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Electrical power engineering

Reactive power market mechanism for pricing

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Summary:

The present master thesis addresses reactive power management, a crucial factor for the stability and effectiveness of power systems. Correct valuation and pricing of reactive power are important for efficient operation of power networks. In this contribution, we introduce a novel reactive power pricing mechanism, which we expect to be more realistic and reliable in contrast to existing approaches, and at the same time serve as a basis for future optimization approaches. The proof of concept of the proposed pricing algorithm is accomplished by implementation of Python-based simulator via PyPSA, which is a useful tool for network theory and optimization. The algorithm will help to compute reactive power price per unit at each bus, and total cost involved of reactive power in the power network.

As a case study, IEEE 30 and 33 Standard Bus system have been used. The simulation results show that the proposed price mechanism reflects the real situation in the environment and is suitable for comparison with the existing methods. Subsequently, the Power Flow (PF) analysis is executed, and results from the simulation are analyzed with and without reactive power market. To show reasons for higher prices at each bus and providing a solution to tackle those problems by realistic and reliable approach compared to existing methods.

With proper reactive power pricing mechanism, it can lead to reliable voltage stability, lower system loss operation of the power network. It is the combination of technical-economic operational reality, transparency and fairness that makes such a reactive power market an ideal market design for managing reactive power in modern and future power systems. This thesis adds to the literature by creating a methodological framework for proper price design of reactive power, which results in further study and practical implementation of such a market in the real power system.

Preface

William Faulkner: "You cannot swim for new horizons until you have courage to lose sight of the shore."

This master's thesis was completed in the spring of 2024 at the University of South-Eastern Norway as part of the master's program.

Sincere gratitude to my supervisors, Sambeet Mishra, Sulabh Sachan, Thomas Øyvangfor providing me with this opportunity to expand my knowledge in this area. Lastly, I would like to express my profound gratitude to my parents for their unwavering support and selfless efforts in guaranteeing that I am afforded the most favorable prospects in life.

Drammen, May 2024

Gholamreza Shahmohammadi

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Gholamreza Shahmohammadi

Contents

Nomenclature

LMP - Locational Marginal Price

IEEE - Institute of Electrical and Electronics Engineers

PF - Power Flow

ISOs - Independent System Operators

RTOs - Regional Transmission Organizations

TSO - Transmission System Operator

DNOs - Distribution Network Operators

DSOs - Distribution System Operators

DERs - Distributed Energy Resources

DLMP - Distribution Locational Marginal Pricing

EV - Electric Vehicle

RBTS - Roy Billinton Test System

ADNs - Active Distribution Networks

DR - Demand Response

DG - Distributed Generation

ES - Energy Storage

BBO - Biogeography-Based Optimization

CLPSO - Comprehensive Learning Particle Swarm Optimization

SOA - Symbiotic Organisms Search Algorithm

PSO - Particle Swarm Optimization

PEIP-DGs - Power-Electronically Interfaced Distributed Generations

MISOCP - Mixed-Integer Second-Order Cone Programming

OLTC - On-load Tap Changing

MCP - Marginal Cost of Production

MCC - Marginal Congestion Cost

MCL - Marginal Cost of Losses

RES - Renewable Energy Sources

OED - Ministry of Petroleum and Energy (Norway)

N2EX - Nord Pool’s UK power market

p.u. - per unit

1 Introduction

One of the most important factors in ensuring the reliability and stability of contemporary power systems is to regulate and control reactive power. Stability and reliability are of vital importance in modern power systems because they are loaded with an ever-increasing demand for alternative energy sources such as wind and solar, both of which operate on their own terms. Therefore, reactive power management has become a matter of significant concern due to its impact on the stability and reliability of the system [1].

The locational marginal prices mechanism serves as an essential method to optimize reactive power. These mechanisms foster incentives for locations, both on the supply and demand sides, in the electricity network in relation to reactive power. The analysis of this comparative data can produce valuable information about economic indicators associated with reactive power generation and consumption by various substations, but emerging networks require new ideas. While recent efforts such as US Federal Energy Regulatory Commission FERC Order 2222 demonstrate the difference in distributed energy resources reform, new energy standards need to be used to ensure high ease of understanding and support the creation of a good partnership while protecting the grid[2]. This research discusses the economic aspects of reactive power supply and consumption, with an emphasis on the dual price mechanism. Specifically, it aims to find out if the alternative approaches are better by examining costs associated with IEEE 30-bus system configuration type as well as that for 33-bus standard configurations; this is crucial to understand how much efficiency has been realized along the way and what kind of economic changes this can bring into place.

The analysis will be carried out using a combination of theoretical aspects and numerical simulations[3]. Initially, we constructed the power network model for the 30 and 33 IEEE standard bus configurations, considering the generators and load models. Secondly, based on the power flow model, we derived the reactive power distribution as well as costs incurred in both the provision and consumption of reactive power. It is then that the LMPs will be shown with the objective of assessing their effects in driving the cost of reactive power. We will carry out a comparative study on the two algorithms to determine the rate at which they are able to lead in terms of cost and benefits for both 30- and 33-bus configurations [4].

1.1 Literature review

The aim of this chapter is to examine the most relevant literature on active and reactive power active power efficiency and network stability and furthermore available market mechanism and their regulations which are affecting last price of power production.

In [5] author worked on a novel approach using a Local Particle Swarm Optimization (PSO) variant algorithm optimizes Distributed Generation (DG) in Distribution Networks (DNs) to minimize losses. It identifies the optimal number, siting, and sizing of DG units, recommending DG types based on node power requirements and embedding a penalty term for reverse power flow to the slack bus. Tested on 30 and 33 bus systems, it assesses impacts of permissible reverse power flows through two scenarios, showing effectiveness in networks with varying load demands and pre-existing DG units. The methodology offers a flexible, superior approach to traditional DG optimization methods, focusing on comprehensive solutions for DG penetration and installation.

In [6] author studied about assessed the performance of a load flow program utilizing Newton-Raphson and Fast Decoupled techniques, coded in MATLAB and applied to an IEEE 30-bus system. The findings confirm the validity of both methods, demonstrating comparable results while indicating that the Fast Decoupled approach achieves quicker convergence. Critical parameters examined encompass bus voltage magnitudes, angles, as well as active and reactive power at each bus, revealing minimal line loss of approximately 2.86 MW. The study emphasizes the superior efficiency of the Fast Decoupled method for addressing load flow challenges. It compares the Newton-Raphson and Fast Decoupled load flow methodologies on an IEEE 30-bus system, establishing their effectiveness in optimizing power distribution with similar outcomes. Nevertheless, it highlights that the Fast Decoupled technique exhibits faster convergence and greater reliability compared to its counterpart; thus, favoring it as a more efficient method for conducting load flow analysis through MATLAB simulations.

In [7] author worked on research about optimal reactive power flow minimizes active power losses using control variables such as generator bus voltages, transformer tap settings, and compensating device outputs. The Biogeography-Based Optimization (BBO) technique, following Migration and Mutation steps, has been applied to IEEE 30-bus and 57-bus systems, demonstrating effective active power loss reduction under various constraints. The BBO method shows superior solution quality, computational efficiency, and robustness compared to other techniques like SOA and CLPSO, making it a promising approach for solving optimal reactive power flow problems.

In [8] author worked on the demand response however focuses on the traditional balance between end customers and distribution network operators with primary focus on reduction of peak loads and dynamic load adjustments. In this article, a DR scheme for ADNs using unbalanced feeder lines and consumer loads has been proposed, in conjunction with day-ahead dynamic pricing to reduce the network load and avoid new peaks, considering the behavior of the distribution networks. The complex issues of unbalanced networks and the integration of distributed generation have been handled very well, through a novel approach using the symmetrical domain components. The reactive power component of the power-electronically interfaced DGs (PEIP-DGs) operating in constant power and constant voltage modes have also been incorporated. The operation constraints taken into consideration are constant voltages at each converter terminal and voltage/reactive current limitations at each sequence domain bus. The optimal power flow has been modified for social welfare maximization subjected to constraints of the network. The global optimality and efficiency of the same have been established with case studies. It can be clearly seen that the proposed DN-OPF-based DR scheme with day-ahead dynamic pricing considers the social welfare of the customers within a dynamic metering system under unbalanced ADNs managed with reactive power limit in sequence domains to operate the DGs in a proper manner. This greatly reduces the computational burden and, at the same time, leads to significant efficiency through extensive case studies. The proposed methodology can be extended to weakly meshed ADNs with ES and enhanced further by integrating predictions of human behavior and with penalties for deviations to increase the robustness and effectiveness of the model.

In [9] author proposed a day-ahead market-clearing model for smart distribution systems. allowing various distributed energy resources (DERs) such as energy storage, generators, microgrids, and load aggregators to bid into a distribution-level electricity market. To calculate distribution locational marginal pricing (DLMPs) for both active and reactive power, the model considers system Volt/VAR management, network reconfiguration, and interactions with the wholesale market. To provide price signals that incentivize DER involvement in voltage support and congestion management, DLMPs are divided into components that represent costs for active power, reactive power, congestion, voltage support, and losses. Case studies validate the model's effectiveness. This framework integrates feeder reconfiguration and Volt/VAR control using an MISOCP model for Distribution System Operator (DSO) optimization, considering network losses. DLMP decomposition highlights the compensation for services provided by DERs, motivating them to support voltage and relieve network congestion. Demonstrations show that feeder reconfiguration and On-load Tap Changing (OLTC) optimize power flow and voltage profiles, making this DLMP method practical by factoring in reactive power and voltage constraints. The proposed market-clearing model and DLMP effectively reduce line loading and maintain nodal voltage in distribution systems.

In [10] author introduced an integrated distribution locational marginal pricing (DLMP) method aimed at mitigating congestion caused by electric vehicle (EV) loads in future power systems. The distribution system operator (DSO) calculates DLMPs by solving the social welfare optimization problem, considering EV aggregators as price takers in the local DSO market with demand price elasticity. Nonlinear optimization is employed to derive the DLMPs, and the effectiveness of this approach is demonstrated using the Roy Billinton Test System (RBTS) bus 4 distribution system and Danish driving data. Results indicate that the integrated DLMP methodology effectively alleviates congestion from EV loads and enables the implementation of socially optimal charging schedules through a decentralized mechanism, where loads autonomously respond to DLMPs by maximizing their individual net surplus. Further, the paper proposes extending the current framework to scenarios where the DSO has imperfect information about locational marginal prices and must use forecasted values in decision-making.

In [11] author studied the effects of data quality on real-time locational marginal prices (LMPs), highlighting how inaccuracies in network topology and system state estimations due to bad data can impact real-time LMP calculations. The study demonstrates that the power system state space is divided into price regions of convex polytopes and examines the worst-case impacts of bad data on real-time LMP through numerical simulations for IEEE-14 and IEEE-118 networks. The results provide a geometric characterization of real-time LMP, illustrating the relationship between data quality and price calculations, and discusses scenarios involving both analog meter measurements and digital breaker state data as potential sources of bad data. The analysis adopts an adversarial approach, considering scenarios where data may be maliciously tampered with, which, although possibly overly conservative, offers a measure of assurance for system security. The implications for cybersecurity in smart grid operations are considered, emphasizing the need for effective countermeasures against malicious data attacks. While the findings are based on smaller academic benchmark networks, the observed trends suggest that bad topology data have a more significant and persistent detrimental effect on real-time market operations than bad meter data, a trend expected to continue in larger practical networks.

In [12] author researched about the impact of wind production on locational marginal prices (LMPs) in a fully competitive pool-based electricity market, modeling wind productions as negative loads using historical data. The analysis focuses on the structural relationship between wind production and LMPs, excluding the effects of strategic offering. It statistically characterizes LMPs based on data from wind plants and the structure of the electric energy system. The paper also provides a simulation methodology to quantitatively assess how increasing wind power integration affects LMPs, analyzing both average values and volatilities. Findings indicate that greater integration of wind power generally lowers LMPs across the network until network bottlenecks arise, localizing the reduction in LMPs. A high correlation among wind plants significantly impacts LMP volatilities and less so on average values, due to the statistical cancellation of wind fluctuations providing stable average values. The methodology enables visualization and numerical calculation of these impacts. Future work will compare these simulation results with empirical analyses from various power markets and enhance the simulation algorithm to include inter-hour complexities like temporal correlations of wind speeds and generation unit ramping capabilities.

In [13] author worked on a paper about impact of wind power and electricity demand on the relevance of different short-term electricity markets: The Nordic case. Electricity wholesale markets are transforming due to rising variable renewable energy sources, prompting a shift from the traditionally dominant day-ahead market to markets closer to real time. This study examines how increased wind power integration affects wholesale electricity markets, noting that increased wind power typically lowers price levels due to its low marginal costs, impacting the profitability of conventional thermal power plants. Furthermore, greater stochastic wind generation results in larger deviations between real-time power generation and day-ahead forecasts, potentially increasing the need for balancing services and associated costs.The study also observes changes in the relationship between different marketplaces due to the growing share of weather-dependent renewable energy, highlighting that markets closer to delivery—such as intraday and regulating markets—are gaining importance in trading activity and price discovery. This shift is crucial as the day-ahead market has historically been a basis for electricity generation investments and pricing strategies. Through an analysis of price spreads between day-ahead, intraday, and regulating power markets in Nordic countries, the study uses vector autoregression (VAR) models to explore the interrelationships between price spreads and the effects of wind forecast and demand forecast errors, among other variables. The study reveals that wind forecast errors significantly affect price spreads in areas with high wind power shares, suggesting that these markets are becoming increasingly relevant for hedging and other decision-making processes due to the growing penetration of variable renewable energy sources. This has implications for future market design, emphasizing the need for markets closer to real time to play a more prominent role.

In [14] authors explore the integration of electricity markets within the European energy union framework, focusing on balancing markets that require harmonization due to significant design differences across regions. These differences are often shaped by the activation philosophy of the Transmission System Operator (TSO), which may depend on unique structural conditions.

The study identifies key balancing market design variables influenced by the TSO's activation philosophy and introduces a set of indicators to differentiate between proactive and reactive market designs. Using these indicators, the paper classifies various Northern European balancing markets based on their market incentives and the use of proactive activations. Despite some data uncertainties noted in the study, such as the reserve replacement processes used by Nordic TSOs, the classification reveals a clear polarization between markets, suggesting strong correlations among the indicators for reactive markets. This polarization highlights "natural partners for balancing" like the Nordic countries and a group consisting of Belgium, the Netherlands, Germany, and Austria, while also pointing out significant design gaps between neighboring areas like Belgium and France. These findings illustrate how differences in TSO activation philosophies can act as barriers to market integration, emphasizing the need for a deeper understanding of proactive and reactive balancing market designs to facilitate effective market integration in Northern Europe.

In [15] author studied the benefits of coordinated bidding strategies in multiple electricity markets, quantifying gains by comparing profits from coordinated bidding with those from a purely sequential bidding strategy. The study particularly assesses how the size of the production portfolio affects these gains. Using stochastic mixed-integer programming, a coordinated planning problem for a hydropower producer is formulated, accompanied by a comprehensive scenario-generation methodology. An extensive case study of the current Nordic market is conducted, revealing that the gains from coordinated bidding are modest—below 1% for one watercourse and about 0.5% for two or three watercourses. These gains from coordinated bidding decrease as portfolio size increases, yet they stabilize at a certain level. The research developed a stochastic mixed-integer programming (SMIP) model for constructing bid curves for the day-ahead market, considering subsequent market opportunities. The findings indicate that while coordinated bidding offers a slight potential for increasing profits given the current Nordic reserve market prices and volumes, its value diminishes with the expansion of water courses in the planning. The presence of more generators increases recourse options, diluting the value of coordinated planning as production can be reallocated to meet reserve market opportunities. The study concludes that although gains from coordinated bidding decrease with larger portfolios, there is a tendency towards stabilization. The flexibility in production when planning for larger portfolios dilutes the value of coordination. However, opportunities like committing units for later delivery of primary reserves and downward balancing services are aspects that sequential planning cannot leverage, regardless of portfolio flexibility. Insights from this study on how portfolio size influences gains from coordinated bidding may be applicable to other dispatchable production systems like thermal generators. Nonetheless, reserve markets' small size relative to day-ahead markets and their unpredictable nature limit the reliability and potential benefits of any coordination strategy between these markets.

In [16] writer discussed about the shift from traditional power plants to distributed energy resources and the need for efficient reactive power exchange across voltage levels. The authors propose a decentralized multi-level reactive power market, allowing distributed energy resources to provide reactive power to higher voltage levels. Each grid operator manages a local market and contributes to a larger network by sharing cost curves and flexibility ranges. This approach minimizes communication between participants and allows for local customization of market rules and optimization methods. Initial findings from a case study suggest that this decentralized market could nearly match the efficiency of a centrally optimized solution without breaching local grid restrictions. The market uses time series data to assess various load and generation profiles and compares favorably to other methods, providing efficient multi-level reactive power provision while adhering to grid constraints. Technical and economic outcomes are almost equivalent to those of central optimization, with minor differences due to the quadratic approximation of the Electric Power Functions (EPFs). The implementation of this market requires minimal communication about reactive power ranges and other parameters and is relatively simple if local reactive power markets already exist. It operates under the assumption that there is only one vertical grid coupling point, which is a common limitation in proposed markets. The paper calls for further research into the profitability of participants and the adequacy of quadratic cost function approximations, suggesting more complex models and advanced optimization techniques as alternatives.

1.2 Objectives

the objectives of the thesis outlined in bullet points.

