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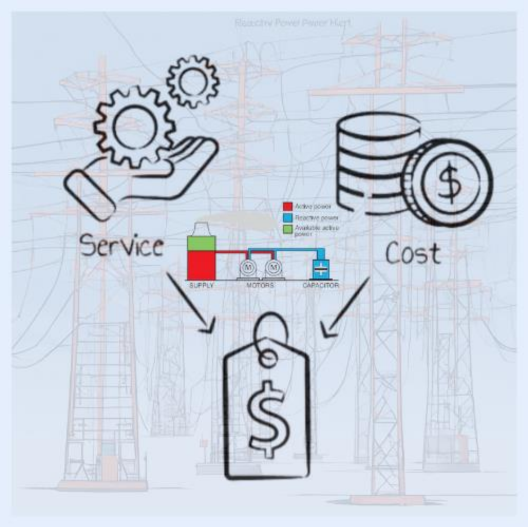
FMH606 Master's Thesis 2024

A Symmetric Review of Reactive Power Market Mechanism for Pricing



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Summary:

This thesis paper aims to explore various market mechanisms and pricing strategies for reactive power, assess operational regulations, and conduct a comparative analysis of these elements across different market setups. The unpredictable nature of renewable producers and price-responsive loads, the expensive computational effort, and the possible violation of the privacy of generators and load aggregators are all factors that may provide substantial issues for distribution network operators when it comes to administering the centralized energy market. In the presence of a significant amount of renewable energy sources, particularly hydropower, a model such as this one may provide the necessary adaptability to manage the variability and decentralization of power sources by including dispersed producing units into the grid.

By delving into these aspects, the paper seeks to identify optimal practices that can be adopted to improve reactive power management and pricing, providing actionable insights for policymakers and industry stakeholders.

Preface

This report was created in the Spring of 2024 as an assessment requirement at the University of South-Eastern Norway (USN). I express my gratitude to the supervisors, Sambeet Mishra and Thomas Øyvang, Sulabh Sachan (Co-Supervisor) and the project partner, University of South-Eastern Norway (USN, Porsgrunn Campus). It's an honor and I'm very appreciative of all your assistance and contributions towards the success of this Thesis article.

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Nomenclature

FACTS	Flexible Alternating Current Transmission System
ISO	Independent System Operator
NERC	National Energy Resources Conservation Council
TOU	Time of Use
RTP	Real Time Pricing
SVC	Static Var Compensator
STATCOM	Static Compensator
OPF	Optimal Power Flow
MC	Marginal Cost
CAPEX	Capital Expenditures
SG	Synchronous Generator
TSO	Transmission System Operator
SC-OPF	Security-Constrained Optimal Power Flow
PAB	Pay As Bid
PEF	Payment Expectation Function
DSO	Distribution System Operator
DER	Distributed Energy Resource
SO	System Operator
P2P	Per-to-Per
NVE	The Norwegian Water Resources and Energy Directorate
DG	Distributed Generation
RMP	Regional Marginal Price

CI	Current Injection
NEM	National Electricity Market
RPAF	Reactive Power Adjustment Factor
PF	Power Factor
NordREG	Norwegian Regulation
EU	European Union
REMIT	Regulation on Wholesale Energy Market Integrity and Transparency
MARI	Manually Activated Reserves Initiative
PICASSO	The Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation
RTO	Regional Transmission Organization
FERC	Federal Energy Regulatory Commission
AEMO	Australian Energy Market Operator
CERC	Central Electricity Regulatory Commission
ENTSO-E	European Network of Transmission System Operators for Electricity

1 Introduction

This introductory section sets the stage for a comprehensive review of the background research, the importance of reactive power pricing mechanisms and goals for this thesis work.

1.1 Overview of Reactive Power

Reactive power is essential for regulating the voltage of the local electricity network to ensure that it remains within the acceptable limits and to ensure the efficient functioning of electrical power equipment. The voltage limit requirements can be modified by various components of the power system, including loads and transformers which typically consume reactive power, overhead lines which can either consume reactive power under heavy loads or supply reactive power under light loads, and underground cables which generate reactive power [1]. Various sources of reactive power, preferably located at the point of intake, are necessary to compensate for the imbalance. Reactive power serves as both the cause and the remedy for voltage difficulties within an interconnected system [2]. One of the non-frequency auxiliary services that system operators must acquire at the transmission level for the management and balancing of the transmission system is reactive power. In liberalized power markets, reactive power compensation schemes implemented by system operators such as cost-based with set rates, bilateral agreements, and tenders have just lately begun to make a significant impact [3].

