taken out of service if they deviate from those limits. If an incident occurs in the system that continues to operate despite deviating from permissible limits, that incident may trigger a series of other incidents and take other equipment out of service. If this continues, the entire system or a large part of it may collapse. Most power systems are operated in such a way that the outage of any single component does not cause overloading of other components [118].

Contingency analysis is an important factor in reliability analysis. The results of such analyses allow systems to be operated reliably. Many issues that occur in a power system can create very serious problems in a very short time frame, making it impossible for the operator to act quickly enough, especially in the case of cascading outages. Due to this operational situation, modern control center computers are equipped with contingency analysis programs that model potential system events before they occur and are used to study contingencies and warn operators of any possible overloads or voltage deviations. Preventive operation methods aim to operate the system in such a way that no problems occur in the continuity of power flow if any of the aforementioned equipment is taken out of service. This requires having sufficient generation capacity to supply more than the consumption demand and having spare capacity on limited exchange lines in the network. In this case, the network is operated so that each piece of equipment is loaded below its thermal limit under normal operating conditions and below its emergency limit under the worst contingency conditions, with the reserve capacity being used in those conditions. However, in practice, it is not possible to fully meet such requirements, and in the event of certain failures, depending on the type, location, and function of the equipment, load shedding occurs in some parts of the network. Another important factor in system reliability is the examination of corrective actions that allow operating personnel to change the system's operating status in the event of an overload or when the contingency analysis section predicts a serious issue in the event of a specific interruption. A simple example of such corrective actions is the transfer of power from one unit to another. Such transfers can change the power transferred from lines and, consequently, the load on overloaded lines. In such conditions, considering that switching can be a powerful and cost-effective tool for relieving transmission line congestion, it can probably help reduce the limitations of delivering spinning reserve in potential contingency conditions and also reduce the amount of load shedding in the network caused by these failures. However, this issue should be simulated and studied using available tools in standard test systems [113].

4-2-4 Possibility of Transmission Line Switching in Real Systems

Generally, the planning for the construction of transmission networks is such that they can withstand various operating conditions of the system, including normal conditions and potential contingencies, different load levels, and the distribution of generation at different points in the network. These conditions are not always constant, so it may be necessary for a line to be in service under certain conditions, but not under others, and its absence may even be economically beneficial. When using a transmission line incurs no cost for the operator, the operator will certainly use this line in the network to transfer power and increase system reliability. Therefore, line switching is feasible, and given the limitations in constructing new lines, it is appropriate to make better use of the capacity of existing lines in the network. Kirchhoff's laws also allow the opening of lines for economic load distribution correction. Line opening for load distribution correction has previously been done on a small scale. There is evidence that system operators take lines out of or bring them into service for reactive power consumption or production or other reasons. The Northeast Power Coordinating Council has included the removal of internal transmission lines in the list of actions that can be taken to avoid inappropriate voltage conditions. Additionally, system operators are prepared to quickly close lines in emergencies. In PJM, these special protection schemes allow operators to take lines out of service during normal operation and return them to the network during emergencies [119].

4-2-5 Objectives of Switching

- Relieving overloads
- Reducing overvoltage
- Minimizing losses
- Increasing security
- System resilience against potential contingencies
- Reducing operating costs [105]

4-2-6 Optimal Transmission Line Switching

Transmission line switching was initially proposed as a method to control the network against common network problems. In the optimal transmission line switching problem, an objective function is defined to obtain the optimal distribution of generated power and transmission structure at different load levels. The model of this problem is a mixed-integer linear or nonlinear programming. In this model, binary variables are defined to indicate whether each transmission line is connected or disconnected. The problem is based on the optimal direct current load flow (DCOPF). The objective function is the cost of generator production, which must be minimized considering the physical constraints of the network and Kirchhoff's laws. Due to some specific characteristics of electrical energy, the cost of power distribution in the network can be reduced by removing some transmission lines. Therefore, the optimization problem initially considers zero disconnected lines, and by removing one or more lines from the network, the value of this objective function improves. For this purpose, binary variables are defined for the transmission lines in the network, where zero indicates the line is open and one indicates the line is closed. The networks studied in this research are the standard 118-bus and 57-bus networks. Additionally, the number of lines allowed to change state is limited by a parameter in this thesis. The results obtained show that using optimal transmission line switching and an appropriate network structure can save up to 25% in costs [119].

The problem of optimal transmission line switching in the optimal unit commitment problem with network security constraints is proposed to prevent transmission-related deviations and reduce operational costs [116]. This problem is decomposed into two sub-problems: optimal unit commitment as the main problem and optimal transmission line switching as the sub-problem. The unit commitment problem determines the optimal generation levels for generators at different hours, and the optimal transmission line switching problem is used to find the best possible power distribution based on network constraints. Optimal transmission line switching is also used to test network line congestion and propose necessary changes for the optimal unit commitment problem. The algorithm used for decomposition in this problem is the Benders decomposition algorithm. Due to the large volume of calculations in networks with more realistic constraints, the direct current approximation is used. Although sometimes these approximations may not be beneficial and may not only fail to reduce costs but also increase production costs. Initially, we use the optimal alternating current load flow to obtain the desired parameters, then in the optimal transmission line switching problem, due to the long computation time, we use the optimal direct current load flow. A parameter is defined to rank the network transmission lines for applying changes. This parameter is obtained based on the dual of some alternating current load flow constraints. Then the problem is formulated as a mixed-integer linear programming problem, reducing the volume and computation time. Various other methods have also been investigated to speed up the process of solving the optimal transmission line switching problem [120].

The optimal transmission line switching problem, considering sensitivity analysis and other explanations, is examined in [121]. This paper considers changes in marginal and nodal prices, net generator revenues, line congestion permissions, and power distribution prices with optimal switching for different network loads. It is also stated that there is no guarantee that increasing the number of removed lines will necessarily reduce production costs. Sensitivity analysis is also performed using the bus angle constraint to examine whether different configurations cause changes in results. One of the noticeable results of these analyses is the significant changes in nodal prices for different configurations. Another issue in optimal transmission line switching is network reliability. Ensuring network reliability after switching is a very important issue that must be carefully examined. The analysis of stochastic processes and network reliability with the removal of a component has been studied [122]. For two different applications of switching, planning and operational, there are differences in the priorities examined. Initially, an optimal network switching model without considering a component and based on the optimal direct current load flow is presented, where the absence of a component affects both the objective function and the problem constraints. The only constraint that must always be met is the load supply issue. Then the proposed model is decomposed into sub-problems using some decomposition methods to make solving the problem faster and easier overall. This paper shows that the optimal transmission line switching problem not only does not jeopardize network reliability and stability but also significantly reduces production costs. Optimal line switching is also used as a tool to improve network security.

Transmission Network Security

Evaluating network security is one of the important issues in the planning, design, and operation phases of power networks. Events that occur in the power network are the result of natural phenomena (such as lightning striking a transmission line, ultimately leading to the line's outage) or human factors (such as switching a line). The occurrence of events can cause small disturbances (over a long time frame) or larger and faster ones. For example, the timing and extent of the consequences of the following two events are significantly different [121]:

- Change in consumer behavior, consumers randomly due to an unexpected incident
- b) Outage of a transmission line or a power plant

Numerical simulation of an event is usually used to evaluate its impact on the power network, but the nonlinear and unpredictable nature of natural phenomena and the increasing complexity of power networks make security evaluation challenging. Every small change in any of the network loads causes a change in the system's state, and the accumulation of these small changes (no matter how small) brings the system closer to or further from security margins. However, network security is only evaluated for large events that lead to widespread state changes in the system. For example, the operation of relays, which often cause the outage of lines and transformers, is one of the important factors in changing the state of power networks. After any change in the network, each part of the system reacts to the changed operating conditions and may reach a new operating state. Evaluating the numerical response of each component to the applied change and examining the new operating conditions of each element is called security evaluation [123].

Chapter 5: Efficient Hydrogen-Based Water-Power Strategy to Alleviate the Number of Transmission Switching within Smart Grid

A version of this section of the manuscript has been accepted by the ScienceDirect Advances in Electrical Engineering, International Journal of Hydrogen Energy. A.A Niaki conducted the research under the guidance of M. Jamil, who served as the co-author. A.A Niaki was responsible for performing the literature review, system selection, design, calculations, simulations, and efficiency analysis. The co-author contributed by refining the research concepts and providing critical feedback and revisions to the manuscript.

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Chapter 5 introduces an innovative hydrogen-based water-power strategy aimed at reducing the need for transmission switching and enhancing smart grid efficiency. It details the integration of a grid-connected system that uses electrolysis, powered by excess renewable energy, to generate hydrogen, which is then stored and used in fuel cells. This chapter explores the system's technical design, operational dynamics, and its potential to stabilize power flows by mitigating the variability of renewable energy sources. Through simulations, it demonstrates how this system significantly lowers the frequency of transmission switching, thereby easing the wear on infrastructure and reducing operational costs. The findings highlight the system's benefits in improving grid reliability and efficiency while discussing scalability and future research directions for broader implementation. This approach underscores the potential of hydrogen technology in transforming energy management and enhancing grid resilience.