- Develop a novel reactive power pricing mechanism to better reflect real-world conditions and provide a more reliable basis for future optimization approaches.
- Implement and validate the proposed pricing algorithm using Python-based simulations via PyPSA on IEEE 30 and 33 bus systems.
- Conduct a power flow analysis on 33 buses and 30 bus systems to achieve active and reactive power of the system.
- Analyze the results obtained from the power flow analysis to demonstrate system improvements and facilitate further studies.
- Apply the Locational Marginal Pricing (LMP) method following the power flow analysis to accurately determine the reactive power prices at each bus.
- Analyze the reactive power prices at each bus to identify the factors contributing to price differences and assess the effectiveness of the proposed pricing mechanism.

1.3 Novelty and contribution

The thesis introduces a new reactive power pricing mechanism using a Python-based simulator (PyPSA) for the IEEE 30 and 33 Bus systems, to show reasons of higher prices at each bus and its reasons and providing a solution to tackle those problems by realistic and reliable approach compared to existing methods. Through simulations, identify the factors affecting the prices and demonstrate its potential to improve power system stability and enhance cost efficiency. The key contribution is the development of a methodological framework for reactive power pricing that accurately detects system losses and aims to optimize voltage stability and operational costs, serving as a foundation for future research and optimization in power systems.

1.4 Structure of the Thesis

The thesis's structure is organized in the manner of 6 chapters that comprise the following categories:

Chapter 1: Introduction This chapter gives an overview of the dissertation. It contains the significance of the main topic and shows the research goal and research motivation. The chapter emphasizes the importance of managing reactive power for the grid to operate in a stable and optimum manner. In addition, a literature survey is included in this chapter to propose the main idea and motivation of the study.

Chapter 2: Basic Definitions of Grids This chapter will discuss key technical definitions that are important to understand power systems. Active power, reactive power and apparent power, power flow, Gauss-Seidel method, Newton-Raphson method, and Fast Decoupled Load Flow method will be described in this chapter. This background knowledge will be fundamentally important for understanding issues related to power systems and power system operations in this dissertation.

Chapter 3: Electricity Market In this chapter, the layout and working of electricity markets is explained. The chapter will explain about marginally priced clearing, pay-as-bid clearing and different types of market clearing systems. Various Independent System Operators (ISOs) and Regional Transmission Organizations (RTOs) in the USA will be compared in this chapter. It also explains the situation between Distribution System Operators (DSOs) and Transmission System Operators (TSOs).

Chapter 4: Simulation This chapter will present the methodology of simulation studies. A description of the AC power grid models and a full description of the software tools used for power flow analysis and analysis of the proposed reactive power pricing mechanism will be included. This chapter is a gateway for the results and discussions given in more detail in the next chapters.

Chapter 5 Results and Discussions This chapter covers the python simulation results carried out on the IEEE 30 and 33 bus systems. It includes detailed analysis on active power and reactive power distributions, the voltage magnitudes on each bus and finally the LMPs has been calculated. A comparative study has been made of the two systems for congestion, losses and considering the overall cost.

Chapter 6 Conclusion The final chapter summarizes the key findings of the research, emphasizing the effectiveness of the proposed reactive power pricing mechanism. It discusses the broader implications of the study for power system operation and stability and suggests areas for future research.

2 Fundamental definitions of grids

In this chapter, we will discuss the fundamental technical definitions of key terms and concepts that underpin the power system. Understanding these definitions is crucial for grasping the market's mechanism.

2.1 Active, reactive, and apparent power

Apparent Power (S) measured in volt-amperes (VA). This is calculated by multiplying the root mean square (RMS) voltage by the current. Active Power (P) quantified in watts (W). This represents the mean rate at which energy is transferred. Reactive Power (Q) expressed in volt-amperes reactive (var). This component of the apparent power does not align phase-wise, or stands in quadrature, to the active power. Apparent power, denoted as S, is relevant under both sinusoidal and non-sinusoidal conditions. The equation for apparent power is as follows:

$$S = V_{rms} \times I_{rms} \tag{2.1}$$

In conditions where the voltage and current are sinusoidal, both waveforms consist solely of the fundamental frequency component. Consequently, the root mean square (RMS) values of the voltage and current can be straightforwardly described as follows:

$$V_{rms} = \frac{1}{\sqrt{2}} V_1 \tag{2.2}$$

$$I_{rms} = \frac{1}{\sqrt{2}} I_1 \tag{2.3}$$

where V_1 and I_1 are the amplitude of voltage and current waveforms, respectively.

The active power P is also commonly referred to as the average power, real power, or true power. It represents useful power expended by loads to perform real work. It is measured in watts (W) and is the power used by electrical devices to produce work, such as turning motors or lighting lamps.

$$P = \frac{V_1 I_1}{2} \cos\theta_1 = V_{1rms} I_{1rms} \cos\theta_1 = S\cos\theta_1 \tag{2.4}$$

where θ_1 is the phase angle between voltage and current at the fundamental frequency.

Reactive power, measured in volt-amperes reactive (VAR), is the portion of electricity that establishes and sustains the electric and magnetic fields of AC equipment. Reactive power is a type of power that does no real work and is generally associated with reactive elements (inductors and capacitors). For example, the inductance of a load such as a motor causes the load current to lag the voltage.

$$Q = \frac{V_1 I_1}{2} \sin \theta_1 = V_{1rms} I_{1rms} \sin \theta_1 = S \sin \theta_1 \tag{2.5}$$

Reactive power affects the efficiency of power transmission. High levels of reactive power can lead to increased losses due to the heat in conductors and transformers. Thus, reducing excessive reactive power by improving the power factor close to unity is a common goal in power system operation [17].

2.2 Power flow

Power flow analysis is an important aspect of power system operation and planning. Power flow study is performed to figure out the voltage and angle of the network bus, and the active and reactive power flowing in each branch of the power system under steady-state condition. The basic intention of the power flow study is to figure out how the power is distributed through network components, including transmission lines, transformers, and other network elements, and to verify that the power distributed is cost-effective, secure as well as in compliance with the limitations on the capacity of the transmission lines. On the other hand, load flow analysis is typically concentrated on the utilization of power by end-users and the way that might affect the whole power system. This helps to make certain that demand anticipated in various regions of the power system is met with enough power, and voltage profiles in the power system show a smooth and consistent operation. The basic notion is matured into three well-known approaches as follows [18].

2.2.1 Gauss-Seidel Method:

The Gauss-Seidel method is a classical iterative method for load flow analysis of power systems. It is very easy to use and highly efficient method particularly for small and moderately complex systems using the most available present estimate for each bus voltage as well as power at each iteration taken from the power balance equation derived from Kirchhoff's law.

$$V_i^{(\text{new})} = \frac{1}{Y_{ii}} \left(S_i^* - \sum_{j \neq i} Y_{ij} V_j^{(\text{old})} \right) \tag{2.6}$$

i=2,3, 4,n

$V_i^{(\text{new})}$ is new voltage at but i, Y_{ii} is the diagonal element of the admittance matrix at bus i, S_i^* is is the complex conjugate of the net power demand at bus i, $V_j^{(\text{old})}$ is previous voltage at bus j

2.2.2 Newton-Raphson Method:

Newton-Raphson Technique Newton-Raphson has been widely recognized as the most robust and efficient method for the solution of nonlinear algebraic equations which can be embedded for the solution of load flow problems also. It uses the Jacobian matrix to linearize the power flow equations and ensure rapid convergence of the iterative load flow solution. In the Newton

Raphson technique, all the bus voltages are adjusted simultaneously for any given mismatch in power throughout the entire network while it is also utilizing the derivative information in the update of bus voltages.

$$\Delta \mathrm{X} = -J^{-1}(X) \cdot F(X) \tag{2.7}$$

$$X_{new} = X_{old} + \Delta X \tag{2.8}$$

ΔX is the vector of corrections applied to the voltage magnitudes and angles, $J(X)$ is the Jacobian matrix, calculated from the partial derivatives of the power mismatch equations with respect to the voltage magnitudes and angles, $F(X)$ is the vector of power mismatches at each bus, and X represents the state variables (voltage magnitudes and angles)

2.2.3 Fast Decoupled Load Flow Method:

The Fast Decoupled Load Flow method is developed as an alternative to Newton-Raphson method. The principle in developing this approach is to simplify the computation by decoupling the active and reactive power equations. The Fast Decoupled Load Flow method assumes the changes in the voltage angles mainly affect the active power and the changes in the voltage magnitude mainly affect the reactive power.

$$\Delta \theta = -(B')^{-1} \Delta P \tag{2.9}$$

$$\Delta V = -(B'')^{-1} \Delta Q \tag{2.10}$$

B' and $B''$are the reduced Jacobian matrices for active and reactive power mismatches, respectively.$\mathit{\Delta} P$ and $\mathit{\Delta} Q$ are the vectors of active and reactive power mismatches [19], [20].

2.3 AC power systems

An AC (Alternating Current) power system is a network of electrical components used to generate, transmit, and distribute electricity in the form of alternating current simply a network, in which All voltage and current sources are sinusoidal and share the same frequency. AC systems are commonly used in power systems because they are cheaper to build, more efficient, and safer than DC systems [21]. An AC power system can be represented as in figure 2.1.

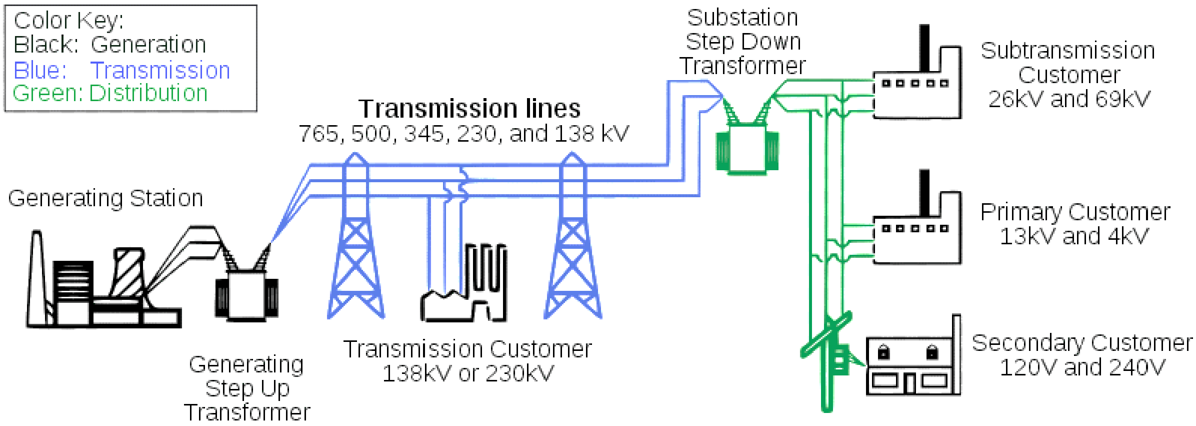

Figure 2.1: Simplified diagram of AC electricity system [22].

2.4 The Norwegian Electricity Grid

Three sub-levels make up the Norwegian power grid, and they control the voltage level and operator. Power import and export are made possible by the transmission grid, which connects producers and consumers across great distances both domestically and internationally at a voltage level of 300 or 420 kV. Statnett, the transmission system operator (TSO), operates it. The transmission and distribution grids are connected via the regional grid, which has a voltage level of either 132 or 66 kV. The end customers are supplied via the distribution grid, which has voltages ranging from 22 kV to 230 V. Transformers are used to scale down the voltage to lower levels when consumers are connected to the distribution grid. The DSO, which is in charge of the grid in a certain area, runs the distribution grid [23].

Figure 2.2: Nordic power grid system.

Figure 2.2 shows the northern portion of the European high voltage power grid includes 380 to 400 kV (red), 300–330 kV (orange) and 200–220 kV (green) transmission lines schematic adapted from ENTSOE [24].

2.5 Reactive power source in AC systems

In AC power systems, devices that either generate or absorb reactive power are crucial for maintaining system stability. These devices fall into two groups: static and dynamic. Static sources, like capacitors and inductors, provide or use reactive power without actively adjusting to voltage changes. On the other hand, dynamic devices such as synchronous generators, synchronous condensers, and Flexible AC Transmission Systems (FACTS), which include Static Var Compensators (SVC) and Static Compensators (STATCOM), can quickly modify their output in reaction to voltage fluctuations. Reactive power management is integral to the functioning of key power system components including generators, power transmission elements, loads, and compensation devices [25].

2.5.1 Loads

Load characteristics closely affect system voltage stability. The reactive power consumption of a load has a great impact on voltage profile at the bus. The response of loads to voltage changes occurring over many minutes can affect voltage stability. When industrial loads have poor power factor (low lagging power factor) they are usually charged by the system operator for their reactive power absorption from the network. And this compels them to install power factor correction devices. Some typical reactive power consuming loads can be use in power system are induction motors, induction generators, discharged lighting, constant Energy Loads [26].

2.6 Active and Reactive Power Flow in AC Power System

In AC power system, reactive power flow is the movement of energy to build and sustain the electric and magnetic fields for the system to operate. Reactive power doesn't instantly supply end consumers with usable energy, in contrast to active power, which really accomplishes tasks like powering appliances and illuminating dwellings. Instead, it ensures that the system functions efficiently and effectively with managing and maintaining the voltage levels in the power grid. For instance, have a glance at busbar 2 in Figure 2.3. A closer look reveals the following diagram, which is shown in Figure 2.4

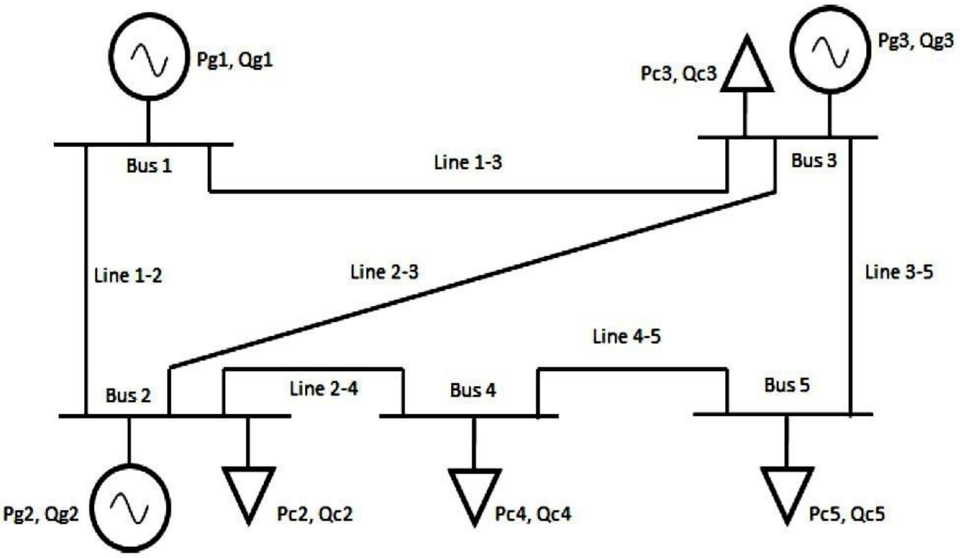

Figure 2.3: schematic view of a power grid.

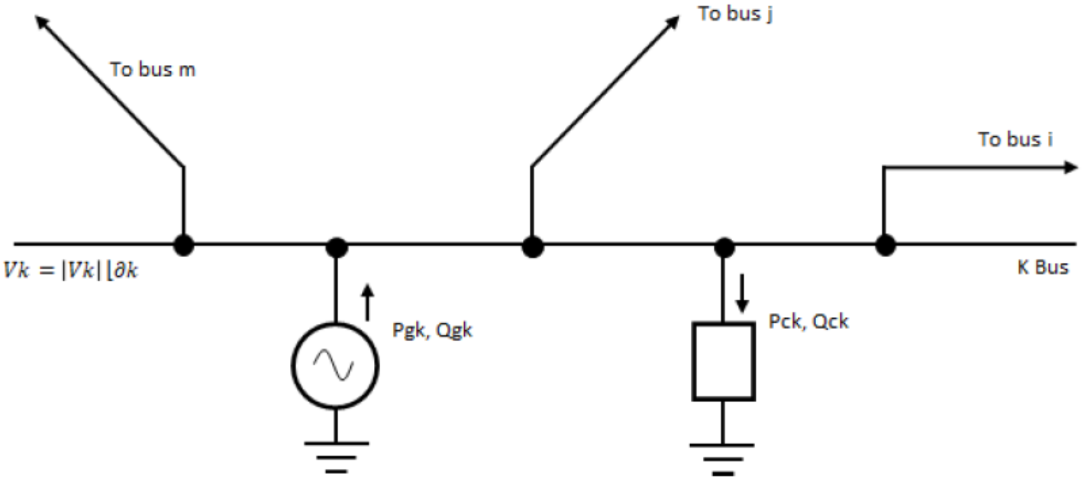

Figure 2.4: detail of k-bus or bus number 2.

For calculation of P_k and Q_k we need to use formula as follows:

$$P_k = P_{gk} - P_{ck} \tag{2.11}$$

$$Q_k = Q_{gk} - Q_{ck} \tag{2.12}$$

$$S_k = V_k \cdot I_k^* = P_k + jQ_k \tag{2.13}$$

Figure 2.5 shows transmission lines equivalent to have better understanding and analyzing power flow of our grid.