As the power industry has been restructured, electricity production has been split off from the combined power system. In centralized power systems, real power has always been assigned based on minimizing a cost goal. In the competitive market, real power was the first good to be traded. The services that keep the security and dependability of the combined power systems running are still offered as extras in the energy market. It will be important to figure out who will provide the services and how much they should cost if power companies, and transportation companies are separate. On the contrary, both the government and the system operator need to think about how to sell these services and how to make markets that work well for them. The regulator oversees making sure the market works well and fairly, and the system operator is in charge of keeping the system safe and making sure it works properly. Some energy markets around the world have already started to offer markets for some of the extra services that go along with electricity. In the electricity balance markets of Nordic countries, for instance, control services are bought and sold. In some North American energy markets, reserve services are also bought and sold [4].

In energy markets that have been deregulated, it is the responsibility of the Independent System Operator (ISO) to provide provisions for reactive power assistance. It is essential to do this to guarantee that the transactions that are governed by the contract are carried out in a secure manner. The acquisition of reactive power services must be carried out with the conditions of the perceived demand being taken into consideration, as well as the composition of the load and the availability of reactive power resources. Reactive power services must be acquired. Most of the time, the resources for reactive support, which include synchronous generators, synchronous condensers, capacitor banks, reactors, static var compensators, and FACTS devices, are held by independent generators or consumers. This is the case most of the time. In order for the ISO to be able to deliver these resources, it is necessary for the ISO to enter into contracts with the different businesses [5]. Technical and economic considerations of reactive capabilities from various resources and improved procurement procedures constitute the bulk of the existing reactive power literature. In terms of management and efficiency concerns, several studies assess how reactive power is affected by grid insertion of fluctuating production [6], [7]. Using optimization algorithms, a separate set of research investigates reactive power procurement competitive market models for both long- and short-term supply [5], [8], [9].

However, due to differences in contract wording and market operation, the reactive power management and payment processes differ throughout deregulated energy markets. Reactive power traders are often rented out to render their offerings to ISO. In the United States, according to the National Energy Resources Conservation Council's (NERC's) Operating Policy-10 [10], the only ancillary services that can be compensated for are those that synchronous generators offer, namely reactive power. Similar holds regarding the markets in Australia and the United Kingdom. Ancillary services, like as reactive power from synchronous condensers, are also taken into account by the Australian market.

1.2 Importance of Pricing Mechanisms

A number of factors contribute to the significance of reactive power management in the operation of distribution networks [11], [12]. These factors include the following: i) reactive power has an impact on the magnitude of the network voltage profile; ii) reactive power flows lead to an increase in network line losses; and iii) reactive power makes use of the VA capacity of networks. There is a substantial correlation between reactive power injections and the effect of power quality disruptions in distribution networks that are working under stress [13]. Putting into effect a price system for reactive electricity would result in an improvement in energy efficiency and power quality of supply, as well as an effective exploitation of the infrastructure that is already in place [14].
In terms of auxiliary services, reactive power is among the most important categories. It was determined that an insufficient reactive power supply, which resulted in voltage collapse, was the cause of the recent international power outages that took place in Italy, Sweden, and Denmark in 2003, as well as in the United States and Canada [15]. This was cited as the principal cause of the power outages. As a result, reactive power is essential for maintaining the reliability and security of the power grid such that it may be traded on in the power market. It is also essential for maintaining the stability of the power system. As a result of the significant distance that separates the generator and the loads in the Nordic Electricity Market, which includes Norway, Sweden, Finland, and Denmark, the reactive power is supplied on a local level. In fact, the provision of reactive power supply is obligatory in the Nordic European nations. For instance, there is no established market for reactive power in Sweden [16]. On the other hand, in Norway, generators are compensated for providing reactive power service if they run in a power factor that is more than the legal operating range of 0.92 lagging to 0.98 leading [17].

The charging structure for electricity to consumers is generally based on their active power consumption, while reactive power pricing has received limited consideration [18], [19], [20]. Active power tariffs may be time-varying schemes, such as time-of-use (TOU) [18] and real-time pricing (RTP) [19] rates, or flat (i.e., prices remain constant over time). In contrast, an alternative author implements a pricing strategy for consumers that is non-nodal and opaque with regard to reactive power, utilizing the cost of transmitting such power [20]. Notwithstanding this, it is asserted that the integration of reactive power rates would be adequate to motivate consumers to rectify the power factor of their loads, thereby enhancing the distribution network's operational efficiency.