5-1 Problem Formulation

This paper proposes an SCUC model that incorporates Transmission Switching (TS) with Dynamic Thermal Line Rating (DTLR) serving as security constraints [123]. The objective function, defined in equation (5-1), aims to minimize both generation costs and load outages. The generation costs include active and reactive powers, and reserved power costs, which are considered to be in access [124]. Constraints (5-2) and (5-3) denote the active and reactive power generation limits. The reserved power for each generator is determined by variable for each scenario $\Delta r_{g,t}^{s}$. Constraints (5-4), (5-5), and (5-6) govern the entry $v_{g,t}$and $w_{g,t}$exit of generators, where and are binary variables. Constraints of ramp up/down are specified in equations (5-7), (5-8). Each generator's reserve capacity is constrained in (5-9). Equation (5-10) represents the active power balance and energy hub system, accounting for line losses and load outages. Similarly, (5-11) expresses the reactive power balance. The operation of TS is described by constraints (5-12) and (5-13), where zc_{k}^{s}represents the contingency state of line k, and variable $z_{k,t}$indicate the connection and disconnection of lines. A high positive integer is denoted by M , and $P_{b,m,k,t}^{s}$represents the power flowing between line b and bus m. ,$z_{k,t}$takes a value of one if the line is in operation, and the power flow is $P_{b,m,k,t}^{s}$. If it is decided to switch off the line, $z_{k,t}$takes a value of 1, and the power flow is set to a high positive or negative integer. Constraints (5-14)-(5-15) impose limits on the lines' power flow. Additionally, constraints for active and reactive power line losses can be given in (5-16)-(5-19) considering losses of the line in the power flow. The model also considers limitations on the magnitude and angle of voltage of bus, as defined in equations (5-20)-(5-24). The SCUC problem is planned for a 24-hour day-ahead period. The presented model flowchart can be illustrated in figure 5-1.

$$MinZ^{down} = \sum_{t}\sum_{g}\left[C\left(P_{g,t}\right)+SU_{g,t}+SD_{g,t}+C\,\Delta r_{g,t}^{s}\right] \tag{5-1}$$

$$P_g^{min}u_{g,t}uc_g^s \le P_{g,t}+\Delta r_{g,t}^s \le P_g^{max}u_{g,t}uc_g^s \tag{5-2}$$

$$Q_g^{min}u_{g,t}uc_g^s \le Q_{g,t}^s \le Q_g^{max}u_{g,t}uc_g^s \tag{5-3}$$

$$v_{g,t}-w_{g,t}=u_{g,t}-u_{g,t-1} \tag{5-4}$$

$$\sum_{t'=t-UT_g+1}^{t} v_{g,t'} \le u_{g,t}, \qquad \forall g, t \in \left\{UT_g, \ldots, T\right\} \tag{5-5}$$

$$\sum_{t'=t-DT_g+1}^{t} w_{g,t'} \le 1-u_{g,t}, \qquad \forall g, t \in \left\{DT_g, \ldots, T\right\} \tag{5-6}$$

$$P_{g,t}-P_{g,t-1} \le R_g^{+}u_{g,t-1}+R_g^{SU}v_{g,t} \tag{5-7}$$

$$P_{g,t-1}-P_{g,t} \le R_g^{+}u_{g,t}+R_g^{SU}w_{g,t} \tag{5-8}$$

$$-SR_g^{+} \le \Delta r_{g,t}^s \le SR_g^{+} \tag{5-9}$$

$$\sum_{\forall g(b)}\left(P_{g,t}+\Delta r_{g,t}^s\right)+P_t^{EH} - \sum_{\forall k(b,m)}\left(P_{k,t}^s+0.5PL_{k,t}^s\right)=PD_{b,t}^s \tag{5-10}$$

$$\sum_{\forall g(b)}Q_{g,t}^s+\sum_{\forall k(b,m)}\left(Q_{k,t}^s-0.5QL_{k,t}^s\right)=QD_{b,t} \tag{5-11}$$

$$P_{b,m,k,t}^{s} - M\left(1 - z_{k,t} zc_{k}^{s}\right) \le P_{k,t}^{s} \le P_{b,m,k,t}^{s} + M\left(1 - z_{k,t} zc_{k}^{s}\right) \tag{5-12}$$

$$Q_{b,m,k,t}^{s} - M\left(1 - z_{k,t} zc_{k}^{s}\right) \le Q_{k,t}^{s} \le Q_{b,m,k,t}^{s} + M\left(1 - z_{k,t} zc_{k}^{s}\right) \tag{5-13}$$

$$-P_{k}^{max} .z_{k,t} .zc_{k}^{s} \le P_{k,t}^{s} \le P_{k}^{max} .z_{k,t} .zc_{k}^{s} \tag{5-14}$$

$$-S_{k}^{max} .z_{k,t} .zc_{k}^{s} \le Q_{k,t}^{s} \le S_{k}^{max} .z_{k,t} .zc_{k}^{s} \tag{5-15}$$

$$g_{k} \sum_{l=1}^{L} k(l) \Delta\delta_{k,t}^{s}(l) - M\left(1 - z_{k,t} zc_{k}^{s}\right) \le PL_{k,t}^{s} \le g_{k} \sum_{l=1}^{L} k(l) \Delta\delta_{k,t}^{s}(l) + M\left(1 - z_{k,t} zc_{k}^{s}\right) \tag{5-16}$$

$$0 \le PL_{k,t}^{s} \le z_{k,t} .zc_{k}^{s} . g_{k} \left(\delta_{k}^{max}\right)^{2} \tag{5-17}$$

$$-b_{k} \sum_{l=1}^{L} k(l) \Delta\delta_{k,t}^{s}(l) - M\left(1 - z_{k,t} zc_{k}^{s}\right) \le QL_{k,t}^{s} \le -b_{k} \sum_{l=1}^{L} k(l) \Delta\delta_{k,t}^{s}(l) + M\left(1 - z_{k,t} zc_{k}^{s}\right) \tag{5-18}$$

$$0 \le QL_{k,t}^{s} \le -z_{k,t} .zc_{k}^{s} .b_{k} \left(\delta_{k}^{max}\right)^{2} \tag{5-19}$$

$$\delta_{k}^{min} \le \delta_{k,t}^{s} \le \delta_{k}^{max} \tag{5-20}$$

$$\Delta V^{min} \le \Delta V_{b,t}^{s} \le \Delta V^{max} \tag{5-21}$$

$$-\Delta SP_k^{max} - M\left(z_{k,t-1} - z_{k,t} + 1\right) zc_k^s \le \delta_{k,t}^s \le$$
$$\Delta SP_k^{max} + M\left(z_{k,t-1} - z_{k,t} + 1\right) zc_k^s \tag{5-22}$$

$$\delta_{k,t}^{+s} - \delta_{k,t}^{-s} = \delta_{k,t}^s \tag{5-23}$$

$$\Delta V_{b,t}^{+s} - \Delta V_{b,t}^{-s} = \Delta V_{b,t}^s \tag{5-24}$$

$$\sum_g \left(GS_g^k \Delta P_g \right) + P_k^0 \le P_k^{\max} \tag{5-25}$$

$$\sum_g \Delta P_g = 0 \tag{5-26}$$

$$GS_g^k = \frac{\Delta P_k}{\Delta P_g} \tag{5-27}$$

$$GS_g^k = \frac{\partial P_k}{\partial \delta_b} \cdot \frac{\partial \delta_b}{\partial P_g} + \frac{\partial P_k}{\partial \delta_m} \cdot \frac{\partial \delta_m}{\partial P_g} \tag{5-28}$$

In this model, because of congestion management, generated power of generators changes ideally in a contingency scenario, in order to reduce congestion in lines, and decrease the switching number. The reduction in the switching number will lead to decreased repair, maintenance, and operation costs. Common equations of the SCUC problem are not mentioned for the sake of briefness. Equations (5-25) - (5-28) express congestion management. These equations limit the power flow of lines in the SCUC problem with TS, and are fully discussed in [125]. Congestion management calculates the sensitivity of each generator's power to each line and determines the power variation in each generator to prevent congestion in lines.

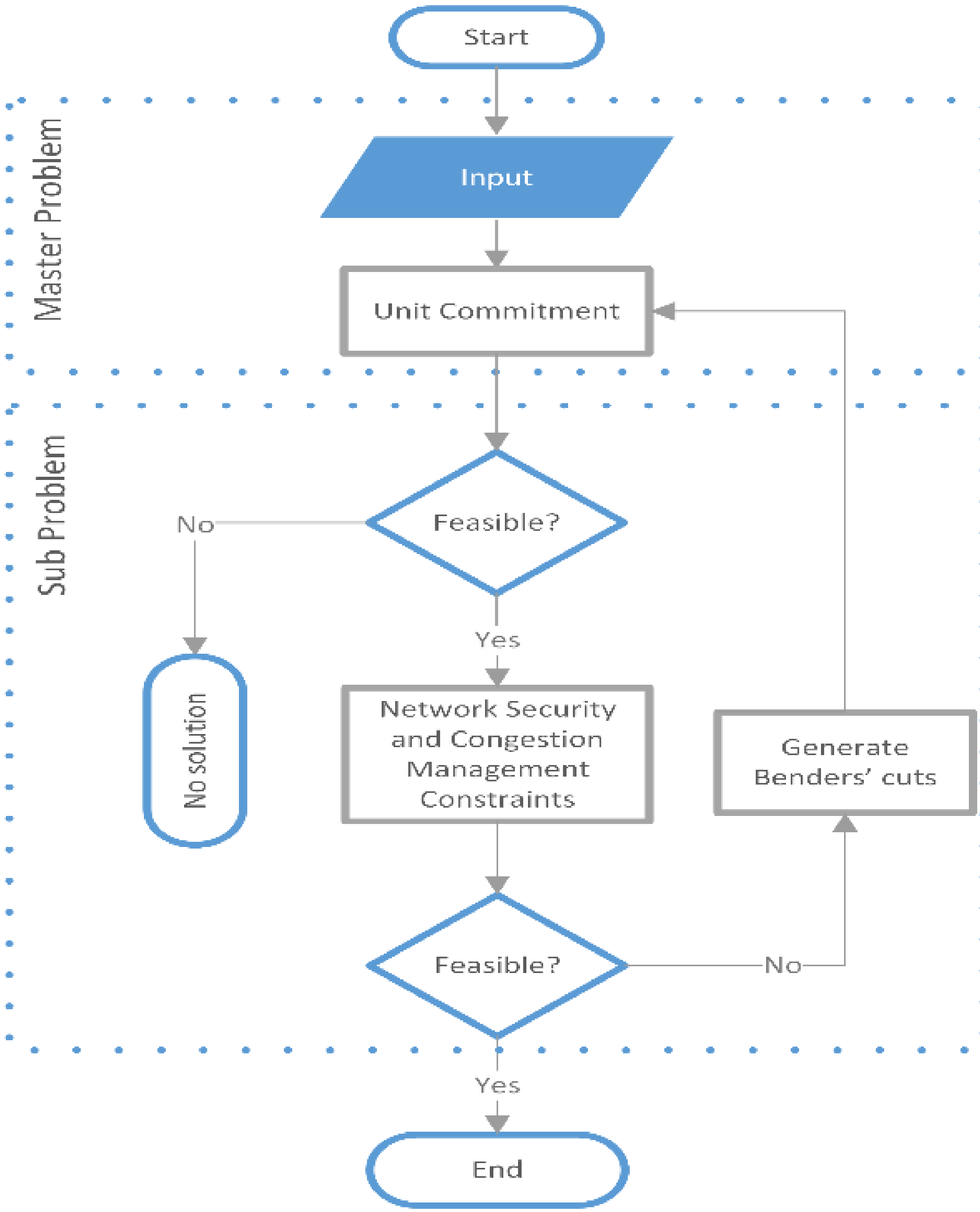

Figure 5-1: The introduced model flowchart of the SCUC with CB

5-1-1 The Mathematical Definition of the Introduced Water-Power System

As previously mentioned, the water-power system is recognized as a multi-energy system owing to supplying the different electrical, thermal, and water energy carriers [125]. To be more precise, we discuss a comprehensive structure of the introduced water-power system to delineate how the sundry energy resources command the energy linkage to facilitate energy management. Hence, each energy segment that is distinct from another in the forms of the objective function, load type; the corresponding constraints are individually explanted as (5-29) – (5-49) [126].