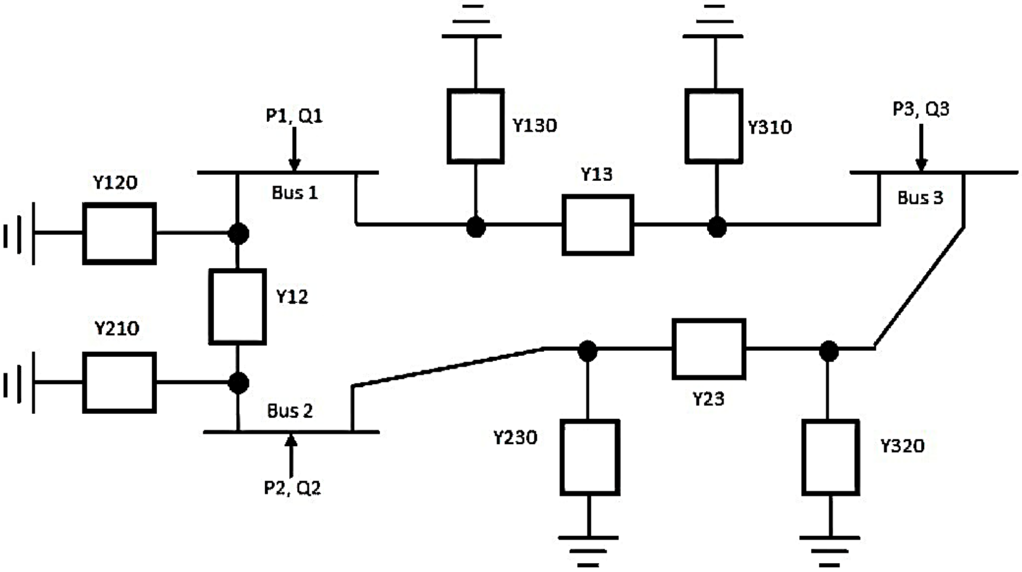

Figure 2.5: transmission lines equivalent.

Y_{ii} is self-admittance while Y_{ij} is called mutual admittance, for understanding of admittance easily it means how easily electricity can flow through the pathway or lines. Higher admittance means less resistance so current can easily flow. Therefore, for current can write as follow:

$$I_{\text{bus}} = Y_{\text{bus}} \cdot V_{\text{bus}} \tag{2.14}$$

Y bus represents the admittance matrix for network. Where with solving linear algebraic equations in matrix form, we can have nodal voltages.

$$I_k = \sum_{n=1}^{N} Y_{kn} \cdot V_n \rightarrow I_1 = Y_{12} \cdot V_1 + Y_{12} \cdot V_2 + Y_{13} \cdot V_3 \tag{2.15}$$

Power at given bus is:

$$S_k = P_k + jQ_k = V_k \cdot I_k^* \tag{2.16}$$

By substituting (2.15) in (2.16) we have:

$$P_k + jQ_k = V_k \left[\sum_{n=1}^{N} Y_{kn} \cdot V_n \right]^* \tag{2.17}$$

Now if we consider N nodes we will have:

$$V_n = |V_n| e^{j\delta_n} \tag{2.18}$$

$$Y_{kn} = |Y_{kn}| e^{j\theta_{kn}}$$

By substituting (2.17) in (2.18) we will get:

$$P_k + jQ_k = V_k \sum_{n=1}^{N} Y_{kn} \cdot V_n \cdot e^{j(\delta_n - \delta_k - \theta_{kn})} \tag{2.19}$$

By applying Euler's equality in equation (2.19)

$$\boxed{\begin{aligned} P_k &= V_k \sum_{n=1}^{N} Y_{kn} \cdot V_n \cdot \cos(\delta_n - \delta_k - \theta_{kn}) \\ Q_k &= V_k \sum_{n=1}^{N} Y_{kn} \cdot V_n \cdot \sin(\delta_n - \delta_k - \theta_{kn}) \end{aligned}} \tag{2.20}$$

P_k and Q_k are represent of power flow of system [18].

3 Electricity markets

An electricity market is a system for buying, selling, and trading electricity. Such markets are also regulated by the government and run by independent system operators (ISOs) or regional transmission organizations (RTOs). The primary objective of an electricity market is to secure electricity supply at fair prices by coordinating the production, delivery, and use of electricity in the most efficient way possible. According the existence literature about electricity markets, there are two methods for determining price marginally-priced clearing UP) and pay-as-bid clearing (PAB) [27].

Figure 3.1 show diagram of electricity market from ISO/RTO to end user for better understanding of whole procedure [28],[27].

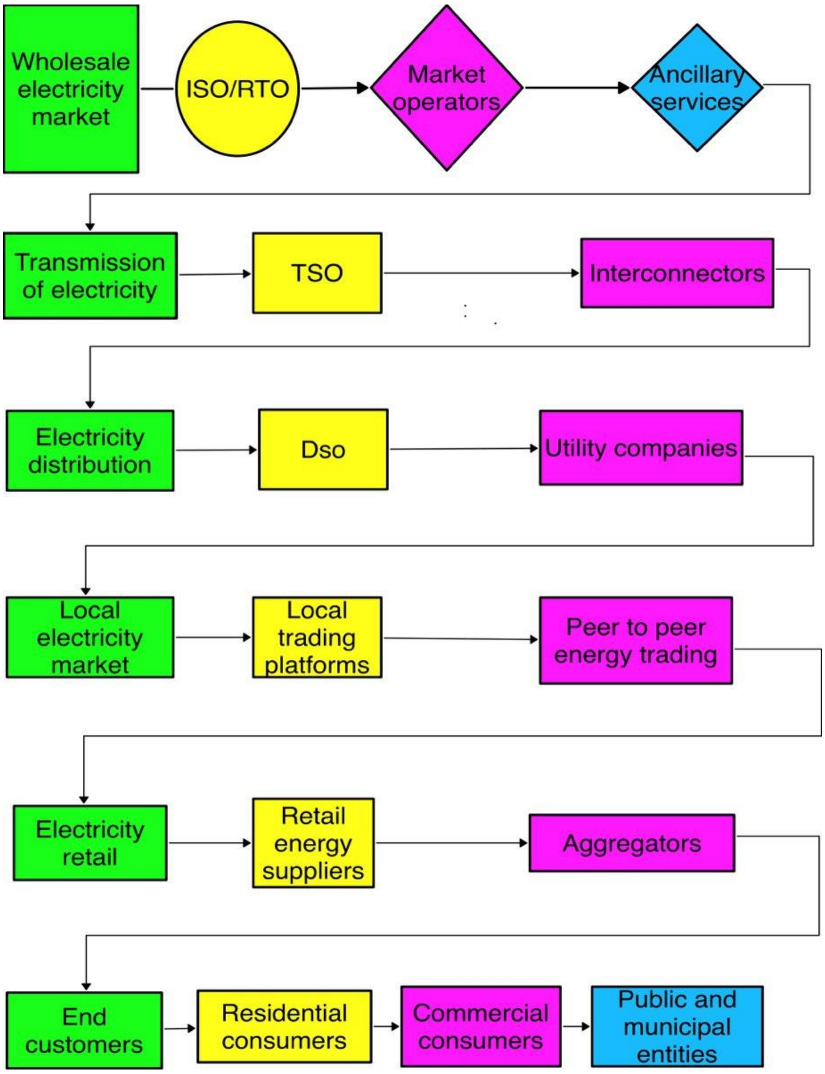

Figure 3.1: Inspired flow chart of electricity market from ISO and RTO to end users [29],[30]..

3.1 market clearing based on marginal price

The price-volume curve for the supply side is formed by arranging short-run marginal generation costs of all the supply assets participating in the market in ascending order according to the amount of available capacity in the supply asset. Once so formed, the available capacity of each supply asset is embedded in the curve. Price-volume curve for the demand side is also drawn to ensure that the market can identify an exact market-clearing point, which is the intersection of the curves for the supply and demand sides, and the market-clearing price is determined at this point. Moreover, in a unified pricing model, the price at which the supply and demand assets that have passed the market survival test are discharged is also a constant. This policy ensures that all supply and demand assets in the market, which are priced in the market, are priced on the same basis. This allows market prices to remain consistent and transparent, and all participants have equal and fair opportunities to participate in the market [29].

3.2 pay-as-bid clearing

Each transaction in a pay-as-bid clearing system can be cleared at a different price, the settlement price, which depends on the accepted bid prices. In a pay-as-bid mechanism, successful generators are paid their own bid. Consequently, winning generators often incorporate a markup over their short-run marginal cost in their bids to recover their long-term costs and earn a return. However, they need to bid for the highest marginal cost that enables them to be selected. Resources that are accepted more often will receive payments based on their submitted bid prices more often. Therefore, these generators bid just below the expected marginally accepted bid price, given that these costs are not below their short-run marginal costs. This strategic bidding allows generators to remain competitive and maximize their surplus [30].

Comparison between pay as bid and marginally priced clearing

The comparison between the two main predominant price clearing systems is very detailed in the available literature. However, it is a topic that is not thoroughly studied, and it is not expected to be a contribution to this work. The models developed in this dissertation are mainly based on the pay-as-bid mechanism, particularly for the continuous intraday electricity market: it operates according to different principles as in the uniform pricing case where auctions are held at predefined time periods. In the pay-as-bid system, the market participants can exchange a given amount of electricity at any time and the trading instances are not a priori scheduled. Figure 3.2 below compares the two price clearing mechanisms, with a summary of their operational details.

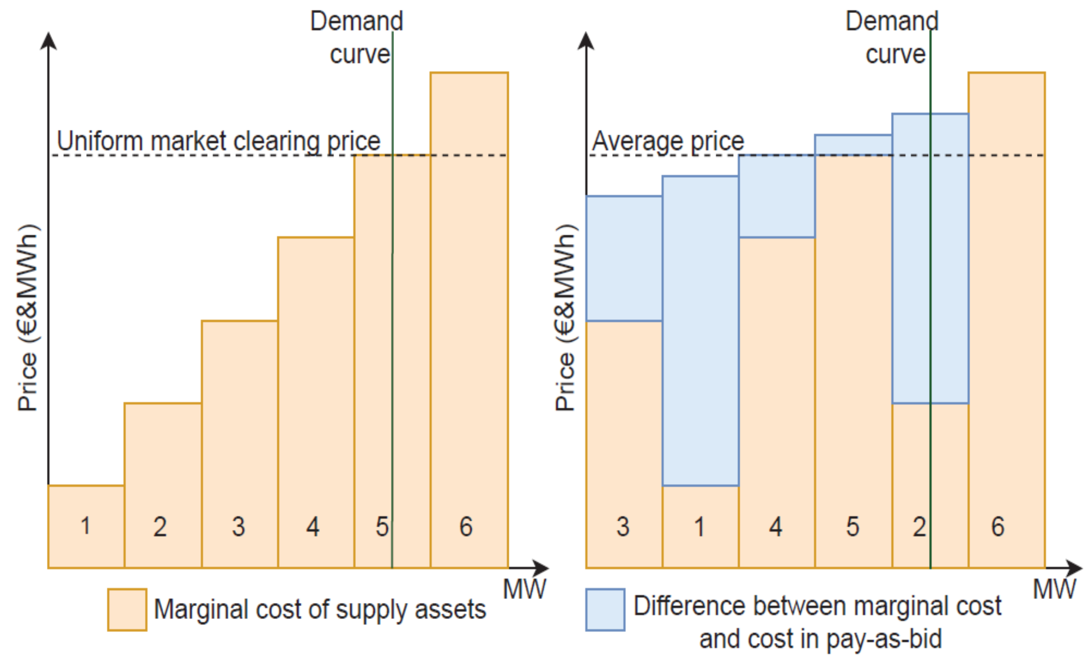

Figure 3.1: Comparison between prices clearing [31].

3.3 Current Independent System Operators and Regional Transmission Organizations in USA

Traditional wholesale electricity markets cover much of the country, such as the Southeast, Southwest, and the Northwest. In these markets, utilities have historically controlled system operations and traditionally sold the power to retail consumers. Utilities there are often vertically integrated, owning the generation, transmission, and distribution systems that serve electricity consumers. Federal entities, such as the Bonneville Power Administration, the Tennessee Valley Authority, and the Western Area Power Administration, also exhibit elements of vertical integration.

Historically, wholesale physical power has been sold through bilateral contracts. Power pools also provided a wholesale market structure. Order No. 888 represents the start of a movement away from this structure. The Order introduced the concept of Independent System Operators (ISOs) or Regional Transmission Organizations (RTOs), in some cases consistent with the then-separate activities of power pools. The purpose of these entities is to facilitate open access to the transmission system and to operate the transmission system in a manner that is independent of market participants and generation owner. These ISOs/RTOs can host Energy and Ancillary Services markets in which market participants can bid or offer to provide generation and other services to the market. These markets use bid-based auctions to determine the hourly schedule for all the resources in the market. Economic dispatch is used to allocate generation to meet the demand of consumers at the least cost or “economic” level.

Order No. 2000 accelerated the movement toward ISOs and RTOs. It required utilities to join or form RTOs. This organization combined the control of the transmission system and devised new mechanisms for how the transmission system should be managed. ISOs were required to develop innovative solutions to manage the transmission in an impartial and efficient manner. ISOs and RTOs are non-profit entities and serve as the initial market monitors for their markets.

Today, there are still significant sections of the country that are served by more traditional market models that continue to buy and sell power through bilateral contracts and power pools. The rest of the country is served by RTOs that have accredited wholesale markets and consist of about two-thirds of the US market. Most of the remaining third is served by utilities that have vertically integrated markets.

The important current ISOs can be seen in Figure 8. The following list includes important ISOs/RTOs from around the world.

3.3.1 United States

- California Independent System Operator (CAISO):
  Manages the power grid and electricity market for most of California.
- Electric Reliability Council of Texas (ERCOT):
  Operates the power grid for most of Texas, notably independent from the rest of the U.S. power grid.
- Midcontinent Independent System Operator (MISO):
  Handles power transmission and electricity markets across parts of Canada and the central USA, including much of the Midwest.
- New York Independent System Operator (NYISO):
  Oversees the power system and wholesale electricity market in New York State.
- PJM Interconnection:
  Manages the electricity grid and market operations across 13 states and the District of Columbia, primarily in the Mid-Atlantic and parts of the Midwest.
- Southwest Power Pool (SPP):
  Regulates the electric grid and wholesale power market in the central United States.
- ISO New England (ISO-NE):
  Responsible for the power system and wholesale electricity markets across the six states of New England.

3.3.2 Canada

- Alberta Electric System Operator (AESO):
  Manages the electricity market and grid operations in Alberta.
- Independent Electricity System Operator (IESO):
  Oversees the electricity market for the province of Ontario.

3.3.3 Europe

- National Grid Electricity System Operator (ESO):
  In the UK manages the electricity system across Great Britain.
- RTE (Réseau de Transport d'Électricité):
  In France Manages the transmission system operator and coordinates the electricity transmission network in France.
- TenneT in Germany and the Netherlands:
  Operates as the transmission system operator in both Germany and the Netherlands.
- ENTSO-E (European Network of Transmission System Operators for Electricity):

Not an operator itself, but a major cooperative assembly of Europe's transmission system operators aiming to integrate the EU's power grid.

3.3.4 Australia

- Australian Energy Market Operator (AEMO):
  Manages the electricity and gas systems and markets across Australia, playing a key role in the National Electricity Market (NEM) and the Wholesale Electricity Market (WEM) in Western Australia.

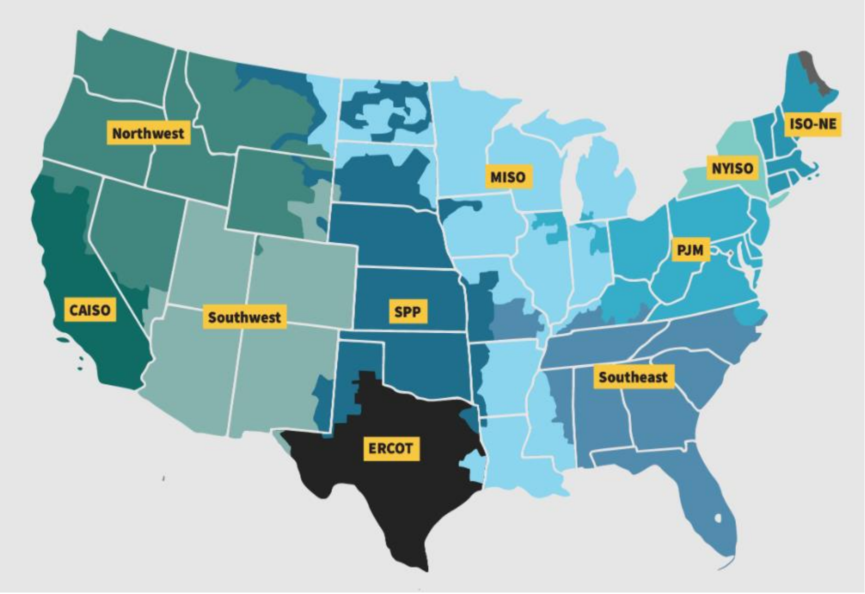

Figure 3.2: USA current ISOs [32].

3.4 Ancillary service in EEA and EU regions

UNIPEDE defines an ancillary service as: any service necessary to constrain the control system management parameters of a power system. These services are offered by generation, transmission, and control equipment to improve the transmission of electric energy from the point of generation to the point of delivery to the end user. They encompass the set of actions involved in maintaining power system reliability, security, and quality, so that the energy sold or transmitted complies with the regulations. They are really at the base of the right to supply, since, without them, the flow of energy, whose volumes, quality, and frequency of flow respond to the needs of the end user, cannot take place.