Objective Function

$$\mathrm{C}^{hub} = \sum_{t \in \Omega^T} \begin{pmatrix} P_t^{EH} \times R_{EH} + Pa_t^{bat} \times Ra_{bat} + \\ Pc_t^{CH} \times Rc_{CHP} + Pb_t^{Boi} \times Rb_{Boi} + \\ + Wa_t^{Grid} \times Ra_{Water} \end{pmatrix} \tag{5-29}$$

Constraints: Electrical

$$P_t^L + P_t^{Des} = \delta_e^T P_t^{EH} + P_t^{FU} + \delta_{ch} Pc_t^{CH} + Pa_t^{bat} \qquad ,\forall t \in \Omega^T \tag{5-30}$$

$$\underline{Ea}^{bat} \le Ea_t^{bat} \le \overline{Ea}^{bat} \qquad ,\forall t \in \Omega^T \tag{5-31}$$

$$Ea_t^{bat} = \left(1 - \varphi_e^{loss}\right) Ea_{t-1}^{bat} + Pa_t^{bat} \qquad ,\forall t \in \Omega^T \tag{5-32}$$

$$\frac{1}{\delta_e} \underline{P}a^{bat} \le Pa_t^{bat} \le \frac{1}{\delta_e} \overline{P}a^{bat} \quad ,\forall t \in \Omega^T \tag{5-33}$$

$$\underline{P}_t^{EH} \le P_t^{EH} \le \overline{P}_t^{EH} \qquad ,\forall t \in \Omega^T \tag{5-34}$$

$$P_t^{FU} = P_t^{FL} + P_t^{FB} \qquad \forall t \in \Omega^T \tag{5-35}$$

$$P_{FC}^{\min} \le P_t^{FL} + P_t^{FB} \le P_{FC}^{\max} \qquad \forall t \in \Omega^T \tag{5-36}$$

$$0 \le nH_2^t \le nH_2^{\max} \qquad \forall t \in \Omega^T \tag{5-37}$$

$$nH_2^t = (P_t^{FL} + P_t^{FB}) \times \frac{3.6\,{}^{MJ}\!/_{kWh}}{119.96\,{}^{MJ}\!/_{Kg}} \qquad \forall t \in \Omega^T \tag{5-38}$$

Constraints: Heat (5-39)

$$P_t^H = \delta_{ch} Pc_t^{CH} + \delta_{boi} Pb_t^{Boi} \qquad ,\forall t \in \Omega^T \tag{5-40}$$

$$P_t^G = Pc_t^{CH} + Pb_t^{Boi} \qquad ,\forall t \in \Omega^T \tag{5-41}$$

$$\delta_e^{Trans} P_t^{EH} \le Cap^T \qquad ,\forall t \in \Omega^T \tag{5-42}$$

$$\delta_{ch} Pc_t^{CH} \le Cap^{CH} \qquad ,\forall t \in \Omega^T \tag{5-43}$$

$$\delta_{boi} Pb_t^{Boi} \le Cap^{Boi} \qquad ,\forall t \in \Omega^T \tag{5-44}$$

Constraints: Water (5-45)

$$S_t^T = S_{t-1}^T + W_t^{Grid} + W_t^{sea} - W_t^l \qquad ,\forall t \in \Omega^T \tag{5-46}$$

$$\underline{S}^T \le S_t^T \le \overline{S}^T \qquad \forall t \in \Omega^T \tag{5-47}$$

$$\underline{W}^{sea} . I_t^{DT} \le W_t^{sea} \le \overline{W}^{sea} . I_t^{DT} \qquad \forall t \in \Omega^T \tag{5-48}$$

$$P_t^{Des} = W_t^{sea} . CF^{Des\_W} \qquad \forall t \in \Omega^T \tag{5-49}$$

As can be seen in (5-29), the objective function conforms to three various terms related to the energy segments like electricity, heat, and water. First, the goal is to lessen the energy power transaction cost alongside the accessory cost of the storage unit. the second term delineates the costly aim of the heat segment related to the input gas cost involved by the boiler and CHP units. In the end, the water energy management undertakes to pay the additional cost once the water grid supplies distinctly the surplus water to compensate for the demand at the peak-load time. But, all these goals would be fructified if getting kept in all the corresponding constraints (5-30) – (5-49). Looking over the first segment, equation (5-30) shows the power balance between the output power of CHP, the storage's power, and the power received/sent from/to the grid to handle the electrical demand. it can be seen that the demands including the load and the desalination unit's power are defined on the left-hand of the equation while the supply resources are inserted on the opposite side. Also, limitations associated with the storage unit's performance can be met by (5-31) – (5-33). The power exchange is limited by (5-34). The Protein Exchange Membrane Fuel Cell (PEMFC) is widely recognized among the efficient fuel cell types in various implementations [127]. In a PEMFC, the primary fuel for generating electrical power is hydrogen (H2), which is typically supplied from a hydrogen tank. The required mass of hydrogen to meet the desired output power can be determined using the constraint specified in equation (5-35). The PEMFC output power consists of two components: the power sent to the loads and the power transferred to the storage system, as indicated in equation (5-38). To ensure optimal performance, the total power sent from the PEMFC to the loads and batteries must fall within the permissible range of the PEMFC's minimum and maximum output powers, as described in equation (5-36). It is worth noting that the PEMFC efficiency is considerably mitigated as long as the output power drops below a certain threshold. To address this concern, the output power is assumed to be 10% of the normal output power to mitigate the adverse effects. Additionally, constraints on the absorbed hydrogen mass is imposed, as illustrated in (5-37) [128-130]. Similar to the power segment, the thermal balance needs to be brought about between heat resources and the thermal demand as followed by equations (5-40) and (5-41). Indeed, the heat outputs of CHP and boiler units should be up to a normal level to satisfy the thermal loads at any time s. The input gas bulk of both units is equaled to the gas generation of the main grid as shown in (5-41). It should be noted that the generation capacity of all these units are essential to be considered in the energy dispatching by (5-42) – (5-44). In the last part, the water balance is established using water grids and the seawater desalinated by the relevant unit. What the equation (5-46) indicates is the water balance between the demands and the water resources. The grid's water is promptly applied to the water balance while the desalinated seawater is saved in the tanker which is limited by equation (5-47)- (5-48). Also, the desalination unit's power is computed by (5-49) based on the seawater bulk. All in all, for better realization of the proposed energy strategy, Figure 5-2 illustrates the coign of vantage of the grid-connected water-power energy framework.

5-1-2 Uncertainty Approach

Modeling the probability of events in the power system poses a significant challenge due to the interdependent and complex structure of generation units, lines, and stations. Essentially, addressing the uncertainty problem requires modeling based on two key concepts: 1) the probability of equipment failure, and 2) the correlation probability among these failures. When a contingency occurs in the system, cascading failures become highly probable due to operational protection issues. Therefore, a robust uncertainty method is necessary to model both the probability of failures and their correlations during system operation. The UT method is adept at accurately determining these features compared to other