System services are all the services that system operators or grid operators make available to users connected to the grid. Ancillary services, on the other hand, are specific services that system operators or grid operators purchase from users of the system to provide these system services. Ancillary services can be divided into services that guarantee the integrity of the power system and economical exchange of power. As a model for the electricity markets evolves and with the continued transformation of the electricity sector, a new kind of ancillary service is gaining importance in various European electricity markets.

Such services are particularly needed in the context of the high integration of renewable energy sources, in particular wind energy, in the electricity sector. The electricity generated by renewable sources such as wind energy normally benefits from priority access to the transmission as well as the distribution grid. However, the intermittent and unpredictable nature of renewable energy sources causes the reliability and quality of electricity supply to be confronted with new challenges. Therefore, system operators increasingly require an alternative, rapidly deployable source of energy that can automatically provide the necessary replacement capacity whenever renewable energy production would unexpectedly decrease [33].

3.5 Transmission system operator responsibilities from Pennsylvania-New Jersey-Maryland Interconnection perspective

PJM's manual number 3 describes operational responsibilities and processes that deliver a number of those functions which traditionally sit within the PJM operational structure. PJM a Regional Transmission Organization (RTO), in addition to traditional TSO functions, oversees and expands TSO functions into system security and reliability, coordinating the operation of the system for scheduled maintenance, system enhancement, and facility additions, as well as market operations. PJMs principal tasks are associated with the functions of a TSO.

- Ensure the reliability and security of the electric power transmission system.
- Manage and monitor the network to ensure that energy produced is delivered to meet demand.
- Coordinate with market participants to ensure reliability and performance of the network.
- Ensure compliance with all regulatory and operational standards.

The functions create a more conventional TSO role in the PJM-RTO and carry the forward of the integration of transmission operations, market operations and network security into functions that are greatly simplified, and more RTO based, as they relate to TSO core functions [34].

3.6 Distribution System Operators and Transmission System Operator

Distribution System Operators or DSO is the enterprise that is responsible for distribution and management of energy from the sources of generation to the end users. The digital transformation of grid systems is key for the development of the DSO infrastructure. It will include investments in automation, smart meters, real-time systems, big data and data analytics [35]. Electrical energy consumers are now increasingly able to take part in the market as active players thanks to flexibility in the generation and usage of electricity. This participation, be it individually or via organized energy communities, is expected to expand significantly. In this process, Distribution Network Operators (DNOs) shall have to rapidly evolve into Distribution System Operators (DSOs). Furthermore, a transition is expected in the interconnected duties, responsibilities, and developments of the DSO with Transmission System Operator (TSO) and other main actors in the power system. These include aggregators, fleet operators, balancing service providers, retailers, and major grid users. DSOs and TSOs are to undergo a significant evolution in their interactions, as well as redefine the coordination of operational duties and responsibilities with the newly emerging market participants, including aggregators and operators of Distributed Energy Resources (DERs). They are the ones to ensure that consumers have secure, flexible, scalable solutions that foster the sustainability, affordability, and reliability of the entire power system.

In this regard, it is found that DSOs need to ensure that consumers can benefit from a wide range of market offerings, from energy lighting to ancillary services, system balancing, flexibility activation or peer-to-peer transactions, in which a high level of security is maintained as well as supply quality. Otherwise, they shall not be left behind in using the growing volume of energy sources at the distribution level, those being solar panels, wind turbines, and storage systems. These resources are very important in that it is possible to offer flexible services that improve the entire power system, allowing for increased penetration of renewable energy sources at lower prices and costs for the average consumer. This approach will also help to reduce dependence on traditional power generation, as well as to reduce greenhouse gas emissions, which will benefit consumers. Figure 3.4 shows local market vision of DSOs [36].

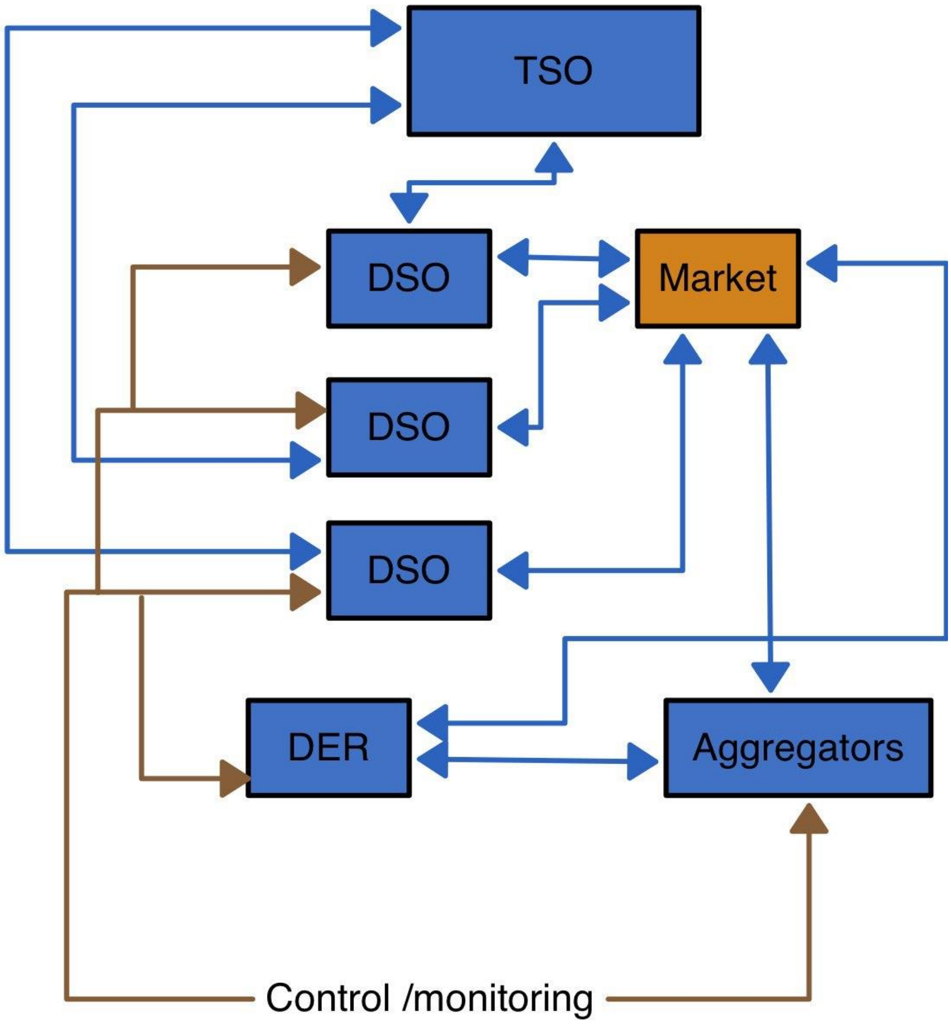

Figure 3.3: local market vision of DSOs.

3.7 History of Reactive Power Pricing

Historically, utilities structured transmission rates based on the costs associated with a plant allocated to the transmission function. In terms of reactive power, customers who only used the transmission system were charged for reactive power support. The design of these rates varied depending on the use of reactive power or adjustments made for a transmission customer's actual power demand or energy consumption based on the customer's power factor. Reactive power was crucial for the reliable operation of the transmission system, and utilities often applied penalties or rewards for large customers depending on whether their power factor fell below or exceeded a set threshold or trigger power factor. Additionally, reactive power costs were included within a defined "deadband."

In 1990, in the case involving Northern States Power Company, the Commission determined for the first time that imposing a separate charge for reactive power was not inherently unjust or unreasonable. In a later case also involving Northern States Power Co., the Commission established procedures for utilities to set unbundled wholesale prices for reactive power service. The Commission specified that Northern States would need to aggregate the total costs of all sources of reactive power when developing a proposed charge for reactive power. The utility was required to pinpoint the actual costs of the portion of the generator used in producing reactive power. Moreover, Northern States was expected to identify and exclude from the base transmission rate calculation any costs related to transmission equipment dedicated to generating reactive power.

This approach ensured that all costs associated with reactive power supply were aggregated to develop a singular charge for this service, acknowledging that reactive power is provided by various sources across a utility's system. Following the outlined general methodology, Northern States could choose to propose either an average or incremental rate design in specific cases. However, the utility would carry the burden of proof to justify its proposed [26].

3.8 Locational Marginal Price in PJM

Locational Marginal Price (LMP) is defined as the marginal price for energy at the location where the energy is delivered or received and is based on forecasted system conditions and the latest approved real-time security constrained economic dispatch program solution. LMP is expressed in dollars per megawatt-hour ($/MWh). LMP is a pricing approach that addresses Transmission System congestion and loss costs, as well as energy costs. Therefore, each spot market energy customer pays an energy price that includes the full marginal cost of delivering an increment of energy to the purchaser's location.

The formula to calculate LMP at each node is generally expressed as follows:

$$\mathrm{LMP} = \mathrm{MCP} + \mathrm{MCC} + \mathrm{MCL} \tag{3.1}$$

Where:

- MCP (Marginal Cost of Production) reflects the cost of producing the next MW of power at the node. This component reflects the cost of producing the next increment of

electricity at the node, based on the cheapest available set of generators, considering their offers in the market.
- MCC (Marginal Congestion Cost) indicates the cost due to transmission constraints.
- MCL (Marginal Cost of Losses) accounts for the cost of power losses during transmission[37],[38].

3.9 Norwegian market

The Norwegian electricity market is distinguished from many others in the sense that it is almost completely dominated by hydroelectric power generation. In 2017, hydro power constituted 95.8% of the country's total annual electricity generation of 149 TWh. Among the countries that we can study, most countries have a mixed portfolio, although often with a large proportion of thermal power. In Norway, only 2.3% of the electricity consumption was covered by thermal power. Wind power contributed the remaining 1.9% of electricity production. As a result, Norway's electricity mix has the highest proportion of intermittent renewable energy sources (RES) in Europe.

Norway's extensive hydro power reservoir capacity and its connectivity with neighboring countries help stabilize supply and demand fluctuations across these regions [39].

In 2017, Norway had an interconnector capacity of 6200 MW with other countries, which means it had an interconnector capacity of 18.1% of its total installed electricity production capacity, at 34200 MW [40].

The amount of electricity Norway exports or imports is highly variable by year, depending significantly on meteorological factors that determine hydro reservoir levels Historically, Norway has been a net exporter of electricity; the net electricity export in 2017 was 15 TWh [41].

3.10 Energy policy in Norway

The deregulation of the Norwegian electricity market was initiated by the Energy Act of 1990. The purpose of the Norwegian Energy Act is to ensure the organization of electricity production, transformation, transmission, trading, distribution, and usage in a socio-economically efficient manner. Following the deregulation, along with several amendments to the Energy Act, the Norwegian electricity market has evolved into an open, market-based system for the production and trading of electricity, while the operations of the grid remain under strict regulation. The Norwegian Parliament denes the political framework for energy resource management. Ministry of Petroleum and Energy (OED) has the overall responsibility to implement the policies [42].

3.11 Nord Pool

The deregulation of the Norwegian electricity sector established the groundwork for a power exchange to be set up [43]. This power exchange was subsequently renamed Nord Pool. Over the next few years, the other Nordic electricity markets undertook similar deregulation efforts as Norway and joined Nord Pool, apart from Iceland. Subsequently, Estonia, Lithuania, and Latvia became members of Nord Pool. Nord Pool initiated the N2EX power market in the UK. Nord Pool is segmented into bidding zones determined by the local TSOs to manage congestion in the national electricity grids. Currently, the Norwegian electricity market is split into bidding zones, depicted in Figure 10. The electricity market in the UK is segmented into two market areas. Great Britain comprises England, Scotland, and Wales, while Northern Ireland participates in the Single Electricity Market with Ireland [44]. Nord Pool acts as the physical power exchange and manages the day-ahead and intraday markets in the Nordics, the Baltic states, and the UK [45].

Most of the trading volume is concluded in the day-ahead market, Elspot, which settles at noon, with electricity delivery occurring the next day. At Nord Pool, prices for each hour of delivery in each bidding zone are determined by its customers. Following this, Nord Pool computes the system price by considering buy and sell orders, ignoring the transmission capacity limits between the bidding zones [46].

Figure 3.4: Nord Pool zones areas.

The system price is used as a reference price for trading and clearing of financial contracts. The intraday market, Elbas, works as a supplement to balance day-ahead contracts due to changes in demand or supply, and offers trading up until one hour before delivery.[47]

4 Simulation

This chapter will cover the configuration and simulation of AC networks utilizing the IEEE 30-bus and 33-bus systems through Python. The examination of power flow within these networks will be detailed, and the application of Locational Marginal Pricing (LMP) will be demonstrated to reveal the impact of different network conditions on pricing.

4.1 Ac power grid

In this study it has been chosen to run simulation on Python to get power flow and case study are standard IEEE 30 and 33 bus. Figure 4.1 shows IEEE standard 33 bus diagram.

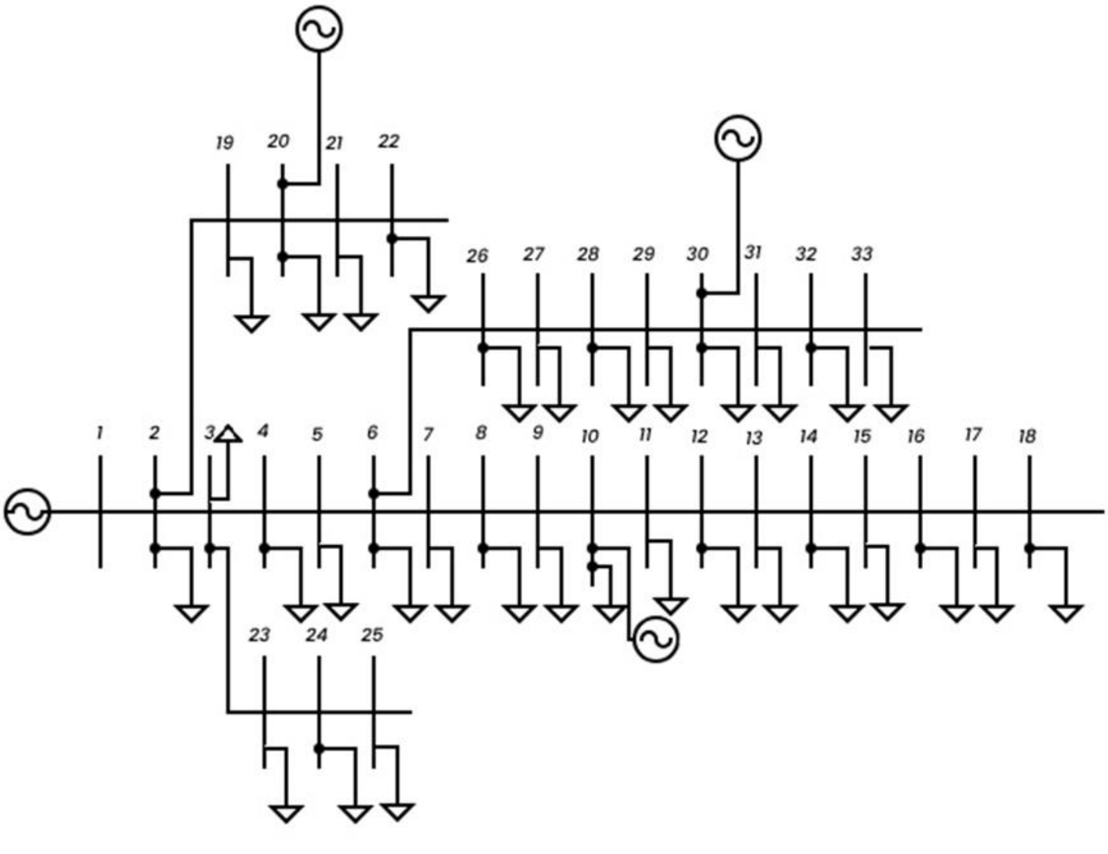

Figure 4.1: IEEE standard 33 bus diagram [48].

As it can be seen from figure bus 1 is slack bus and first generator is connected to bus 1, also generator 2 ,3, 4 connected to bus 10,20,30 respectively. It has been shown DGs parameters in table 4.1.

Table 4.1: Nominal Power Ratings for Generators

Generator ID	Nominal Power (MW)
Slack Generator	100 MW
DG1	0.8 MW
DG2	1.0 MW
DG3	0.5 MW

Also, line data for standard IEEE 33 bus is shown on table 4.2.

Table 4.2: line data for IEEE 33 bus [49]

From Bus	To Bus	Resistance (R)	Reactance (X)
1	2	0.0922	0.0470
2	3	0.4930	0.2511
3	4	0.3660	0.1864
4	5	0.3811	0.1941
5	6	0.8190	0.7070
6	7	0.1872	0.6188
7	8	0.7114	0.2351
8	9	1.0300	0.7400
9	10	1.0440	0.7400
10	11	0.1966	0.0650
11	12	0.3744	0.1238
12	13	1.4680	1.1550
13	14	0.5416	0.7129
14	15	0.5910	0.5260

15	16	0.7463	0.5450
16	17	1.2890	1.7210
17	18	0.7320	0.5740
2	19	0.1640	0.1565
19	20	1.5042	1.3554
20	21	0.4095	0.4784
21	22	0.7089	0.9373
3	23	0.4512	0.3083
23	24	0.8980	0.7091
24	25	0.8960	0.7011
6	26	0.2030	0.1034
26	27	0.2842	0.1447
27	28	1.0590	0.9337
28	29	0.8042	0.7006
29	30	0.5075	0.2585
30	31	0.9744	0.9630
31	32	0.3105	0.3619
32	33	0.3410	0.5302

Table 4.3: Load data for standard IEEE 33 bus [50]

Bus	P_set (MW)	Q_set (MVAR)
Bus_2	0.100	0.060
Bus_3	0.090	0.040
Bus_4	0.120	0.080

Bus_5	0.060	0.030
Bus_6	0.060	0.020
Bus_7	0.200	0.100
Bus_8	0.200	0.100
Bus_9	0.060	0.020
Bus_10	0.060	0.020
Bus_11	0.045	0.030
Bus_12	0.060	0.035
Bus_13	0.060	0.035
Bus_14	0.120	0.080
Bus_15	0.060	0.010
Bus_16	0.060	0.020
Bus_17	0.060	0.020
Bus_18	0.090	0.040
Bus_19	0.090	0.040
Bus_20	0.090	0.040
Bus_21	0.090	0.040
Bus_22	0.090	0.040
Bus_23	0.090	0.050
Bus_24	0.420	0.200
Bus_25	0.420	0.200
Bus_26	0.060	0.025
Bus_27	0.060	0.025
Bus_28	0.060	0.020

Bus_29	0.120	0.070
Bus_30	0.200	0.600
Bus_31	0.150	0.070
Bus_32	0.210	0.100
Bus_33	0.060	0.040

Figure 4.2 shows topology of the IEEE standard 30 bus.

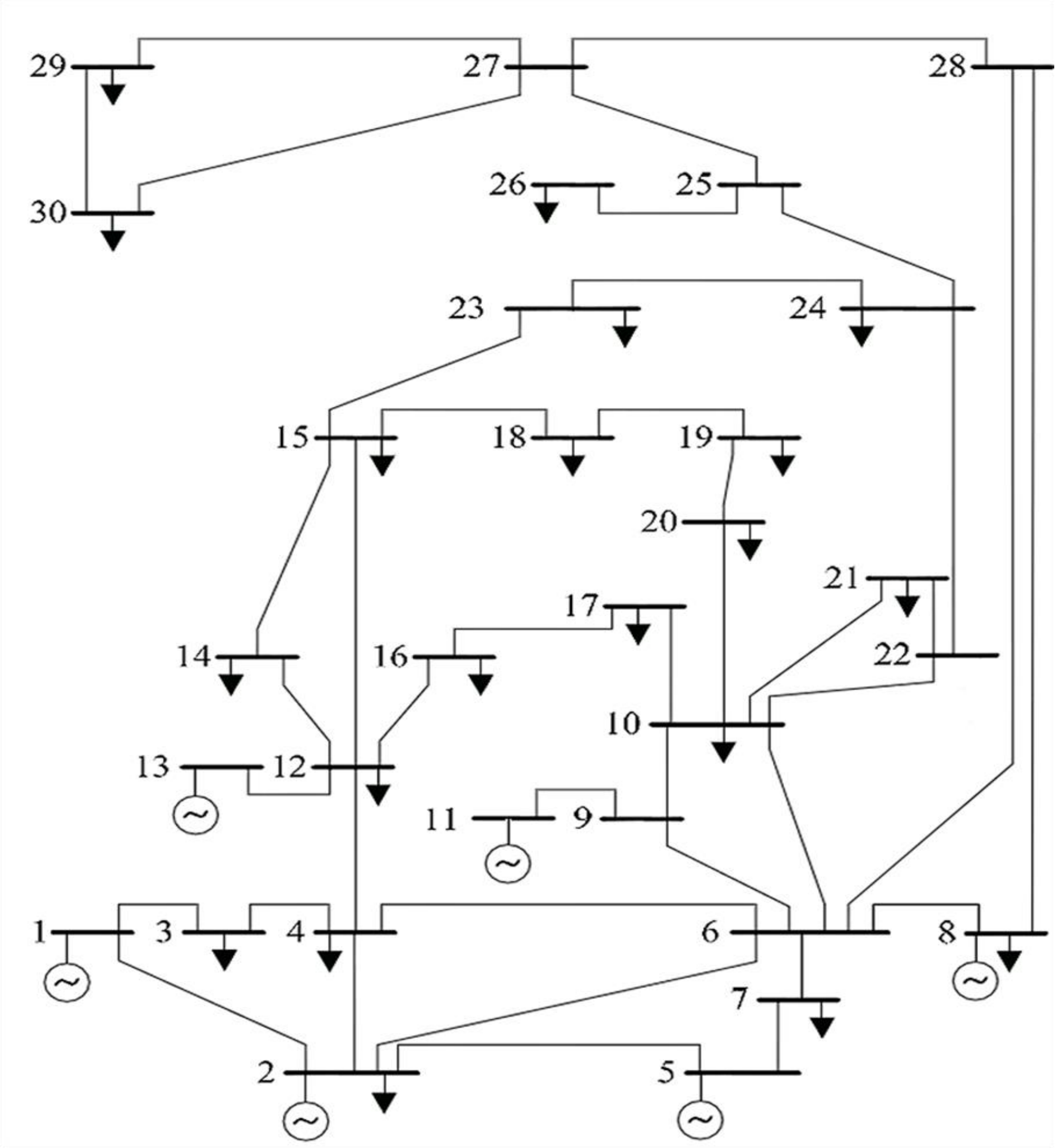

Figure 4.2: IEEE standard 30 bus[51].

Nominal power rating for generators is also mentioned in table 4.4.

Table 4.4:IEEE 30 bus nominal power rating for generators

Generator	Bus	Nominal Power
Slack Generator	Bus_1	138.48 MW
DG1	Bus_2	57.56 MW
DG2	Bus_5	24.56 MW
DG3	Bus_8	35.00 MW
DG4	Bus_11	17.93 MW
DG5	Bus_13	6.00 MW

Line data for IEEE 30 bus is mentioned in table 4.5.

Table 4.5: Line data for standard 30 bus IEEE [52].

From Bus	To Bus	Resistance (R)	Reactance (X)
1	2	0.0192	0.0575
1	3	0.0452	0.1852
2	4	0.0570	0.1737
2	5	0.0472	0.1983
2	6	0.0581	0.1763
3	4	0.0132	0.0379
4	5	0.0472	0.1983
4	6	0.0818	0.1763
5	7	0.0460	0.1160
6	7	0.0267	0.0820
6	8	0.0120	0.0420

6	9	0.0000	0.2080
6	10	0.0000	0.5560
9	11	0.0000	0.2080
9	10	0.0000	0.1100
4	12	0.0000	0.2560
12	13	0.0000	0.1400
12	14	0.1231	0.2559
12	15	0.0662	0.1304
12	16	0.0945	0.1987
14	15	0.2210	0.1997
16	17	0.0824	0.1932
15	18	0.1070	0.2185
18	19	0.0639	0.1292
19	20	0.0340	0.0680
10	20	0.0936	0.2090
10	17	0.0324	0.0845
10	21	0.0348	0.0749
10	22	0.0727	0.1499
21	22	0.0116	0.0236
15	23	0.1000	0.2020
22	24	0.1150	0.1790
23	24	0.1320	0.2700
24	25	0.1885	0.3292

25	26	0.2544	0.3800
25	27	0.1093	0.2087
28	27	0.0000	0.3960
27	29	0.2198	0.4153
27	30	0.3202	0.6027
29	30	0.2399	0.4533
8	28	0.0636	0.2000
6	28	0.0169	0.0599

For load data table 4.6 is used.

Table 4.6: Load data for 30 bus IEEE [53].

Bus	P_set (MW)	Q_set (MVAR)
Bus_1	0.0	0.0
Bus_2	21.7	13.02
Bus_3	2.4	1.44
Bus_4	67.6	40.56
Bus_5	34.2	20.52
Bus_6	0.0	0.0
Bus_7	22.8	13.68
Bus_8	30.0	18.0
Bus_9	0.0	0.0
Bus_10	5.8	3.48
Bus_11	0.0	0.0
Bus_12	11.2	6.72
Bus_13	0.0	0.0

Bus_14	6.2	3.72
Bus_15	8.2	4.92
Bus_16	3.5	2.1
Bus_17	9.0	5.4
Bus_18	3.2	1.92
Bus_19	9.5	5.7
Bus_20	2.2	1.32
Bus_21	17.5	10.5
Bus_22	0.0	0.0
Bus_23	3.2	1.92
Bus_24	8.7	5.22
Bus_25	0.0	0.0
Bus_26	3.5	2.1
Bus_27	0.0	0.0
Bus_28	0.0	0.0
Bus_29	2.4	1.44
Bus_30	10.6	6.36

4.2 Software for power flow analysis

PyPSA (Python for Power System Analysis) is a highly advanced open-source software library, which has been developed for the study and analysis of electrical power infrastructure. Buses, lines, generators, loads, and other components of power systems are represented and managed in this software. This way, all the relevant parameters of different power system components are interconnected with each other to facilitate dynamic analysis and optimization.

A physical topology is inherently embedded in the network model in PyPSA. Every The physical topology is an integrated component of the network model in PyPSA. The buses, lines, generators, and loads are physical entities and possess corresponding attributes, such as nominal power, that represent the physical facets of the power system design. These components are also connected with each other, forming a physical network in which the topological relations and power-flow-related constraints are fixed. Generators in the network are constrained by the available power, as well as various sources of uncertainty. The loads in the network are constant power injections.

PyPSA uses advanced techniques like the Newton-Raphson method to solve power flow equations. Such techniques ensure that non-linear algebraic equations, which specify the operational behavior of the power system, are resolved in a computationally efficient manner. As a result, the software can calculate steady-state power flow for system configurations, thereby laying the groundwork for proper grid management in the real world.[54]

4.3 History and methods for price in Pennsylvania-New Jersey-Maryland Interconnection

PJM began in 1927 when Philadelphia Electric Company, Pennsylvania Power & Light, and Public Service Gas & Electric Company of New Jersey connected their 230 kV transmission systems to function as a single entity. Over the years, six more utilities from the Mid-Atlantic region joined, forming a regional power pool. By the 1990s, as deregulation took place, PJM had gained a strong reputation for excellence in large-scale power operations. PJM managed the eight member utilities as one entity for scheduling generating units, enhancing economies of scale and passing on the savings to the utilities.

The PJM market started operating under the Two Settlement System on June 1, 2000. The success of the PJM market led to its expansion. On May 1, 2004, the Commonwealth Edison Company of Chicago, IL, joined PJM.

On October 1, 2004, Dayton Power & Light of Dayton, OH, and the American Electric Power Company of Columbus, OH, joined PJM. This was followed by Duquesne Power & Light Company of Pittsburgh, PA, on January 1, 2005, and Dominion Virginia Power Company on May 1, 2005. PJM's footprint encompasses 13 states and the District of Columbia, including 56,250 miles of transmission lines, 164,634 megawatts of generating capacity, and 164,260 square miles of service territory, serving a population of 51 million people.

PJM’s Energy Market functions similarly to a stock exchange, where market participants set electricity prices by matching supply and demand. The market employs locational marginal pricing, which reflects the value of energy at the specific location and time it is delivered. If the lowest-priced electricity can reach all locations, the prices are uniform across the entire grid.

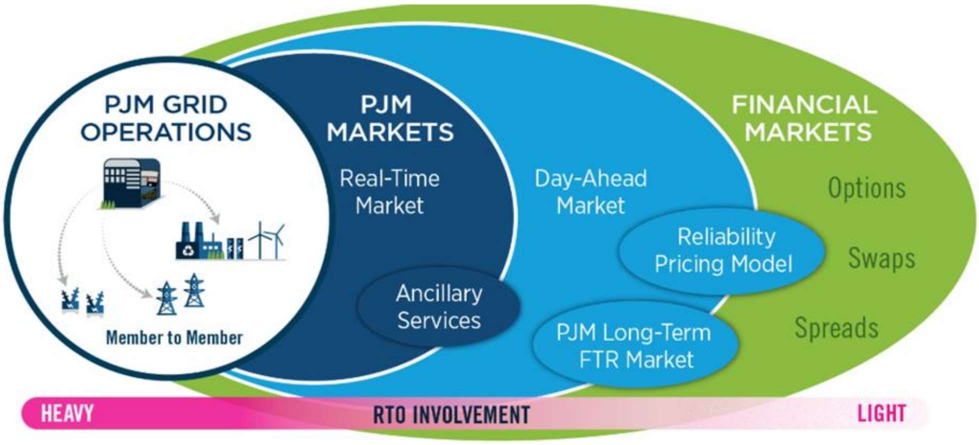

Figure 4.3: Markets and price methods for PJM [56].

When transmission congestion occurs, energy cannot flow freely to certain locations, in that case, more-expensive electricity is ordered to meet that demand. As a result, the locational marginal price (LMP) is higher in those locations. The primary method is Locational Marginal Pricing (LMP), which operates through both the Day-Ahead and Real-Time markets. The Day-Ahead Market sets prices based on supply and demand forecasts for the next day, while the Real-Time Market recalculates prices in real-time based on actual conditions. Figure 4.3 showed whole methods and markets for PJM [55].

5 Results and discussions

In this chapter results of both 30 and 33 IEEE bus are presented, and the price mechanism are evaluated.

5.1 33 bus power flow results

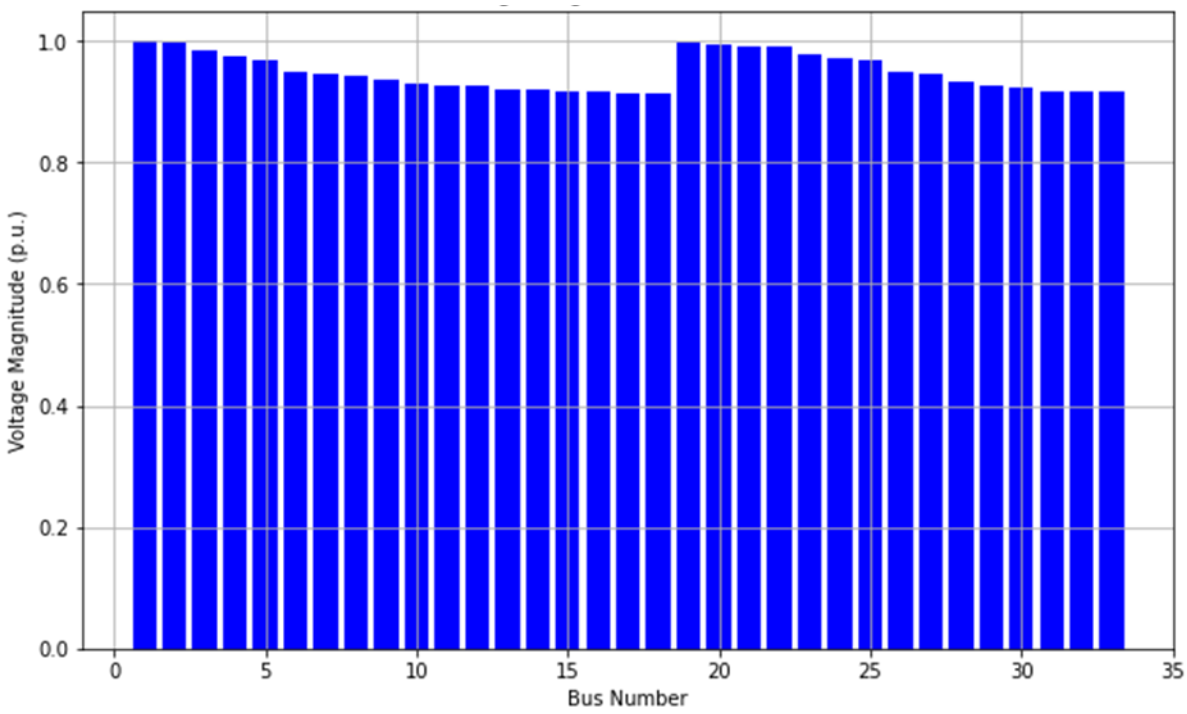

Figure 5.1:Voltage magnitudes.

Figure 5.1 provides a visual representation of the voltage levels at each bus in the network, allowing easy identification of buses with voltages deviating significantly from the nominal value.

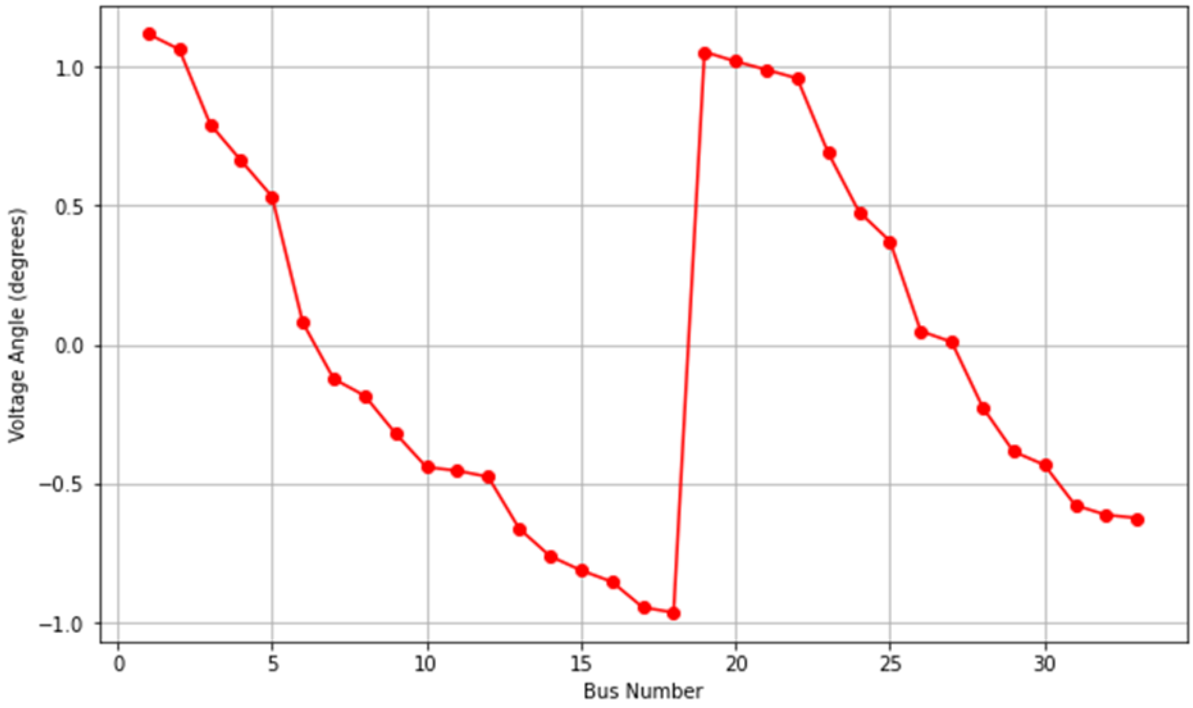

Figure 5.2:Voltage angles at each bus.