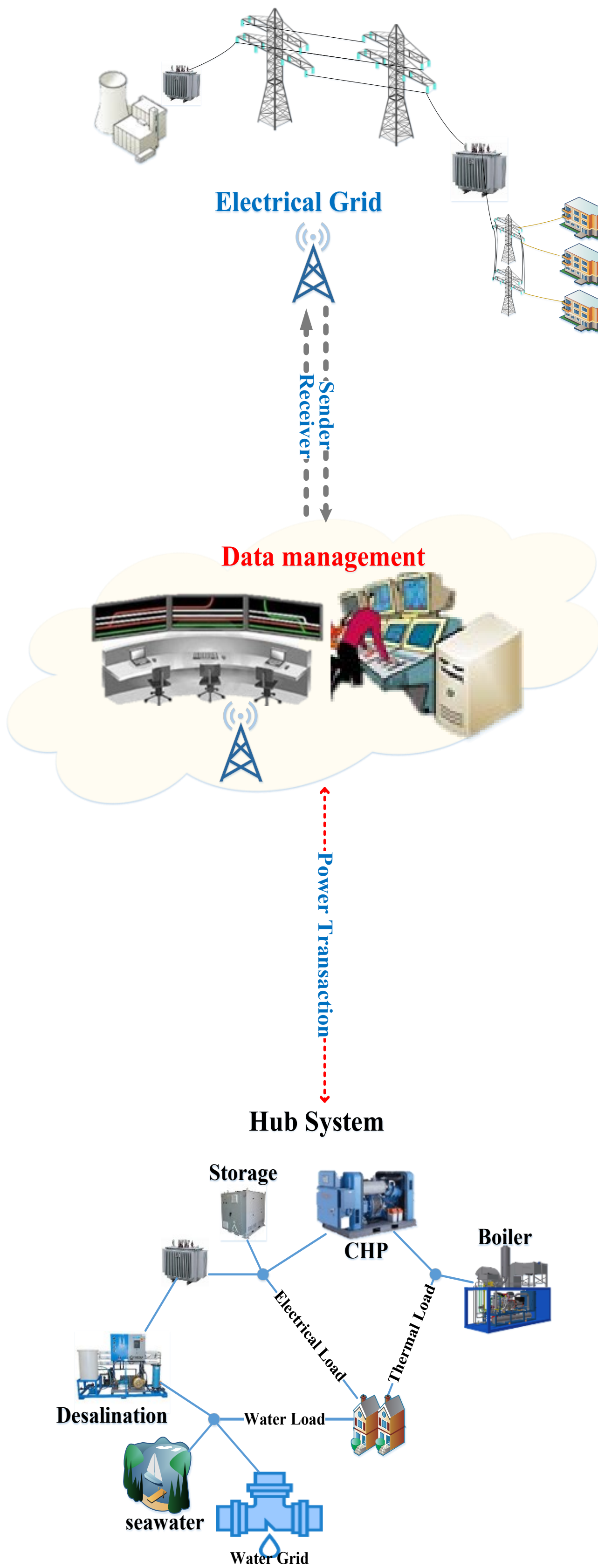

Figure 5-2: Illustration of the proposed energy strategy

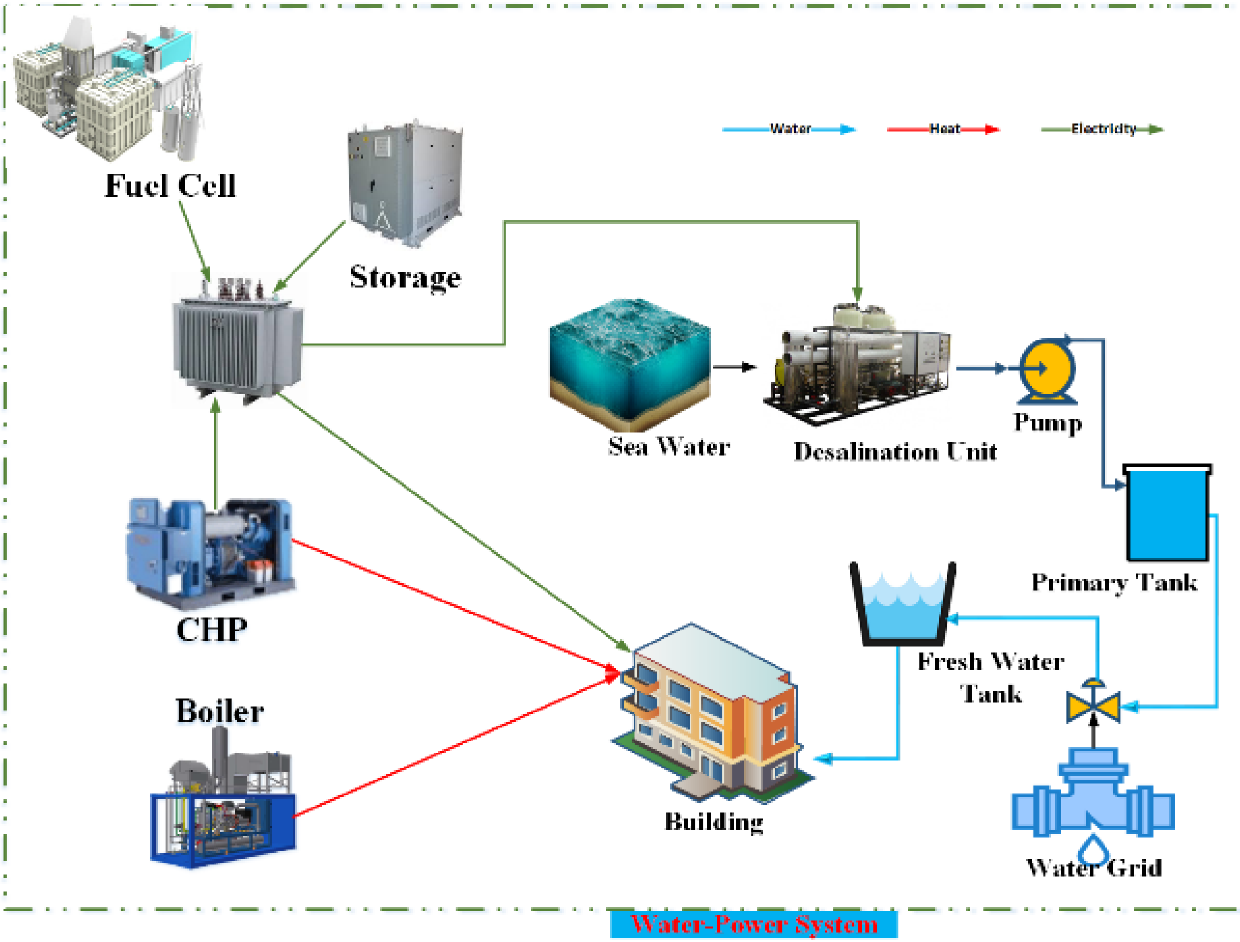

Figure 5-3: The water-power demand supplement system [126]

methods in the literature. As noted already, on account of the uncertain parameters in the system, the proposed energy strategy needs to be evolved in a way to lessen the chance of having the error probability in the conclusive result. To this end, this paper captures an additional layer in reliance on the uncertainty model for the proposed strategy to cover the uncertainty here. Meanwhile, the UT uncertainty model is addressed to anticipate the uncertain parameters including the failure of all lines , generation units which are available in the power system, water demands, thermal demands, and electrical load demands. In this method, the points are randomly generated and converted from the likely space to the discreet space. Then, they are sorted into a matrix X considering the nonlinear relationship $T = \hat{f}(X)$ in which the point covariance A and the mean value are applied. To recapitulate briefly, a three-step framework is presented here:

Step 1: Compute the points by (5-50) - (5-52).

$$X^0 = z \quad (5\text{-}50)$$

$$X^k = z + \left(\sqrt{\frac{p}{1-W^0} Y_{aa}}\right)_k \quad k = 1, 2, ..., p \quad (5\text{-}51)$$

$$X^{k+c} = z - \left(\sqrt{\frac{p}{1-W^0} Y_{aa}}\right)_k \quad k = 1, 2, ..., p \quad (5\text{-}52)$$

Wherein Y_{aa} is the covariance matrix by $\bar{R} = z$.

Step 2: the points' weights are computed using (3539):

$$W^k = \frac{1-W^0}{2p} \quad k = 1, 2, ..., 2p \quad (5\text{-}53)$$

Step 3: Ultimately, the outputs can be obtained by using $\hat{f}(X^k)$ as follows:

$$\bar{T} = \sum_{k=0}^{2p} W^k T^k \quad (5\text{-}54)$$

$$C_{TT} = \sum_{k=1}^{2p} W^k \left(T^k - \bar{T}\right)\left(T^k - \bar{T}\right)^R \quad (5\text{-}55)$$

5-2 Case Study

The obtained results by employing the introduced model for the IEEE standard 6-bus and a larger-scale 118-bus systems are presented in this section [26]. The structure of 6-bus system is illustrated by Figure 5-4. Also, Tables II and III show the detailed information of system. The implementation covers a 24-hour period. Additionally, the proposed SCUC model, incorporating TS and DTLR, and a traditional SCUC model are compared with each other. The computations are performed utilizing the CPLEX solver in the GAMS environment [26] on a desktop computer equipped with a 3.4 GHz processor and 32 GB of RAM.

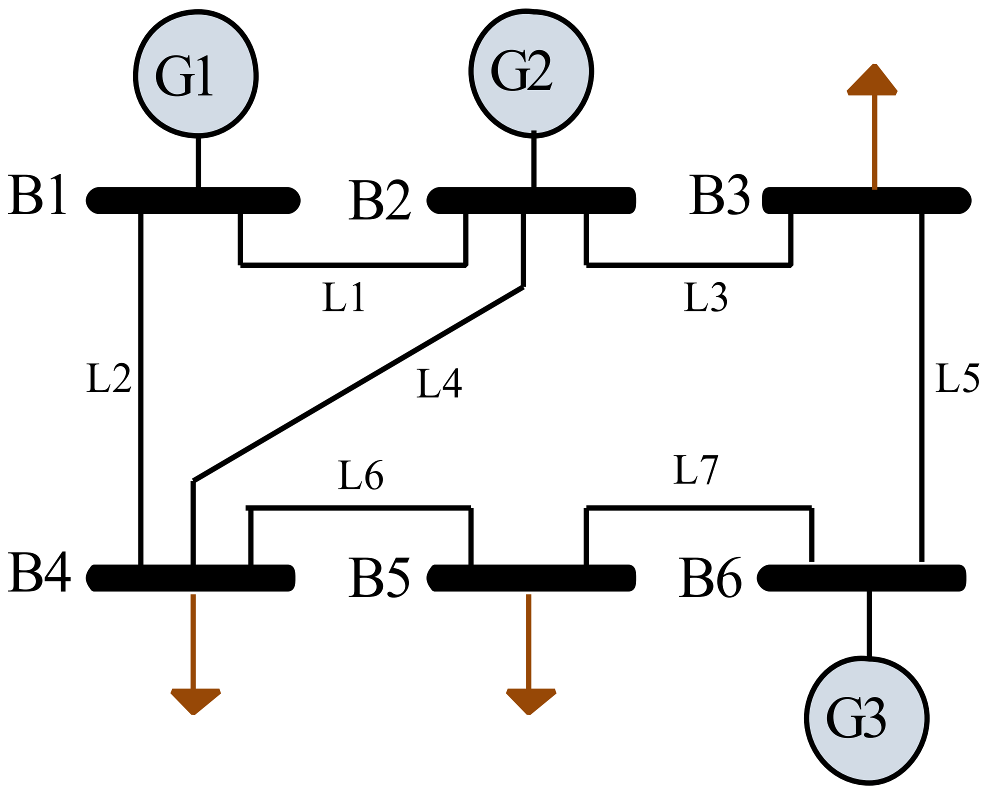

Figure 5-4: 6-bus IEEE testbed grid [123]

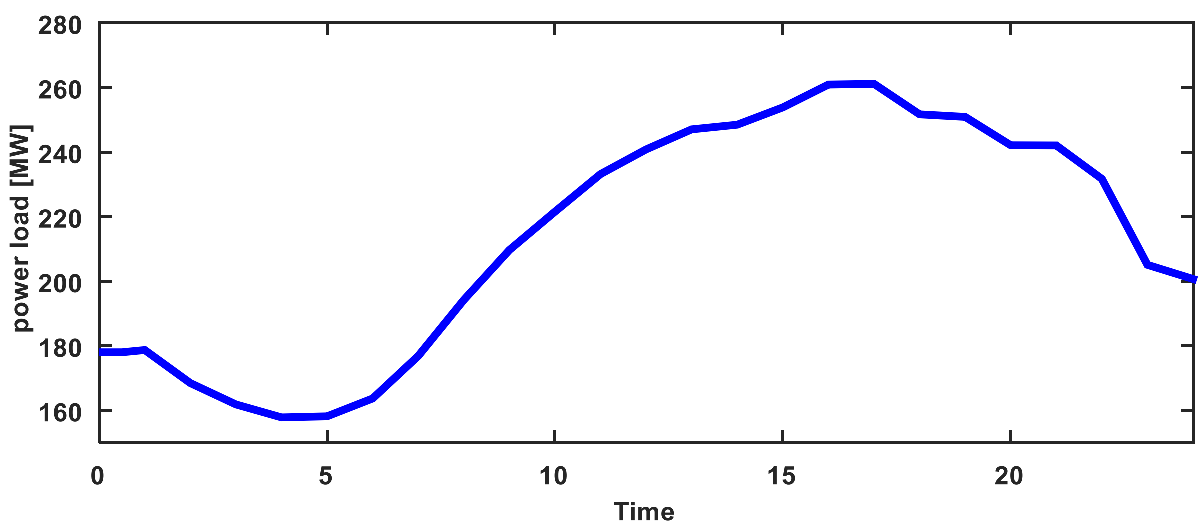

Figure 5-5: Load of 6-bus IEEE test grid [123]

Table 5-1: Generators information

	G1	G2	G3
Price of energy bid ($/MWh)	20	23	35
Ramp up/down rate (MW/h)	55	50	20
Cost of start-up ($)	100	100	100
P_{max} (MW)	220	200	50
P_{min} (MW)	100	10	10
Q_{max} (MW)	200	70	50
Q_{min} (MW)	-80	-40	-40
Minimum up time (h)	4	3	1
Minimum down time (h)	4	2	1

5-3 Evaluation of The Proposed Energy Strategy

Congestion management was commonly used in the real-time market. Here, congestion management was performed during 24-hour period, in order to demonstrate its effects on the TS power flow. In Table 5-2, results for Static Line Rating (SLR) mode (i.e. maximum temperature of lines) and the proposed model are compared during a contingency scenario. Note that the number of switchings related to lines that are main in the grid structure is considered in the scenarios, as the main lines are more susceptible to contingencies compared to other lines.

Table 5-2: Transmission lines data

Line number	From bus	To bus	X_l (pu)	R_l (pu)	Flow limit (MW)
L1	1	2	0.17	0.005	150
L2	1	4	0.258	0.003	150
L3	2	3	0.037	0.022	150
L4	2	4	0.197	0.007	150
L5	3	5	0.018	0.005	150
L6	4	5	0.037	0.002	37
L7	5	6	0.14	0.002	150

As such, scenario case number 10 has been selected for the simulation study, focusing on both the two 6-bus and 118-bus systems as outlined in Table 5-1. Additionally, the outage of generator 2 in the 6-bus system and the outage of generator 13 in the 118-bus system are considered as contingencies here. In this case study, we considered 10 scenarios according to the high-crucial lines and generators for two bus-6 and bus-118 power grids including: 2) outage of generator 2 and switching of line 2-4 in SLR method based bus-6 system, 2) outage of generator 2 and switching of line 4-5 in SLR method based bus-6 system, 3) outage of generator 2 and switching of line 2-4 in proposed method based bus-6 system, 4) outage of generator 2 and switching of line 4-5 in proposed method based bus-6 system, 5) outage of generator 13 and switching of line 30 in SLR method based bus-118 system, 6) outage of generator 13 and switching of line 78 in SLR method based bus-118 system, 7) outage of generator 13 and switching of line 90 in SLR method based bus-118 system, 8) outage of generator 13 and switching of line 30 in proposed method based bus-118 system, 9) outage of generator 13 and switching of line 78 in proposed method based bus-118 system, 10) outage of generator 13 and switching of line 90 in proposed method based bus-118 system.

Table 5-3: Comparison of TS implementation in SLR mode and introduced model with various scenarios

		Case #	Line	Number of switching	Cost ($)
6- bus system (generator 2 is out)	SLR mode	I	2-4	9	3.108×10^5
		II	4-5	14	
	Proposed model	III	2-4	2	2.3935×10^5
		IV	4-5	3	
118-bus system (generator 13 is out)	SLR mode	V	30	11	1.091×10^6
		VI	78	10	
		VII	90	8	
	Proposed model	VIII	30	6	1.0075×10^6
		IX	78	3	
		X	90	4	

In SLR mode, when a generator failure happens, the generators with cheaper costs have to provide more power, until the power of the failed generator is provided. This will lead to congestion in some of the lines, and increase the number of switching, accordingly. As shown in figure 5-6, when generator number 2 is turned off, in hours 1-9, all the power comes from generator number 1, after that generator number 3 starts to provide power for the system too (see Figure 5-7).

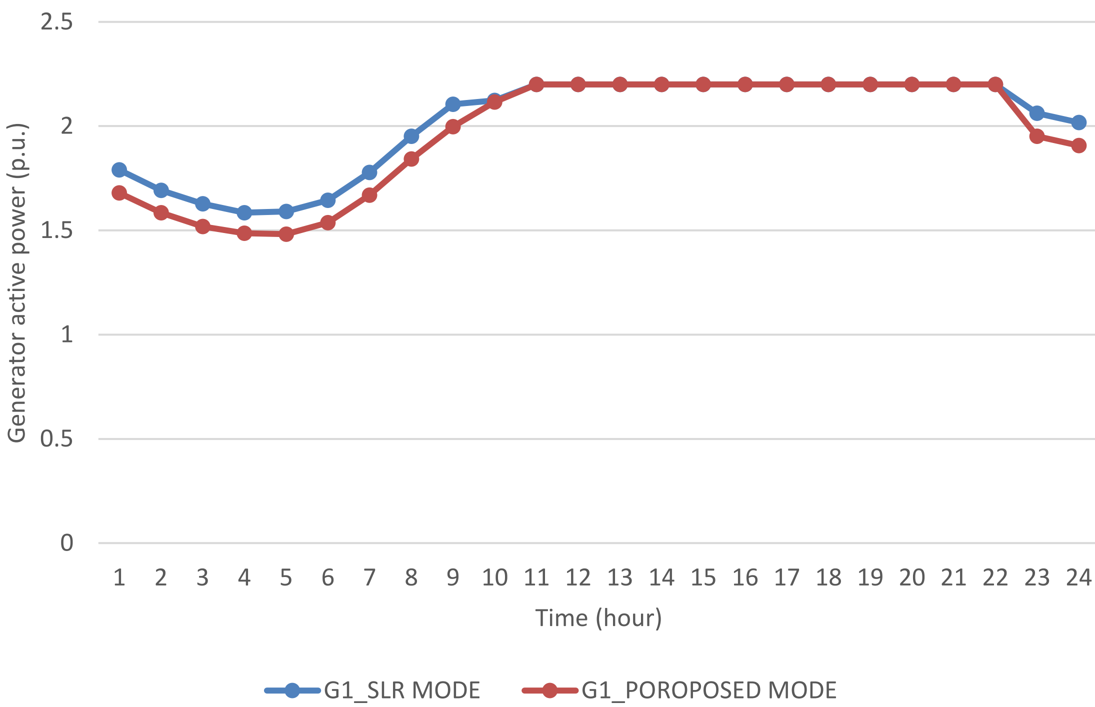

Figure 5-6: Generation schedule of generator number 1 for SLR mode and proposed model.

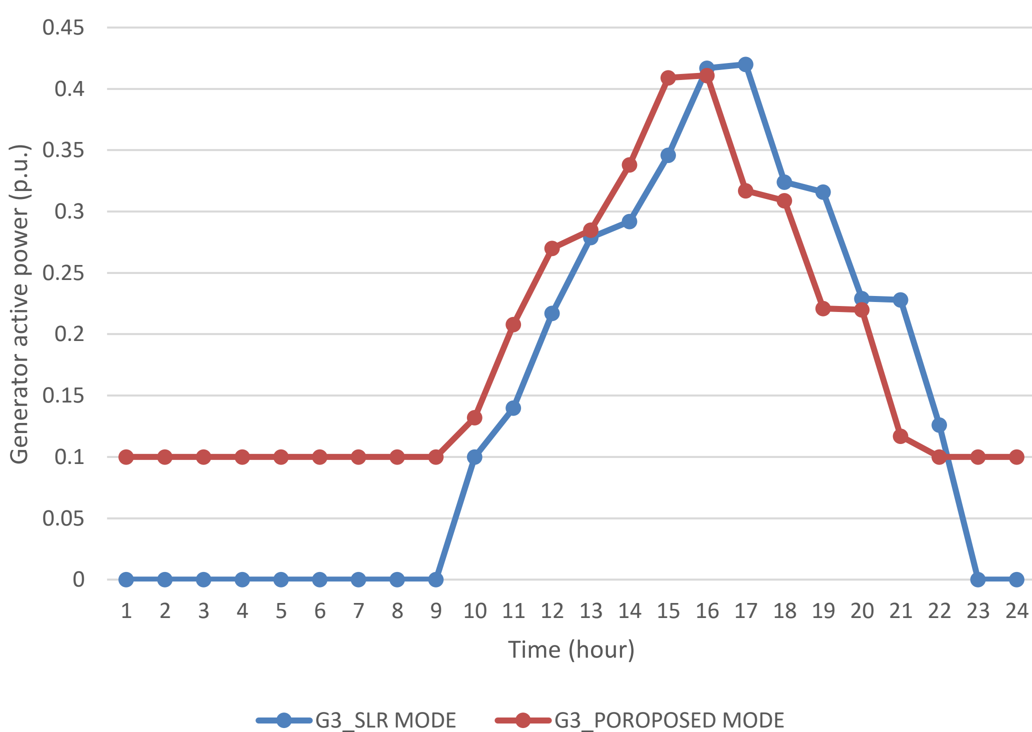

Figure 5-7: Generation schedule of generator number 3 for SLR mode and proposed model.

Looking over Figure 5-8, this will lead to 9 and 14 times switching in lines 2-4 and 5-4, respectively, which is rather high. In the proposed model, congestion management is utilized with TS is also considered. In this case, generator number 1 and generator number 3 both provide power from the beginning. This will prevent congestion in lines and reduces the switching numbers. As shown in the table, the switching numbers for lines 2-4 and 5-4 has reduced to 2 and 4, respectively. Although the major part of the demanded power is generated by generator number 1 which is cheaper, congestion management prevents lines to transmit their maximum power and that diminishes the switching numbers of lines. This reduction of switching will decrease the CBs' failure probability, and improves the security of the system. Considering DTLR as a security limitation in the SCUC problem also decreases operation costs for both 6-bus and 118-bus grids, as shown in Table 5-2. In SLR mode and 118-bus system, when generator number 13 is turned off, the switching numbers for lines 30, 78, and 90 are 11, 10, and 8 respectively. For the proposed model, these numbers have decreased to 6, 4, and 4 respectively. In figure 4, the switching schedule of lines for different cases is presented and SLR mode and the introduced model of this paper are compared. Table 5-5 gives the computation time of different strategies. Also, 0.01 is considered in the codes as the duality gap. Table 5-6 presents the numbers of variables and relationships.