Figure 5.2 shows the voltage angles, indicating the phase differences between the buses. This is crucial for understanding the power flow and stability of the network.

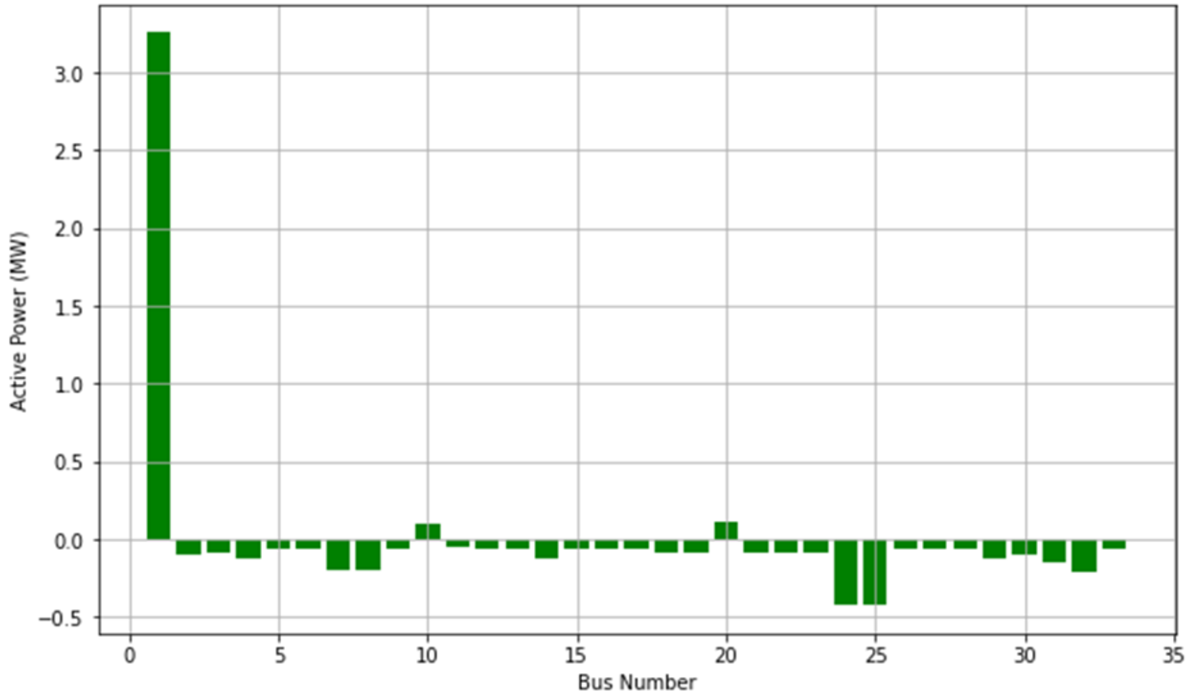

Figure 5.3: Active power at each bus.

Figure 5.3 displays the active power generation or consumption at each bus. Positive values indicate generation, while negative values indicate consumption.

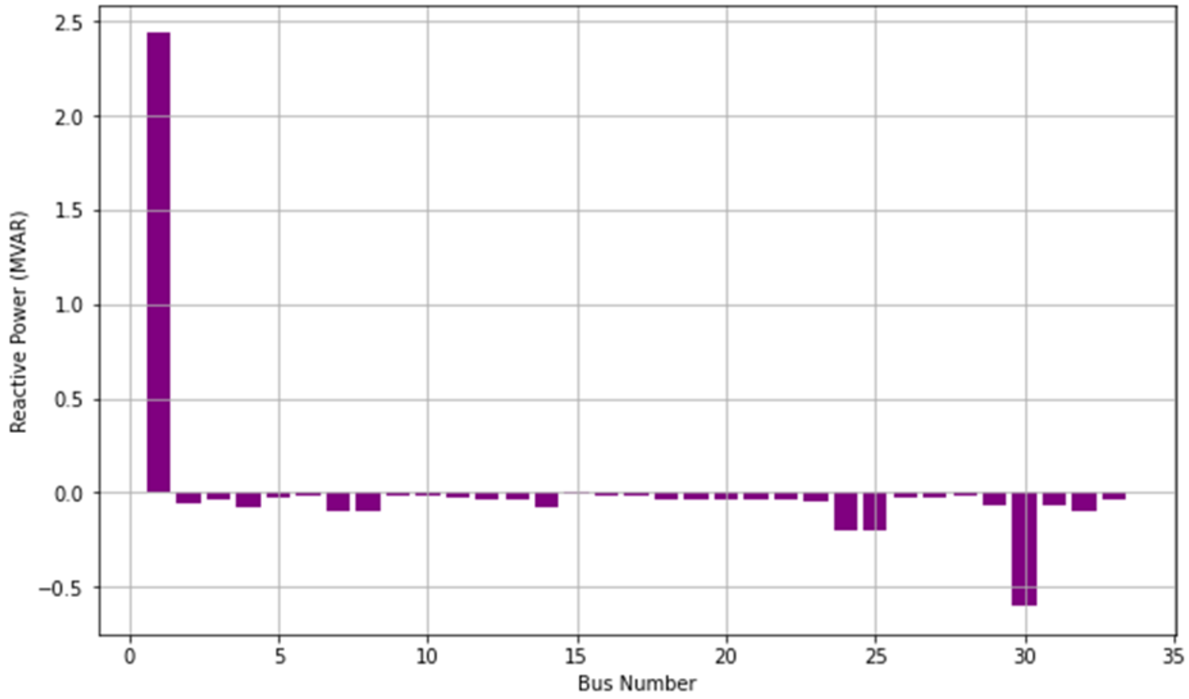

Figure 5.4:Reactive power at each bus.

Figure 5.4 illustrates the reactive power at each bus, highlighting the reactive power support or demand within the network.

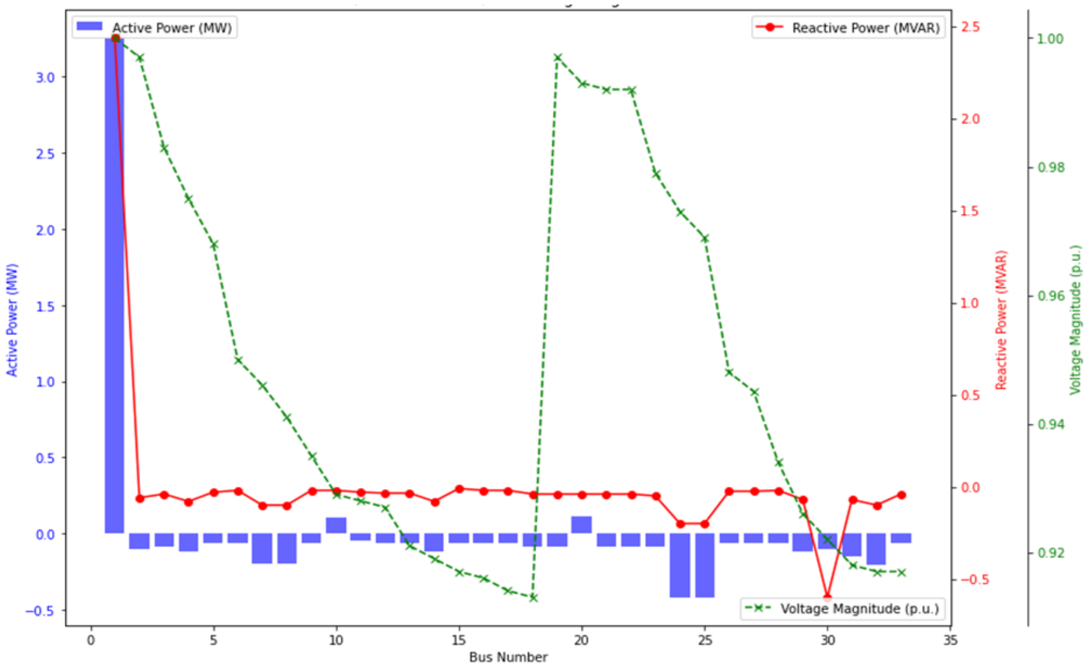

Figure 5.5: Active power, Reactive power, and voltage magnitude of 33 bus.

Figure 5.5 shows active power (blue bars), reactive power (red line), and voltage magnitude (green line) at each bus. Active power is highest at bus 1 and decreases across the buses, with some buses consuming power (negative values). Reactive power remains relatively low and stable. The voltage magnitude starts near 1.0 p.u. at bus 1 but drops as we move through the buses, hitting the lowest point around bus 30. This indicates that the higher line impedances and distributed loads in the 33-bus system cause significant voltage drops and losses.

5.2 Active Power, Reactive Power, and Voltage Magnitudes in the 33-Bus System

Figures 5.1, 5.2, 5.3, 5.4, 5.5 shown values of active power, reactive power and voltage magnitude which will be explaining as follow:

5.2.1 Active power

Bus 1 has a high positive value, indicating power generation or input. Some buses like Buses 10 and 20 have positive values, indicating power generation or less consumption compared to the rest. Buses that show negative values, indicating power consumption.

5.2.2 Reactive Power

Reactive power values generally fluctuated around zero for most buses, indicating that the reactive power demands or supplies are relatively low. Buses with significant negative reactive power values like Buses 24 and 25 might consume more reactive power, possibly indicating loads with inductive characteristics. Some buses like Bus 1 and 2 have higher reactive power values, indicating reactive power generation or compensation.

5.2.3 Voltage Magnitudes

The voltage magnitudes show a decreasing trend from Bus 1 to Bus 33. The voltage at Bus 1 is 1.0 p.u., which is typically the reference voltage or slack bus voltage. Buses 2-33 have voltage magnitudes less than 1.0 p.u., which is common as voltage drops occur due to line impedance and loads drawing power. The sharp drops in voltage magnitude (e.g., around Bus 30) indicate significant power losses.

Buses with high active power consumption generally show lower voltage magnitudes. This correlation aligns with the fact that power consumption causes voltage drops due to line impedance. Buses with substantial reactive power demands also show lower voltage magnitudes, indicating the impact of reactive power on voltage stability.

The voltage profile suggests the need for reactive power support or voltage regulation devices, especially in areas with significant voltage drops.

The significant drop in voltage around Bus 30 suggests potential issues with voltage regulation. Installing voltage support devices like capacitors or voltage regulators could help.

5.3 Sample bus power flow analysis

Bus number 2 is chosen for more power flow analysis. Table 5.2 show direction and values of power flow from bus number 2 to bus 19, 3 and 1.

Table 5.1: Active power flow at bus 2.

From Bus	To Bus	Active Power (MW)	Direction of Flow
1	2	3.255	To Bus 2 (Received by Bus 2)
2	3	0.09	To Bus 3 (Sent from Bus 2)
2	19	0.1	To Bus 19 (Sent from Bus 2)

Table 5.2: Reactive power flow at bus 2.

From Bus	To Bus	Reactive Power (MVAr)	Direction of Flow
2	1	2.495	To Bus 1 (Received by Bus 2)
2	3	0.02	To Bus 3 (Sent from Bus 2)
2	19	0.04	To Bus 19 (Sent from Bus 2)

5.1 Results for 30 standard IEEE bus

In this section results that related to 30 standard buses in figures 5.6, 5.7, 5.8, 5.9,5.10

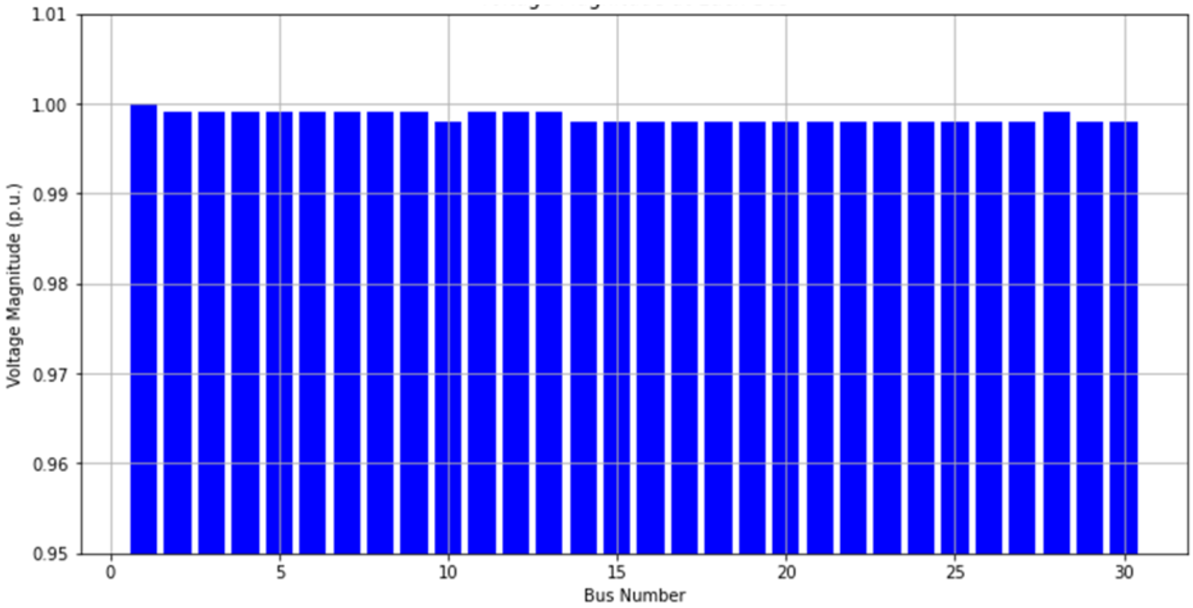

Figure 5.6: Voltage magnitude for 30 bus IEEE.

Figure 5.6 shows the voltage levels at each bus in the network.

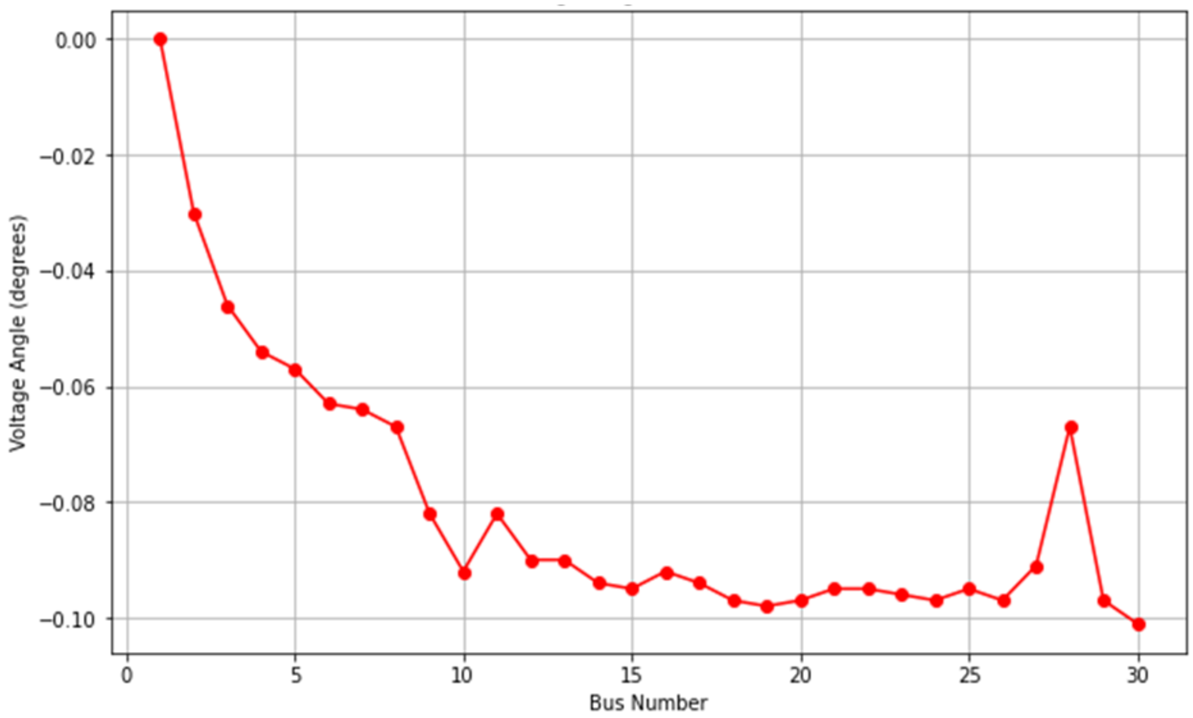

Figure 5.7:Voltage angle of each bus for IEEE 30 bus network.