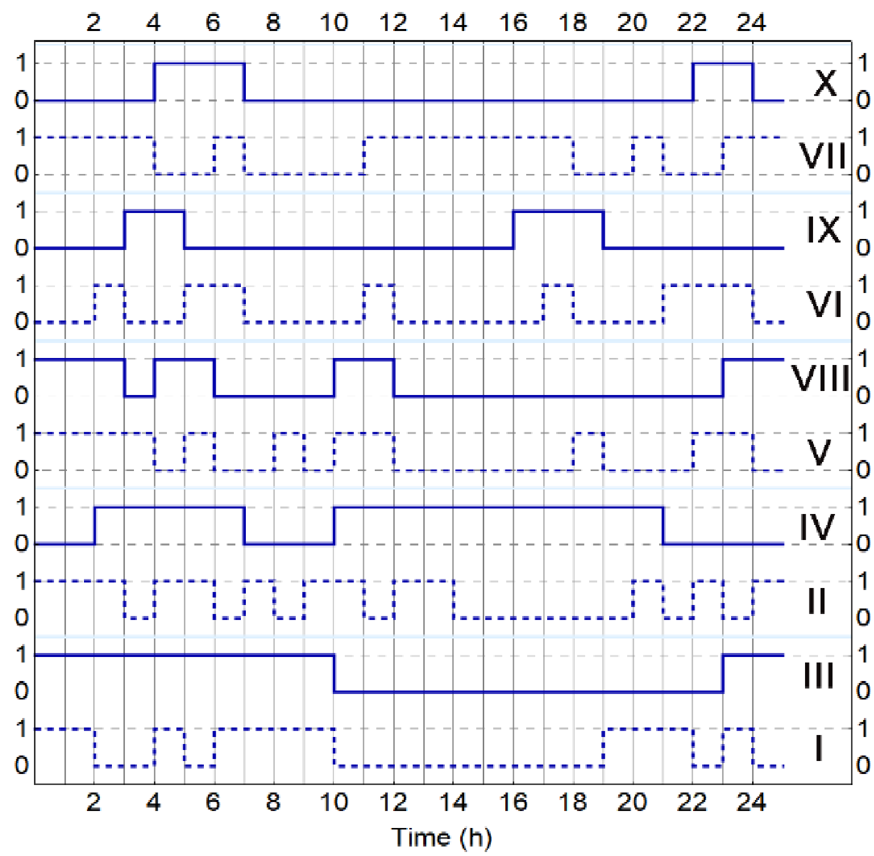

Figure 5-8: Comparing the switching of different cases for SLR mode and proposed model.

As it is evident, congestion management in real-time markets is typically carried out to ensure efficient operation. To clearly observe the impact of the introduced model, we executed it for a 24-hour time interval on 118-bus network. The SLR model results for the 6-bus grid are presented in Table 5-7, while the proposed model results can be observed in Table 5-7. In this type of problem, where the objective is operation cost minimization, the operator utilizes generators with lower costs to meet the demand when the system is running without any contingencies. However, in the event of a contingency (e.g., generator 2 being offline), the remaining generators compensate for the power deficiency. To prevent congestion, congestion management techniques can be employed. The results obtained by the SLR and introduced models demonstrate this. As expected, ΔP is adjusted in a way that reduces the costs in the introduced model in comparison with the traditional model. For instance, at hour 22, a decrease of 0.019 is observed in the SLR model in the power of generator 1, which is then compensated by an increase in the power of generator 3, which has higher costs. This leads to an increase in operational costs. However, in the proposed model, the power deficit of 0.019 is covered by generator 1 itself, which has lower costs.

Table 5-4: Computation time for 6-bus system

	Computation Time(sec)	Number of Iteration
SLR	110	20
Proposed Model	90	17

Table 5-5: Number of variables and equations for 118-bus system

	Variables	Equations
SLR	41,189	468,753
Proposed Model	40,726	79,479

Table 5-6: Computation result of SLR model for 118-bus system

	SLR Model											
Time	1	2	3	4	5	6	7	8	9	10	11	12
$\Delta P_{g=1}$	0	0	0	0	0	0	0	0	0	0.076	0	0
Time	13	14	15	16	17	18	19	20	21	22	23	24
$\Delta P_{g=1}$	0	0	0	0	0	0	0	0	0	-0.019	0	0
Time	1	2	3	4	5	6	7	8	9	10	11	12
$\Delta P_{g=3}$	0	0	0	0	0	0	0	0	0	0.024	0.141	0.218
Time	13	14	15	16	17	18	19	20	21	22	23	24
$\Delta P_{g=3}$	0.281	0.295	0.349	0.42	0.423	0.328	0.32	0.231	0.231	0.145	0	0

Table 5-7: Computation result of proposed model for 118-bus system

	Proposed Model											
Time	1	2	3	4	5	6	7	8	9	10	11	12
$\Delta P_{g=1}$	0	0	0	0	0	0	0	0	0	0.076	0	0
Time	13	14	15	16	17	18	19	20	21	22	23	24
$\Delta P_{g=1}$	0	0	0	0	0	0	0	0	0	0	0	0
Time	1	2	3	4	5	6	7	8	9	10	11	12
$\Delta P_{g=3}$	0	0	0	0	0	0	0	0	0	0.024	0.141	0.218
Time	13	14	15	16	17	18	19	20	21	22	23	24
$\Delta P_{g=3}$	0.281	0.295	0.349	0.42	0.423	0.328	0.32	0.231	0.231	0.126	0	0

5-4 Energy Transaction Analysis of the Water-Power System

The water-power system associated performance analysis is explained in this part. As noted in previous sections, the water load of the electrical grid is satisfied by the proposed hub system. On basis of the strategy, the desalination unit's power needed for balancing the water load is provided by the CHP units within the electrical energy segment. So, the surplus power is exchanged to the grid for lessening the line congestion and along with the energy operation cost at the peak-load time. Hence, the results in Figure 9 delineate how the water-power system could bring the linking management of energy between the heat/electrical resources and the electrical grid (U1: Power Transaction, U2: CHP unit, U3: Boiler unit). Indeed, the negative sign of the hub power means the energy transferred from the hub system to the grid while positive ones are vice versa. On account of the price difference among the hub system and the grid at times, the hub system was encouraged to sell its surplus power to the grid especially at peak load times 11-16 and 18-22. But, the hub system needed to buy the additional power from the grid instead the CHP unit decreased the consumed input gas owing to the high price at times. As mentioned previously, the hub system operates simultaneously with different electrical, thermal, and water energy carriers. Thermal units like CHP and boilers, responsible for meeting the thermal demand, are the heat components of the hub system. Figure 5-10 illustrates the gas consumption of the CHP and boiler units, assuming the input gas. Evidently, the boiler unit consumes a larger amount of gas compared to the CHP one. This indicates that the boiler primarily supplies the thermal loads, as the majority of the CHP output energy is utilized for fulfilling the electrical demands. The higher gas consumption of the CHP unit at t=14 can be attributed to the increased level of thermal loads that need to be adequately supplied. Additionally, Figure 5-11 depicts the amount of hub system generated water to meet the water requirements. Similarly, the performance of the DC units, responsible for serving the DC loads in the DC grid, is visualized in Figure 5-12. Looking over this figure, it demonstrates the negative/positive power values, representing the received/injected powers of the fuel cell and storage units to/from the hub system, respectively.