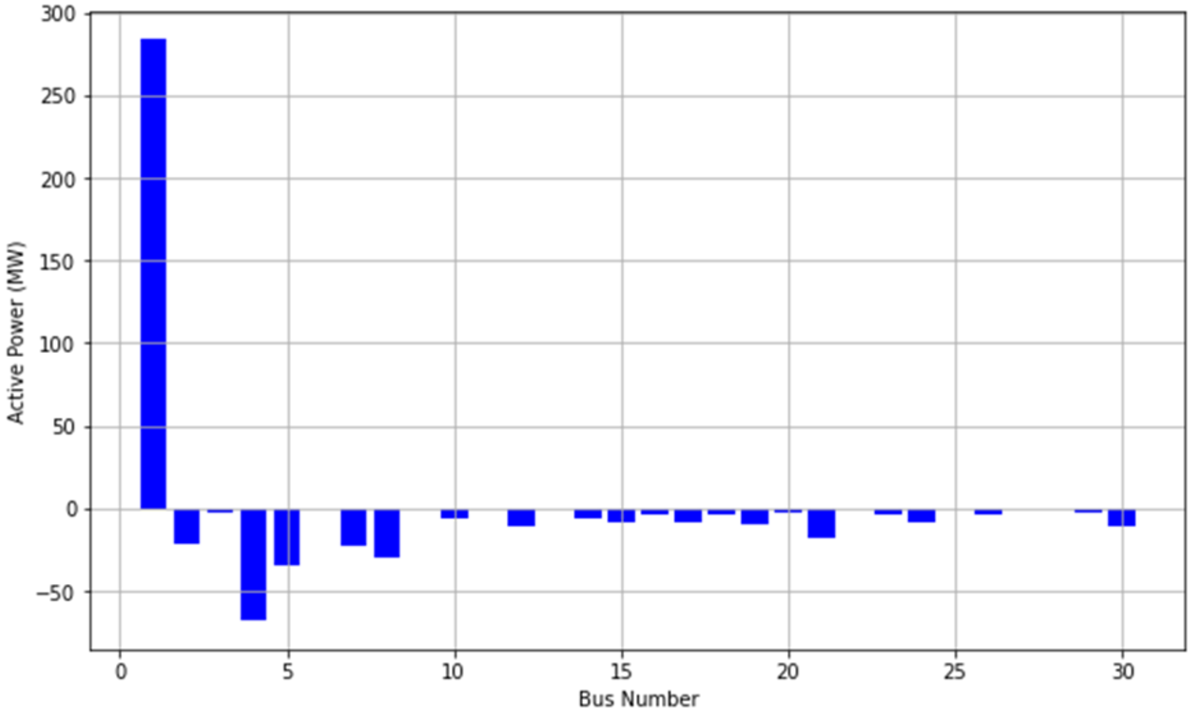

Figure 5.8: Injected active power at each bus (30 bus IEEE)

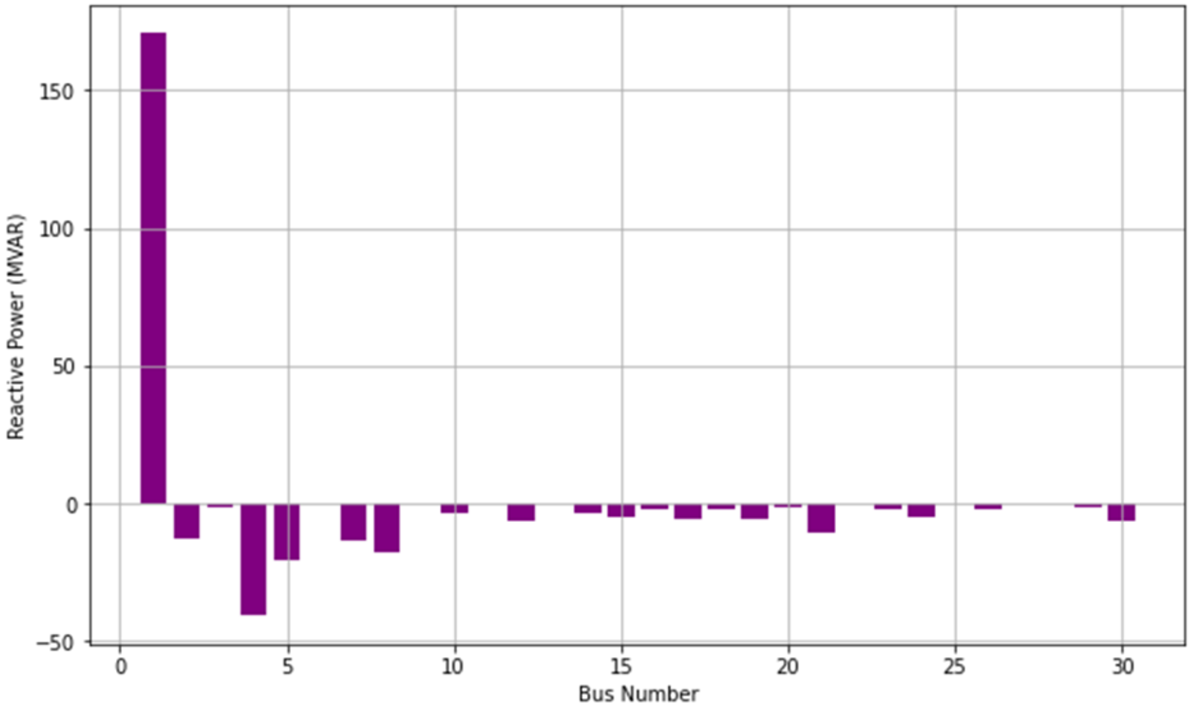

Figure 5.9: Reactive power at each bus (30 bus IEEE)

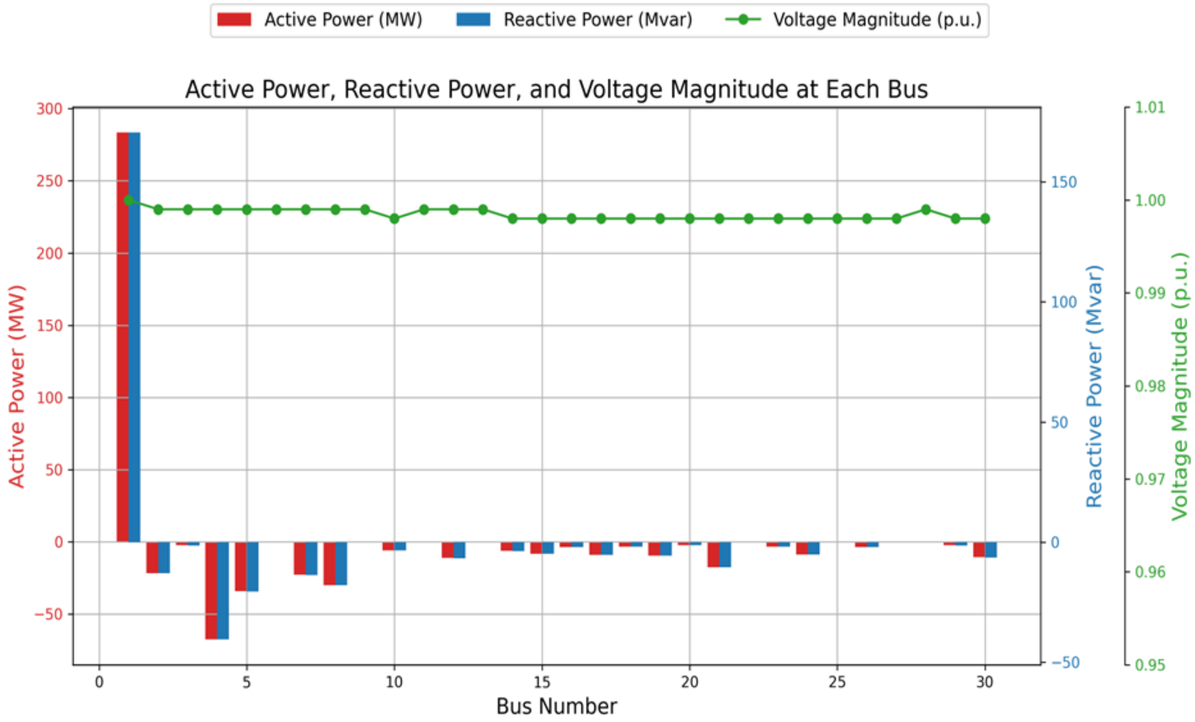

Figure 5.10: Active power, Reactive power, and voltage angle (IEEE 30 bus).

5.2 Analysis for active power and reactive power and voltage magnitude of IEEE 30 bus

5.2.1 Active Power

The graph shows the distribution of active power across the buses. Positive values indicate power generation, while negative values indicate power consumption. Bus 1 generates a significant amount of power (283.55 MW), which is typical for a slack bus that balances the power in the system. Most other buses have negative values, indicating power consumption.

5.2.2 Reactive Power

The reactive power graph follows a similar pattern to the active power graph, with most buses consuming reactive power. Bus 1 is again significant, providing a large amount of reactive power (170.601 Mvar). Reactive power is crucial for maintaining voltage levels within the network.

5.2.3 Voltage Magnitudes

The voltage magnitudes are very close to 1 p.u., indicating that the voltage levels are well-regulated across the system. Slight variations occur due to the distribution of reactive power and the impedance of the lines.

5.3 Analysis

5.3.1 Active and Reactive Power

Buses with significant active power generation or consumption also tend to have corresponding reactive power values. This relationship is critical as reactive power supports the voltage levels necessary for the active power to flow efficiently.

5.3.2 Voltage Magnitudes

The voltage magnitudes are generally stable and close to 1 p.u., reflecting a well-maintained system. The reactive power supplied or absorbed by the buses directly influences these voltage levels. For instance, buses consuming a lot of reactive power may experience slight voltage drops.

By analyzing the graphs, we can ensure that the power system operates within its limits, with appropriate voltage levels and balanced active and reactive power. This visualization helps in identifying any potential issues with specific buses that may require corrective measures.

5.4 LMP results and discussion

The graph shows the LMP for active and reactive power at each bus. Bus 1 has a significantly higher LMP for both active and reactive power, indicating it may be a crucial bus for pricing since it is a slack bus. Buses 24 and 25 also show high LMP for active and reactive power, suggesting they are important nodes in the network. Most other buses have relatively low LMP values.

Figure 5.12 shows the injected active and reactive power at each bus. Positive values indicate power generation, while negative values indicate power consumption. Buses like 1, 10, 19, and 24 have positive injected power, indicating generation. Many buses have negative injected power, showing they are loading consuming power. High LMP values at certain buses correlate with either significant power generation or consumption. Bus 1 stands out as a significant generator with high LMP values. Buses with high consumption or generation can affect the LMP values due to their impact on the network's supply-demand balance and losses.

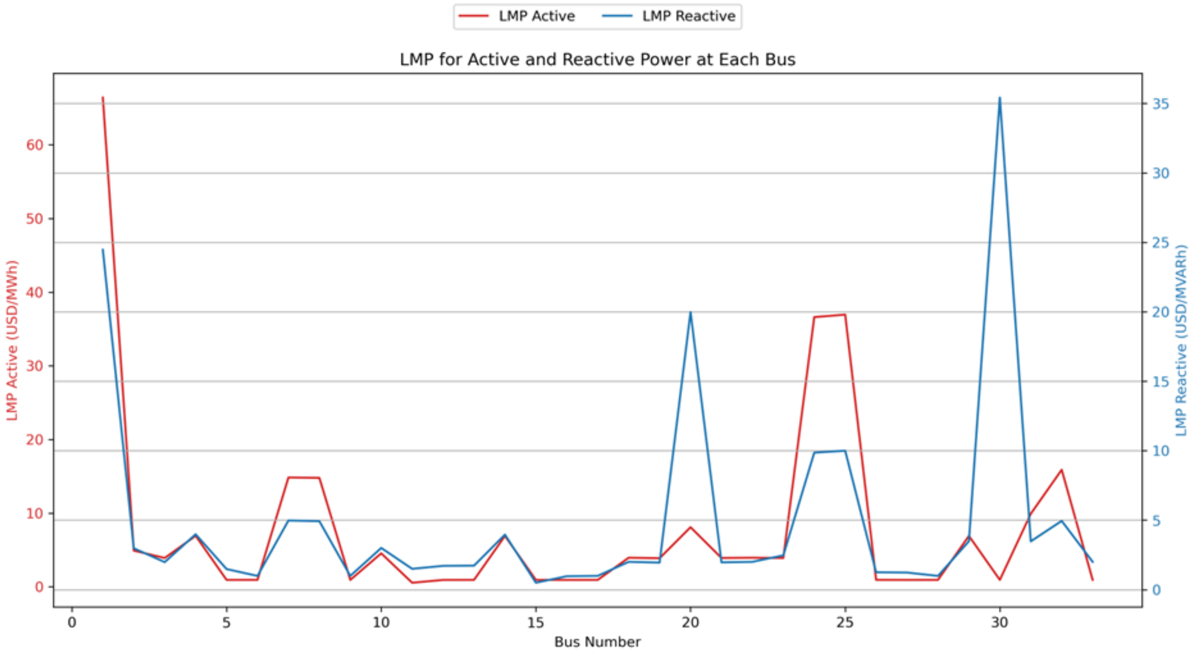

Figure 5.11: LMP for Active and reactive at each bus (33 bus).

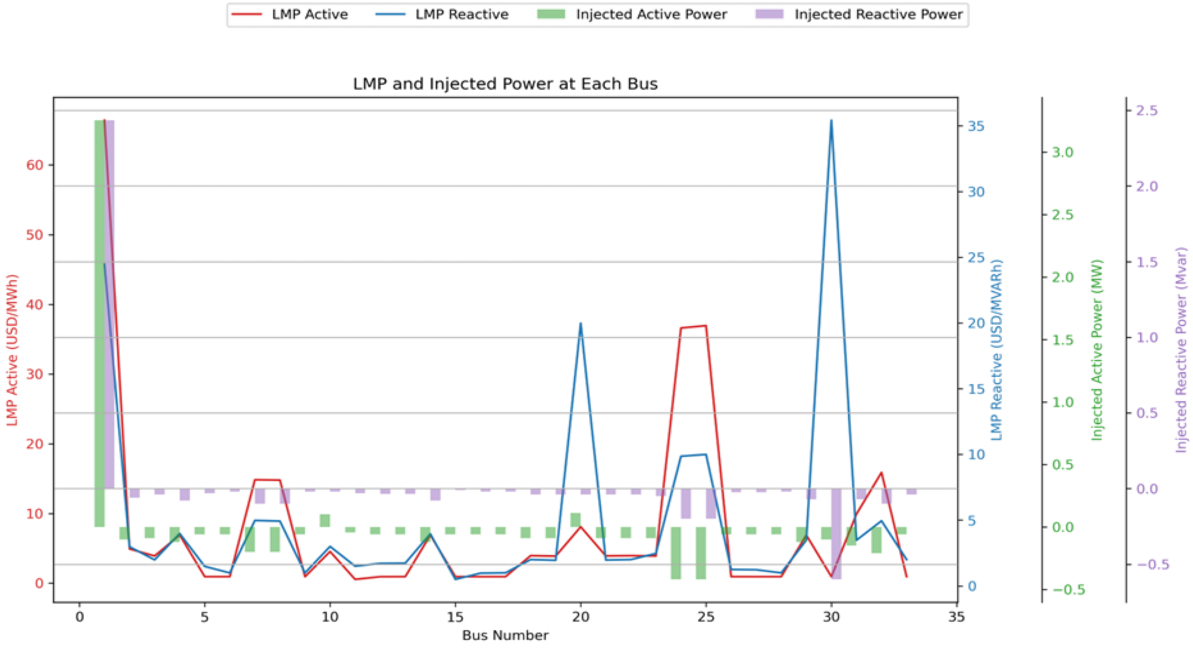

Figure 5.12: LMP and injected power at each bus (33 bus).

As can be seen from figures 5.11 and 5.12, bus numbers 1 and 30 has higher active and reactive and higher LMP values. Reason for higher active and reactive power at bus 1 due to existence of slack bus at bus 1. The slack generator at bus 1 must balance the power system by compensating for any power imbalances. If other buses have loads but insufficient local generation, the slack generator at bus 1 must supply the required power, leading to high active and reactive power flows through bus 1. Higher LMP at bus 1 is due to factors like existence of slack generator at bus 1, marginal cost of generator, transmission losses and overload since power supplied by the slack generator must travel through the network, incurring transmission losses and potentially causing or experiencing overload, which further increases the cost.

The high LMP at bus 30 is because the local generator can't produce enough power to meet the demand, so extra power must be brought in, which increases costs. The transmission lines to bus 30 have high resistance, causing significant power losses and making it expensive to deliver power. Additionally, congestion in these lines further raises the costs, resulting in higher LMPs at bus 30.