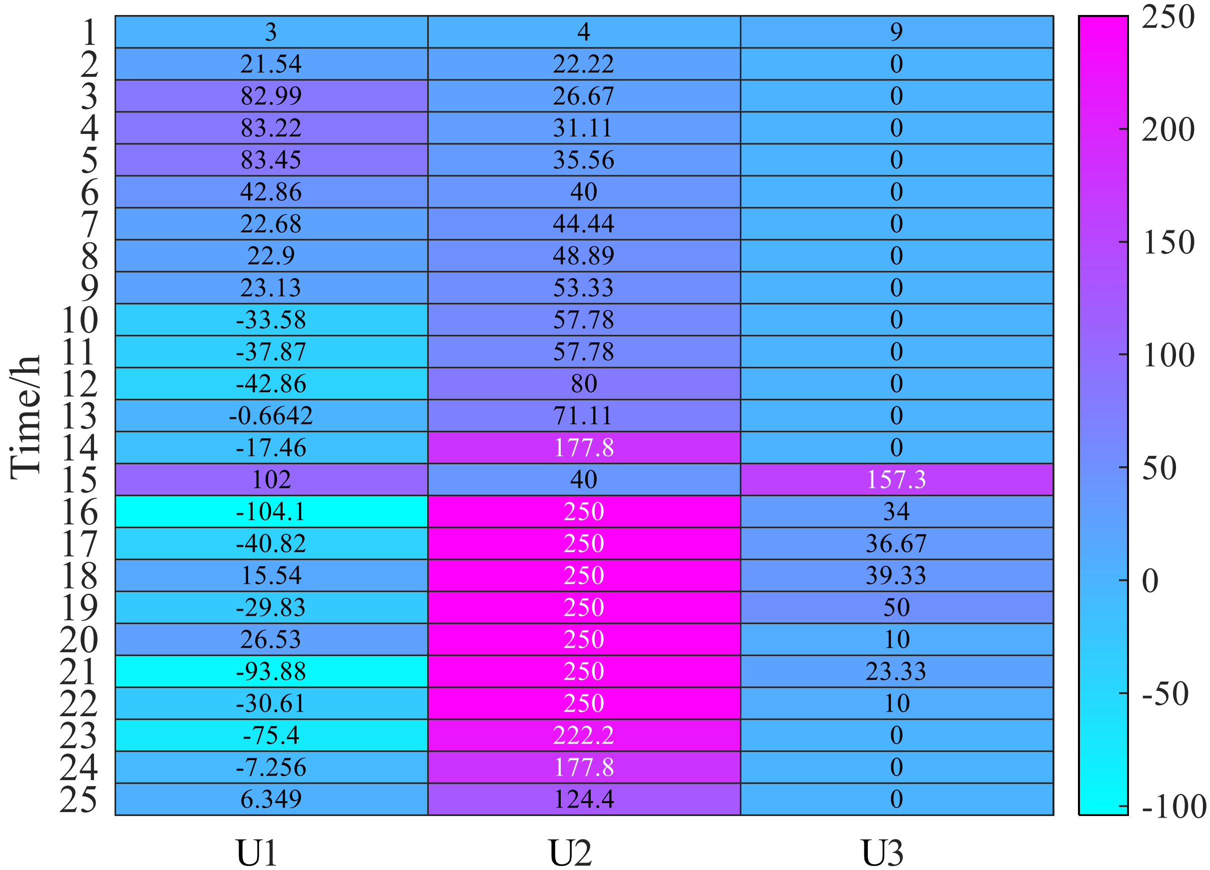

Figure 5-9: energy generation of the water-power system

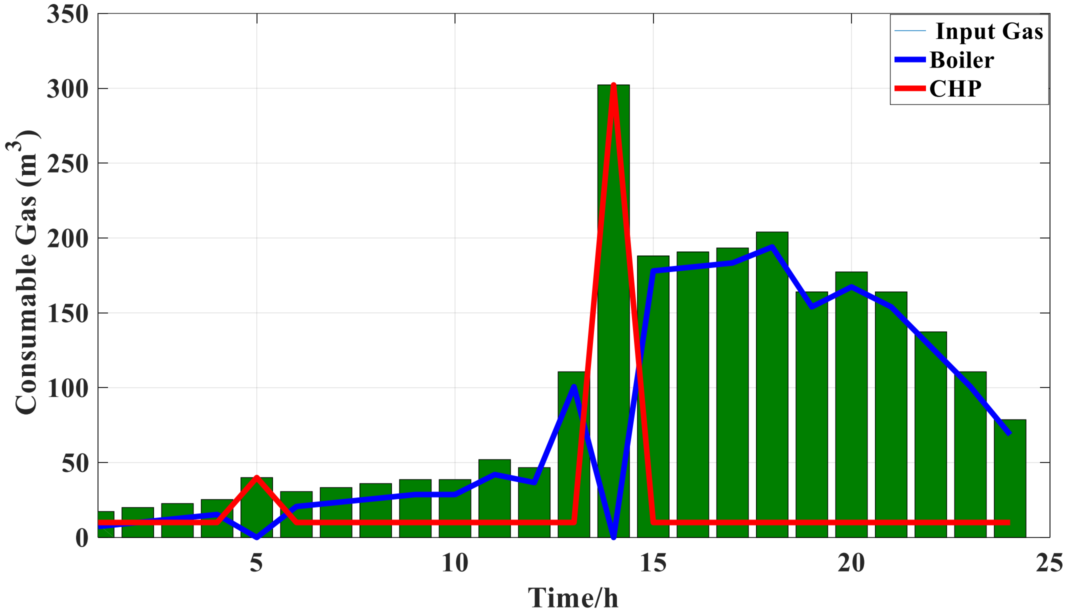

Figure 5-10: The consumption gas of the CHP, boiler and input units

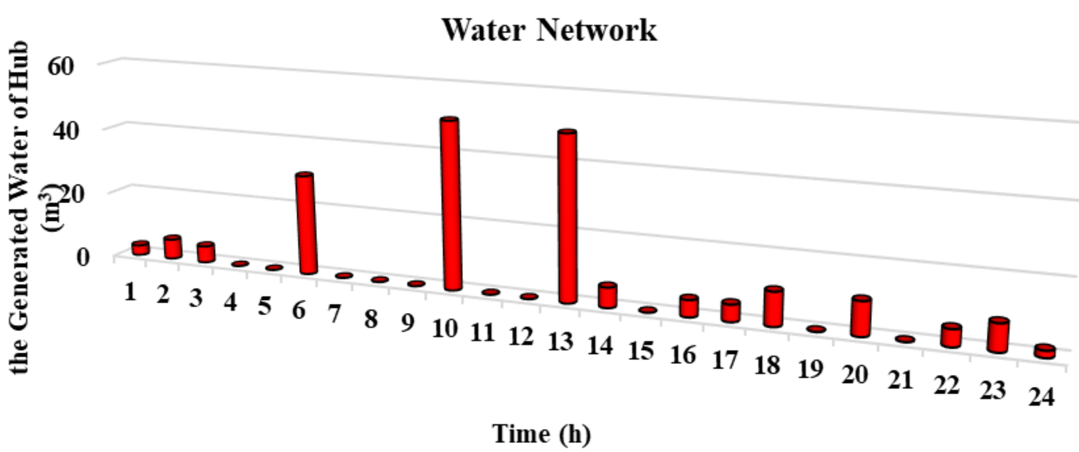

Figure 5-11: The generated water

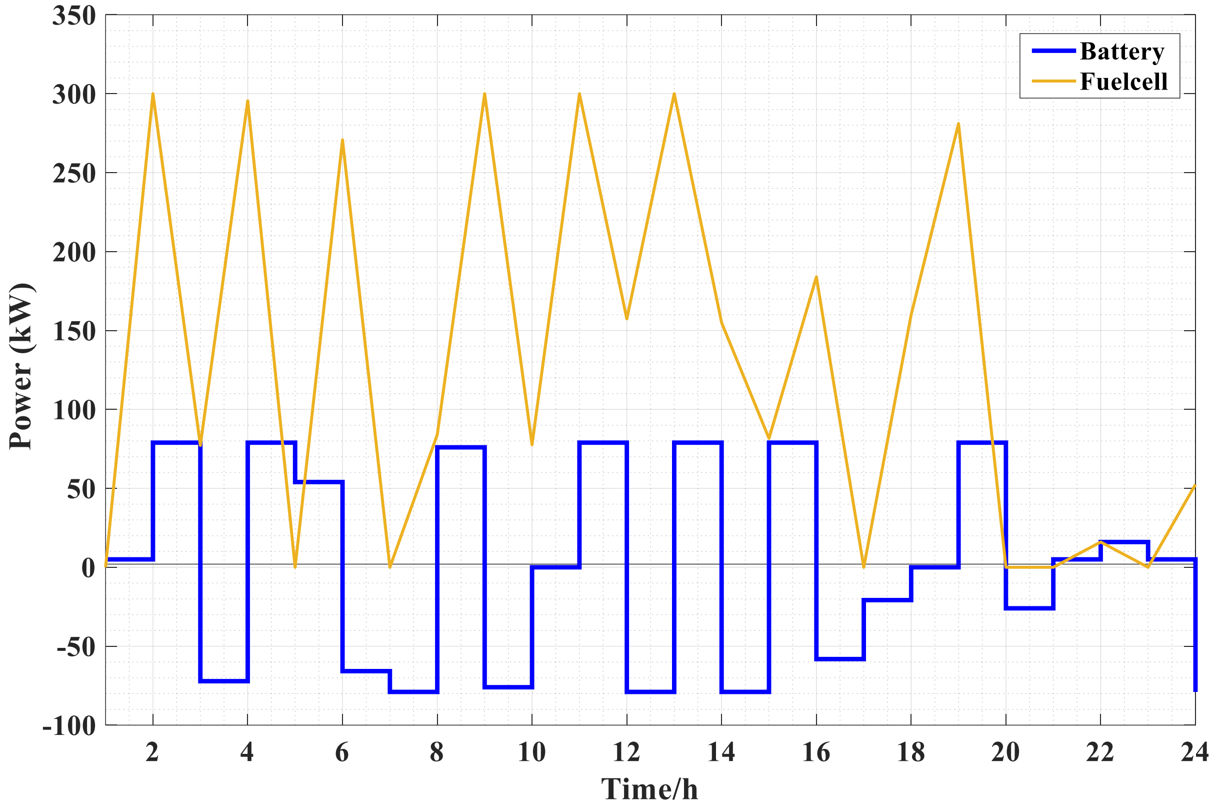

Figure 5-12: The injected powers of fuel cell and storage units

5-5 The Simulation of the Uncertainty Model

The performance assessment of this proposed energy strategy can be effective in substantially amending the grid's line congestion along with the low number of transmission switching if the system's parameters are made certain during the operating system. Therefore, it sounds that modeling the uncertain parameters of the system is a must before the proposed energy strategy is carried out. To this end, as noted, this paper addresses an effective model by inspiring the UT concept to map the parameters consisting of demands close to the real world. Hence, this section concentrates on performing the UT model on the system's parameters and provides the associated result here. Looking over Figure 5-13, the outcomes are related to the energy cost leading to different ways of uncertainty and deterministic models. Notably, the uncertainty model's performance is evaluated based on the cost result because of making it more impressive than other variables. Based on this figure, the grid undertake to pay the cost increase of 3%

thanks to the uncertainty. In fact, it should be noted that the uncertainty impacts need to be considered in large-scale.

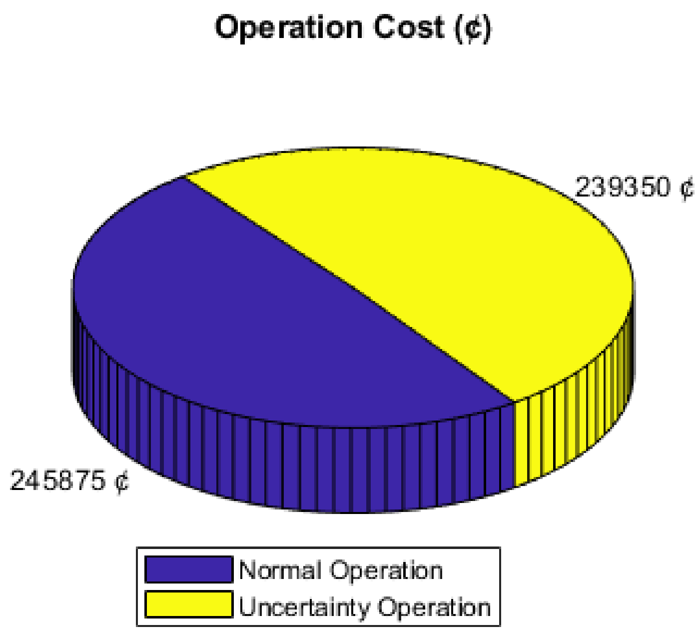

Figure 5-13: The cost of energy for both normal and uncertainty conditions

Chapter 6: Conclusion and Future Work

Chapter 6 concludes the thesis by summarizing the key findings and contributions of the research. It reiterates the effectiveness of the proposed congestion management framework integrated with a hydrogen-based water-power system in reducing the frequency of transmission switching, which in turn enhances the reliability and efficiency of smart grids. The chapter emphasizes how the innovative approach successfully mitigates the operational challenges associated with frequent switching, particularly the wear and tear on circuit breakers, while also achieving significant reductions in operational costs. The research contributions are highlighted, including the development of advanced strategies for integrating renewable energy into power systems and the application of uncertainty modeling to improve grid reliability. The chapter also outlines potential areas for future research, suggesting further exploration into real-time implementation, scalability to larger grids, and the incorporation of cybersecurity measures to protect against potential threats in increasingly digital power networks. Additionally, it encourages the investigation of interdisciplinary approaches to enhance the robustness and applicability of the proposed solutions in diverse and evolving energy landscapes.

6-1 Conclusion

In the realm of Security Constrained Unit Commitment (SCUC) problems, the dual priorities of maintaining system security and minimizing operation costs present a complex challenge. The integration of Transmission Switching (TS) within SCUC frameworks has emerged as a potent strategy to enhance system security by dynamically managing power flows and mitigating congestion. However, this approach is not without its drawbacks. The increased frequency of switching operations required by TS can lead to a higher probability of circuit breaker (CB) failures, which in turn can compromise the reliability and longevity of the power system. These failures not only incur significant maintenance and replacement costs but also increase the risk of unplanned outages and operational disruptions.