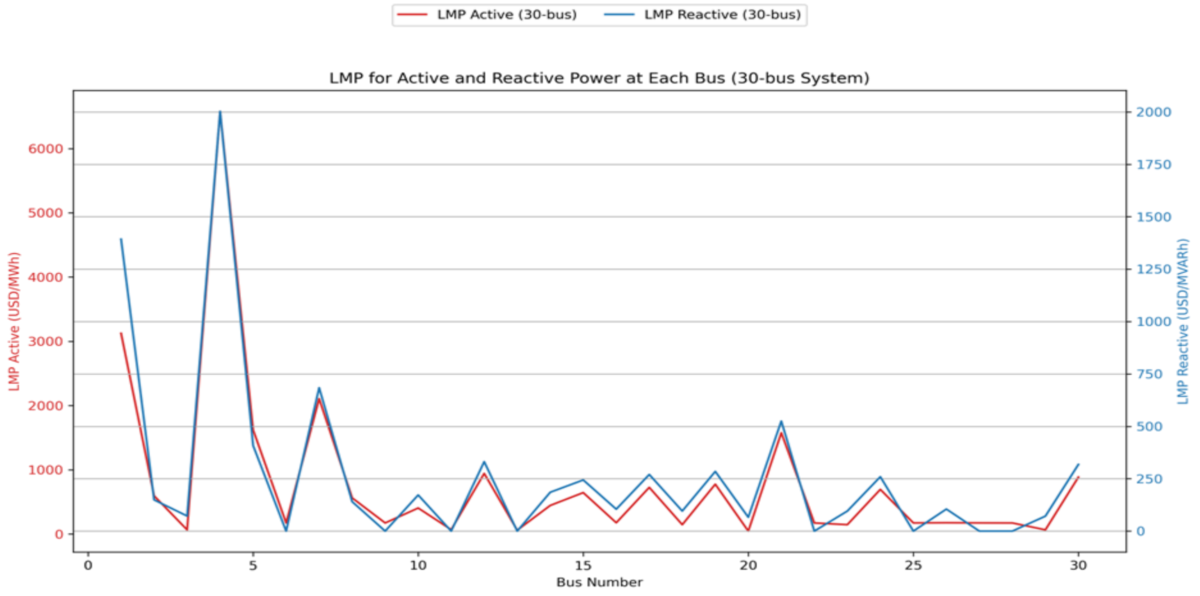

Figure 5.13: LMP for active and reactive power at each bus (30 bus system)

Figure 5.13 indicates LMP for Active and Reactive Power (30-bus System) which varies significantly across different buses, with some buses showing extremely high LMP values, indicating high congestion. The reactive power LMP also varies, though many buses have zero reactive LMP. The differences in LMP values between the 30-bus and 33-bus systems is due to variations in line impedance, load distribution, and generator placement.

5.5 Comparison LMP between 30 and 33 bus systems

The comparison between the 30-bus and 33-bus systems indicates that the 30-bus system has lower impedance lines, including zero impedance connections, leading to reduced losses and more stable LMP values. It also features larger, concentrated loads at specific buses, causing localized congestion and higher LMPs at those points. In contrast, the 33-bus system has higher impedance lines, resulting in significant transmission losses and voltage drops, which increase overall LMPs. The load in the 33-bus system is more evenly distributed, causing widespread losses rather than localized congestion. Additionally, the strategic placement and varying marginal costs of generators in each system impact LMP differently, with the 30-bus system experiencing higher LMPs due to localized congestion, while the 33-bus system faces higher LMPs due to higher overall system losses and widespread congestion. Also, the difference of 6511.812 $/MWh between the highest LMPs in the two systems shows that 30 bus system is more costly than 33.

6 Conclusion

The present master thesis addresses reactive power management, a crucial factor for the stability and effectiveness of power systems. Correct valuation and pricing of reactive power are important for efficient operation of power networks. In this contribution, we introduced a novel reactive power pricing mechanism, which is expected to be more realistic and reliable compared to existing approaches, and at the same time, serves as a basis for future optimization approaches. The proof of concept of the proposed pricing algorithm was accomplished by implementing a Python-based simulator via PyPSA, a useful tool for network theory and optimization. The algorithm aids in computing the reactive power price per unit at each bus, and the total cost involved in reactive power within the power network.

Analysitic dynamic pricing of reactive power was demonstrated, and IEEE 30 and 33 Standard Bus systems were selected as a case study. The simulation reveals that the 30-bus system is more costly due to concentrated loads and localized congestion, leading to very high LMPs in specific areas. In contrast, the 33-bus system, with its higher impedance lines and distributed loads, experiences more widespread but less severe congestion and losses, resulting in lower LMPs. The difference of 6511.812 $/MWh between the highest LMPs in the two systems highlights the impact of network configuration, load distribution, and generator placement on electricity pricing. Also, the proposed pricing approach is accurate and can be compared with the results of existing methods. A power flow analysis was also conducted, and the simulation results with and without a reactive power market were compared. The primary motivation for the introduction of this proposed model is the correct evaluation and dynamic price of reactive power, which may lead to an improvement in the stability margin of the power system and the coordination of power supply and demand on a large scale.

To conclude, the proposed novel reactive power market in this contribution addresses the major power system challenges related to network congestion and efficient power system operation. By contributing to security assessment, loss reduction and cost optimal operation, the mechanism further exemplifies the need for a suitable reactive power market design for modern and future power systems. A successful test run and validation with the IEEE 30 and 33 Standard Bus has the potential for further implementation across the globe leading to enhanced overall power system stability and reliability.

References

[1] “George Morrow”, “PROPOSED STANDARD FOR THE S-100 BUS,” in Preliminary Spefciation 0 IEEE task

[2] J. Zhong and K. Bhattacharya, “Reactive power management in deregulated electricity markets-a review,” in *2002 IEEE Power Engineering Society Winter Meeting. Conference Proceedings (Cat. No.02CH37309)*, New York, NY, USA: IEEE, 2002, pp. 1287–1292. doi: 10.1109/PESW.2002.985223.

[3] M. N. I. Sarkar, L. G. Meegahapola, and M. Datta, “Reactive Power Management in Renewable Rich Power Grids: A Review of Grid-Codes, Renewable Generators, Support Devices, Control Strategies and Optimization Algorithms,” *IEEE Access*, vol. 6, pp. 41458–41489, 2018, doi: 10.1109/ACCESS.2018.2838563.

[4] D. Jay and K. S. Swarup, “A comprehensive survey on reactive power ancillary service markets,” *Renew. Sustain. Energy Rev.*, vol. 144, p. 110967, Jul. 2021, doi: 10.1016/j.rser.2021.110967.

[5] A. S. Bouhouras, K. I. Sgouras, P. A. Gkaidatzis, and D. P. Labridis, “Optimal active and reactive nodal power requirements towards loss minimization under reverse power flow constraint defining DG type,” *Int. J. Electr. Power Energy Syst.*, vol. 78, pp. 445–454, Jun. 2016, doi: 10.1016/j.ijepes.2015.12.014.

[6] P. Sharma, N. Batish, S. Khan, and S. Arya, “Power Flow Analysis for IEEE 30 Bus Distribution System,” vol. 13, 2018.

[7] A. Bhattacharya and P. K. Chattopadhyay, “Solution of Optimal Reactive Power Flow using Biogeography-Based Optimization,” vol. 4, no. 3, 2010.

[8] R. Verma and N. P. Padhy, “Optimal Power Flow Based DR in Active Distribution Network With Reactive Power Control,” *IEEE Syst. J.*, vol. 16, no. 3, pp. 3522–3530, Sep. 2022, doi: 10.1109/JSYST.2021.3106397.

[9] L. Bai, J. Wang, C. Wang, C. Chen, and F. Li, “Distribution Locational Marginal Pricing (DLMP) for Congestion Management and Voltage Support,” *IEEE Trans. Power Syst.*, vol. 33, no. 4, pp. 4061–4073, Jul. 2018, doi: 10.1109/TPWRS.2017.2767632.

[10] R. Li, Q. Wu, and S. S. Oren, “Distribution Locational Marginal Pricing for Optimal Electric Vehicle Charging Management,” *IEEE Trans. Power Syst.*, vol. 29, no. 1, pp. 203–211, Jan. 2014, doi: 10.1109/TPWRS.2013.2278952.

[11] “Jia et al. - 2014 - Impact of Data Quality on Real-Time Locational Mar.pdf.”

[12] J. M. Morales, A. J. Conejo, and J. Perez-Ruiz, “Simulating the Impact of Wind Production on Locational Marginal Prices,” *IEEE Trans. Power Syst.*, vol. 26, no. 2, pp. 820–828, May 2011, doi: 10.1109/TPWRS.2010.2052374.

[13] P. Spodniak, K. Ollikka, and S. Honkapuro, “The impact of wind power and electricity demand on the relevance of different short-term electricity markets: The Nordic case,” *Appl. Energy*, vol. 283, p. 116063, Feb. 2021, doi: 10.1016/j.apenergy.2020.116063.

[14] M. Haberg and G. Doorman, “Classification of balancing markets based on different activation philosophies: Proactive and reactive designs,” in *2016 13th International*

Conference on the European Energy Market (EEM), Porto, Portugal: IEEE, Jun. 2016, pp. 1–5. doi: 10.1109/EEM.2016.7521272.

[15] H. Kongelf, K. Overrein, G. Klæboe, and S.-E. Fleten, “Portfolio size’s effects on gains from coordinated bidding in electricity markets: A case study of a Norwegian hydropower producer,” *Energy Syst.*, vol. 10, no. 3, pp. 567–591, Aug. 2019, doi: 10.1007/s12667-018-0294-8.

[16] J. Bozionek, T. Wolgast, and A. Nieße, “Design and evaluation of a multi-level reactive power market,” *Energy Inform.*, vol. 5, no. 1, p. 6, Dec. 2022, doi: 10.1186/s42162-022-00191-x.

[17] “Electrical Power Systems Quality, Second Edition,” 2004.

[18] B.-G. Risi, F. Riganti-Fulginei, and A. Laudani, “Modern Techniques for the Optimal Power Flow Problem: State of the Art,” *Energies*, vol. 15, no. 17, p. 6387, Sep. 2022, doi: 10.3390/en15176387.

[19] A. Vijayvargia, S. Jain, S. Meena, V. Gupta, and M. Lalwani, “Comparison between Different Load Flow Methodologies by Analyzing Various Bus Systems”.

[20] C. L. Wadhwa, *Electrical power systems*. Tunbridge Wells: New Academic Science, 2012.

[21] “Kwatny and Miu-Miller - 2016 - Power System Dynamics and Control.pdf.”

[22] “De Francesco and Leccese - 2012 - Risks analysis for already existent electric lifel.pdf.”

[23] [Online]. Available: https://www.nve.no/energi/energisystem/nett/?ref=mainmenu

[24] “Grid Map.” Accessed: Apr. 30, 2024. [Online]. Available: https://www.entsoe.eu/data/map/

[25] P. Kundur, N. J. Balu, and M. G. Lauby, *Power system stability and control*. New York: McGraw-Hill, 1994.

[26] “20050310144430-02-04-05-reactive-power.pdf.” Accessed: Apr. 30, 2024. [Online]. Available: https://www.ferc.gov/sites/default/files/2020-04/20050310144430-02-04-05-reactive-power.pdf

[27] D. Zhao, A. Botterud, and M. Ilic, “Uniform Pricing vs Pay as Bid in 100%-Renewables Electricity Markets: A Game-theoretical Analysis,” in *Proceedings of the 14th ACM International Conference on Future Energy Systems*, Orlando FL USA: ACM, Jun. 2023, pp. 236–241. doi: 10.1145/3575813.3595201.

[28] “Snapshot.” Accessed: May 01, 2024. [Online]. Available: https://www.fortnightly.com/fortnightly/2014/06/iso-dso?authkey=0180a472b6921455391b2a154871791cd70b48db1a4335bf84700d54c8d99897

[29] G. Federico and D. M. Rahman, “Bidding in an Electricity Pay-as-Bid Auction,” *SSRN Electron. J.*, 2001, doi: 10.2139/ssrn.271700.

[30] S. Heim and G. Götz, “Do Pay-As-Bid Auctions Favor Collusion? Evidence from Germany’s market for reserve power,” *Energy Policy*, vol. 155, p. 112308, Aug. 2021, doi: 10.1016/j.enpol.2021.112308.

[31] P. Shinde, “Efficient Trading in the Short-term Electricity Markets for Integration of Renewable Energy Sources,” *Renew. Energy Sources*.

[32] “Snapshot.” Accessed: May 02, 2024. [Online]. Available: https://www.ferc.gov/electric-power-markets

[33] “Eurelectric2000-ancillaryservices.pdf.” Accessed: May 03, 2024. [Online]. Available: https://pierrepinson.com/31761/Literature/Eurelectric2000-ancillaryservices.pdf

[34] “m03.pdf.” Accessed: May 03, 2024. [Online]. Available: https://www.pjm.com/~/media/documents/manuals/m03.ashx

[35] I. CORPORATIVA, “DSO, ¿cómo transformar la gestión de redes hacia un modelo más inteligente?,” Iberdrola. Accessed: May 03, 2024. [Online]. Available: https://www.iberdrola.com/innovation/distribution-system-operation

[36] “Morais Valente et al. - 2021 - Transmission system operator and distribution syst.pdf.”

[37] “20201007-item-07b-manual-11-revisions-redlines.pdf.” Accessed: May 05, 2024. [Online]. Available: https://www.pjm.com/-/media/committees-groups/committees/mic/2020/20201007/20201007-item-07b-manual-11-revisions-redlines.ashx

[38] “reserve-shortage-pricing-paper.pdf.” Accessed: May 05, 2024. [Online]. Available: https://www.pjm.com/-/media/markets-ops/energy/real-time/reserve-shortage-pricing-paper.ashx

[39] “Energy Policies of IEA Countries - Norway 2017 Review,” 2017.

[40] “10431: Kraftstasjoner, etter krafttype 1974 - 2022. Statistikkbanken,” SSB. Accessed: May 05, 2024. [Online]. Available: https://www.ssb.no/system/

[41] “08307: Produksjon, import, eksport og forbruk av elektrisk kraft (GWh) 1950 - 2022. Statistikkbanken,” SSB. Accessed: May 05, 2024. [Online]. Available: https://www.ssb.no/system/

[42] “Facts 2015 Energy and Water Web PDF | PDF | Hydroelectricity | Renewable Energy,” Scribd. Accessed: May 05, 2024. [Online]. Available: https://www.scribd.com/document/408876339/facts-2015-energy-and-water-web-pdf

[43] J. J. Lucia, “Electricity prices and power derivatives:”.

[44] Parliamentary Office of Science and Technology and J. Miller, “Overseas Electricity Interconnection,” Parliamentary Office of Science and Technology, Feb. 2018. doi: 10.58248/PN569.

[45] “annual-report_2016.pdf.” Accessed: May 05, 2024. [Online]. Available: https://www.nordpoolgroup.com/49f4c6/globalassets/download-center/annual-report/annual-report_2016.pdf

[46] “annual-report_2018.pdf.” Accessed: May 05, 2024. [Online]. Available: https://www.nordpoolgroup.com/49c112/globalassets/download-center/annual-report/annual-report_2018.pdf

[47] “Snapshot.” Accessed: May 05, 2024. [Online]. Available: https://www.scribd.com/document/408876339/facts-2015-energy-and-water-web-pdf

[48] “Figure 2. Single line diagram of the IEEE 33-bus radial distribution...,” ResearchGate. Accessed: May 07, 2024. [Online]. Available: https://www.researchgate.net/figure/Single-line-diagram-of-the-IEEE-33-bus-radial-distribution-system-20_fig1_319906918

[49] “Table 1 . Line data and Load of System IEEE 33 bus,” ResearchGate. Accessed: May 07, 2024. [Online]. Available: https://www.researchgate.net/figure/Line-data-and-Load-of-System-IEEE-33-bus_tbl1_328771243

[50] P. Diaz, M. Perez-Cisneros, E. Cuevas, O. Camarena, F. A. Fausto Martinez, and A. Gonzalez, “A Swarm Approach for Improving Voltage Profiles and Reduce Power Loss on Electrical Distribution Networks,” *IEEE Access*, vol. 6, pp. 49498–49512, 2018, doi: 10.1109/ACCESS.2018.2868814.

[51] F. Hussian, S. J. Paul, G. R. Goyal, and A. K. Arya, “Network Reconfiguration using Fuzzy Logic for Power Flow Balancing in IEEE 30 Bus System”.

[52] “Table 2 . IEEE 30-bus system line data,” ResearchGate. Accessed: May 07, 2024. [Online]. Available: https://www.researchgate.net/figure/IEEE-30-bus-system-line-data_tbl2_286136216

[53] “Table 5 Bus data for a modified IEEE-30 bus system,” ResearchGate. Accessed: May 07, 2024. [Online]. Available: https://www.researchgate.net/figure/Bus-data-for-a-modified-IEEE-30-bus-system_tbl1_254596776

[54] T. Brown, J. Hörsch, and D. Schlachtberger, “PyPSA: Python for Power System Analysis,” *J. Open Res. Softw.*, vol. 6, no. 1, p. 4, Jan. 2018, doi: 10.5334/jors.188.

[55] Zhenyu Fan, T. Horger, J. Bastian, and A. Ott, “An overview of PJM energy market design and development,” in *2008 Third International Conference on Electric Utility Deregulation and Restructuring and Power Technologies*, Nanjing, China: IEEE, Apr. 2008, pp. 12–17. doi: 10.1109/DRPT.2008.4523372.

[56] “PJM Presentation.pdf.” Accessed: May 12, 2024. [Online]. Available: https://www.scstatehouse.gov/CommitteeInfo/2000000325/santee%20cooper%20ad%20hoc%20committee%20meeting_03022020/PJM%20Presentation.pdf