To address these critical challenges, this thesis proposes a novel congestion management approach that integrates a water-power system within the SCUC problem framework. The essence of this approach lies in leveraging the water-power system to provide additional flexibility in grid management, thereby reducing the need for frequent switching operations. By generating hydrogen through electrolysis and utilizing fuel cells for power generation, the proposed system offers a reliable and sustainable means to alleviate congestion without over-relying on TS. This method not only enhances the efficiency of the power grid but also contributes to the overall sustainability of the energy system by incorporating renewable energy sources.

The effectiveness of the proposed framework was rigorously tested on two benchmark systems: the 6-bus and 118-bus IEEE test systems. These test cases were selected to represent small and large-scale power networks, respectively, thereby allowing for a comprehensive evaluation of the framework's performance across different grid sizes and complexities. The results from these simulations underscore the significant benefits of the proposed methodology. For the 6-bus grid, the implementation of the water-power system resulted in a 77% reduction in CB switching operations. Similarly, for the 118-bus grid, a 45% reduction in switching operations was observed. These substantial decreases in switching frequency directly contribute to extending the lifespan of circuit breakers, reducing maintenance costs, and improving overall system reliability.

In addition to reducing switching operations, the proposed framework also demonstrated a notable decrease in operational costs. For the 6-bus grid, operation costs were reduced from 3.108×10^5 to 2.39×10^5, while for the 118-bus grid, costs were lowered from 1.091×10^6 to 1.0075×10^6. These cost savings are attributed to the optimized management of power flows and the effective utilization of the water-power system to mitigate congestion. The reduction in operational costs highlights the economic viability of the proposed framework, making it an attractive solution for power system operators seeking to balance cost efficiency with reliability.

The proposed methodology was also compared with the traditional Static Line Rating (SLR) method, which is commonly used in power systems for managing line ratings and congestion. The comparison revealed that the proposed framework significantly outperforms the SLR method in terms of reducing CB switching operations and associated costs. This advantage is particularly important in the context of modern power systems, which are increasingly incorporating smart grid technologies and renewable energy sources. As these systems become more complex and dynamic, the need for advanced and flexible congestion management strategies like the one proposed in this thesis becomes even more critical.

Looking forward, the presence of various smart devices and technologies within the power system introduces new challenges and opportunities. While these devices facilitate more efficient and automated operations, they also expose the system to potential vulnerabilities, particularly in the context of cyber-attacks. As the proposed framework relies on the integration of smart technologies and real-time data for decision-making, it is essential to consider its resilience against cyber threats. Future work could involve testing the vulnerability of the proposed framework to cyber-attacks, especially in scenarios involving contingency-based operations. This would ensure that the framework not only optimizes system performance and reduces costs but also maintains robust security in the face of evolving cyber threats.

In conclusion, the proposed congestion management approach, which integrates a water-power system within the SCUC framework, represents a significant advancement in the field of power system optimization. By effectively reducing CB switching operations and operational costs, the framework addresses key challenges associated with TS in modern power grids. The results from this research demonstrate the potential for widespread adoption of this methodology, offering a pathway towards more secure, efficient, and sustainable power systems. As power grids continue to evolve with the integration of renewable energy sources and smart technologies, the principles and strategies developed in this thesis will be invaluable for guiding future innovations in grid management and optimization.

6-2 Research Contribution

This thesis makes several significant contributions to the field of power system optimization, particularly in the context of Security Constrained Unit Commitment (SCUC) and Transmission Switching (TS). The work presented addresses critical challenges in modern power grids, including the need for enhanced system security, reduced operational costs, and the integration of renewable energy sources. The key contributions of this research are outlined below:

1. **Development of a Novel Congestion Management Framework**

The primary contribution of this thesis is the development of an innovative congestion management framework that integrates a water-based power system within the SCUC problem.

Traditional TS methods, while effective at enhancing system security, often lead to frequent switching operations that can degrade circuit breakers (CBs) and increase maintenance costs. This thesis introduces a novel approach that leverages a water-power system to provide additional flexibility in managing grid congestion, thereby significantly reducing the need for TS operations. This integration not only improves system reliability but also contributes to the sustainability of the grid by incorporating renewable energy technologies, specifically hydrogen production and fuel cells.

2. **Reduction in Circuit Breaker Switching Operations**

One of the most impactful contributions of this research is the demonstrated reduction in CB switching operations. Through the implementation of the proposed framework, the thesis achieves a 77% reduction in switching operations for the 6-bus IEEE test system and a 45% reduction for the 118-bus test system. This substantial decrease extends the lifespan of CBs, reduces the likelihood of failures, and lowers maintenance costs, all of which are crucial for the long-term stability and economic efficiency of the power grid. The ability to minimize switching operations while maintaining or even enhancing system security represents a major advancement in power system management.

3. **Economic Optimization and Cost Savings**

The thesis also contributes to the field by demonstrating significant operational cost savings through the proposed methodology. By optimizing the integration of the water-power system and reducing unnecessary switching operations, the thesis reports a reduction in operation costs from 3.108×10^5 to 2.39×10^5 for the 6-bus grid and from 1.091×10^6 to 1.0075×10^6 for the 118-bus grid. These findings highlight the economic benefits of the proposed framework, making it a viable solution for grid operators who are under pressure to reduce costs while maintaining high levels of system reliability and security.

4. **Comparison with Traditional Methods**

Another important contribution of this thesis is the comprehensive comparison between the proposed framework and the traditional Static Line Rating (SLR) method. The results clearly demonstrate that the proposed approach outperforms SLR in both reducing CB switching operations and lowering operational costs. This comparison provides valuable insights into the limitations of existing methods and underscores the advantages of the integrated water-power system in addressing the challenges posed by modern, complex power grids.

5. Introduction of an Uncertainty-Based Approach

To address the inherent uncertainties in power grid operations, particularly those arising from renewable energy sources, this thesis introduces an uncertainty-based Unscented Transform (UT) function within the SCUC framework. This contribution is critical as it enhances the robustness of the proposed methodology, ensuring that it remains effective under various operational scenarios and uncertainties. By incorporating this uncertainty-based approach, the thesis contributes to the development of more resilient and adaptable power systems that can better handle the variability and unpredictability associated with renewable energy integration.

6. Practical Implications and Future Directions

The practical implications of this research are significant. The proposed framework is not only theoretically sound but also practically applicable to real-world power grids, as demonstrated by its successful implementation on standard IEEE test systems. Furthermore, the thesis opens new avenues for future research, particularly in the areas of cybersecurity and resilience. By suggesting that the framework be tested for vulnerability to cyber-attacks in contingency-based operations, the thesis paves the way for future studies to explore the intersection of power system optimization and cybersecurity, an increasingly important area in the digital age.

7. Advancement of Smart Grid Technologies

Finally, this thesis contributes to the advancement of smart grid technologies by integrating smart devices and control systems within the proposed framework. The use of real-time data and automated decision-making processes in the congestion management strategy reflects the growing trend towards smarter, more responsive power grids. This contribution is particularly relevant as power systems evolve to become more digital and interconnected, requiring new approaches to manage complexity and enhance operational efficiency.

6-3 Future Work

The research presented in this thesis lays a solid foundation for optimizing Transmission Switching (TS) in smart grids and integrating a water-based power system to alleviate the associated challenges. However, several avenues remain open for further exploration and enhancement of the proposed methodologies. Future work can focus on the following key areas:

8. **Integration with Advanced Renewable Energy Sources**

While this research incorporates a hydrogen-based water-power system, future studies could explore integrating other renewable energy technologies, such as advanced solar, wind, and battery storage systems. These additional renewable sources could provide further flexibility in grid management and reduce reliance on traditional power generation. Research could focus on optimizing the mix of these energy sources to enhance the overall efficiency and reliability of the grid, especially under varying environmental conditions and grid demands.

9. **Real-Time Implementation and Control Algorithms**

The current research primarily focuses on simulation-based analysis of TS and water-power strategies. Future work could extend these findings to real-time implementation, developing advanced control algorithms that can dynamically adjust TS operations and water-power system utilization based on real-time grid conditions. This would involve creating robust and scalable algorithms capable of handling the rapid fluctuations in power demand and supply, particularly in grids with high penetration of intermittent renewable energy sources.

10. **Enhanced Uncertainty Modeling**

The thesis introduces an uncertainty-based Unscented Transform (UT) function to handle unpredictability in the grid, but there is potential for further refinement. Future research could explore more sophisticated uncertainty modeling techniques, such as stochastic programming, machine learning-based prediction models, or hybrid approaches that combine multiple methods. These enhanced models could provide more accurate predictions of grid conditions, enabling more precise and efficient decision-making in TS operations and congestion management.

11. Scalability to Larger and More Complex Grids

The methodologies developed in this thesis were validated on 6-bus and 118-bus systems, which are relatively small and simplified representations of real-world power grids. Future work could focus on scaling these strategies to larger and more complex grid networks, such as national or continental power grids with thousands of buses and more intricate topologies. This would involve addressing the computational challenges associated with large-scale optimization and ensuring that the proposed methods remain effective and practical in more extensive and diverse grid environments.

12. Economic and Policy Implications

Further research could explore the broader economic and policy implications of implementing the proposed strategies on a large scale. This could include detailed cost-benefit analyses, considering factors such as capital investment, operational savings, environmental impact, and the potential for job creation in emerging renewable energy sectors. Additionally, future work could examine the regulatory frameworks needed to support the widespread adoption of these technologies, addressing potential barriers and proposing policy measures to facilitate their integration into existing power systems.

13. Cybersecurity and Resilience

As power grids become increasingly digital and interconnected, cybersecurity and resilience become critical concerns. Future research could investigate the cybersecurity implications of the proposed TS and water-power strategies, identifying potential vulnerabilities and developing measures to protect against cyber threats. Additionally, studies could focus on enhancing the resilience of the grid, ensuring that the proposed systems can withstand and recover from various types of disruptions, including natural disasters, equipment failures, and malicious attacks.

6-4 List of Publications

- A. A. Niaki and M. Jamil, "An Efficient Hydrogen-based Water-power Strategy to Alleviate the Number of Transmission Switching within Smart Grid," International Journal of Hydrogen Energy, vol. 70, pp. 347-356, 2024.
  doi: https://doi.org/10.1016/j.ijhydene.2024.05.024
- A. A. Niaki, R. Parsibenehkohal, and M. Jamil, "Power Loss Reduction Using Distributed Generation Sources Considering Protection Coordination and Harmonic Limits," in 2024 12th International Conference on Smart Grid (icSmartGrid), Setubal, Portugal, 2024, pp. 675-681, 2024.
  doi: https://doi.org/10.1109/icSmartGrid61824.2024.10578109

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