When buying power from DG units, two-way contracts are also used for active power, and reactive power may be needed to keep the voltage profile of the transmission system within boundaries [21]. Active power production prices vary based on the cost of machinery and the type of energy utilized. For reactive power created by DG units in distribution networks, two main ways to set prices have been found. The initial method is an inaccessible one: the prices of reactive power are linked to marginal loss reduction factors that can only be found by analyzing the system [22]. Lastly, the second method is based on the reactive manufacturing price function. This function has set costs like access and/or investment as well as changeable costs like loses and missed opportunities. This plan might bring in enough money for DG to cover its investment and running costs, but it doesn't promise that the owners will be able to make good money by offering response services [23], [24], [25].

1.3 Objective

The objective of this thesis is to provide a comprehensive and symmetric review of the reactive power market mechanisms, with a specific focus on the pricing structures and operational regulations. Reactive power, essential for maintaining voltage stability and efficient power system operation, has distinct market mechanisms that vary significantly by country.

Reactive power suppliers, which are often awarded EPFs based on fixed costs, have received little attention in the literature [26], which is the main reason for the study gap. Because of this, judging the efficacy of market design is challenging. Optimal market rules that take into account the rational bidding behavior of all market players might be determined by systematically comparing design choices. Assuming the grid operator specifies the rules, most articles on market design only provide a cursory explanation and justification for their selection. As a result, reactive power suppliers may be less motivated to invest, which might have a detrimental effect on overall welfare. To find out what works best for reactive electricity markets, we need to compare uniform pricing with pay-as-bid pricing methodically [27].

Providing insights into the functioning, efficiency, and regulatory environment that influences these mechanisms, as well as providing the viewpoint that is presented below for Norway, the purpose of this thesis paper is to explicate these mechanisms in a thorough manner.

The viewpoints are-

- Viable market structure,
- Pricing techniques for reactive power, and
- Evaluate operational rules, and regulations.

By looking into these viewpoints, the report aims to find optimum methods that can be followed to enhance reactive power management and pricing for Norway. This will provide regulators and industry consumers with insights that can be put into action.

2 Theoretical Background

Comprehending reactive power markets requires a solid grasp of the basic concepts of power system functioning and the economic ideas that underlie power pricing. This section presents a fundamental structure for these notions and examines important literature in the field.

2.1 Basics of Power System Operations

Generators, transmission lines, and distribution systems are the components that make up the intricate networks that make up electric power systems. These components collaborate to ensure that consumers get energy from the producers. Instead of converting into work, reactive power is utilized to maintain voltage levels that are essential for system stability. This is a basic difference between reactive power and active power. It is very important for the management of power flow and voltage stability that it flows back and forth between the reactive components of the electrical system, such as capacitors and inductors.

One of the biggest obstacles in running power systems is controlling reactive power and voltage. Because transmission and distribution networks are fundamentally different, new approaches have emerged to address these differences. Many people are interested in and dedicated to finding ways to reduce voltage collapse, a phenomenon that may cause widespread power outages. To guarantee reliable and efficient operation of the power system, voltage and reactive power regulation should be able to accomplish the following objectives [28].

- All the system's equipment terminals do not have voltages that are higher than what is allowed.
- Enhancing system stability allows for more efficient use of the transmission system.
- Furthermore, in order to reduce losses in RI^2 and XI^2, the reactive power flow is restricted.

This guarantees that the distribution system is primarily intended for the operation of active power. Due to the fact that the power system distributes electricity to a large number of loads and receives its supply from a large number of producing units, there is a challenge in regulating voltages within the requirements that are set out. Because of the fluctuating demand, the distribution system's reactive power needs are also subject to change. Due to the fact that reactive power cannot be transmitted or carried over long distances, voltage management must be accomplished via the use of specialized devices that are positioned throughout the system. These devices have the challenge of maintaining adequate voltage levels within the power system network. This phenomenon has been going on for quite some time, almost from the beginning of the electrical systems. A growing number of requirements are being placed on the supply dependability as well as the quality of the power force that is being delivered via the use of more contemporary gadgets that are speedier, more dependable, and have a wider variety of applications. The engineering of power systems presents a number of significant issues, one of the most significant of which is the selection and coordination of the appropriate equipment for managing reactive power and voltage stability [28]. These issues led to the development of specific devices designed to regulate or offset reactive power. To meet the increased need for reactive power and ensure voltage stability remains within the desired range, different sources of reactive power are utilized. These include SVC (Static Var Compensator) - devices that compensate for reactive power, STATCOM-type systems - generators of static reactive power, and hybrid systems that combine both solutions, known as SVC, based on STATCOM. There has been notable advancement in the development of devices aimed at enhancing voltage stability in power systems in recent decades. The primary reason for this is the advancement of power supply systems worldwide, which necessitates the exploration of more effective methods for regulating and managing power distribution and voltage levels.

2.2 Economic Principles of Reactive Power Pricing

The price of electricity, including both active and reactive power, is determined based on economic concepts such as marginal cost pricing, opportunity cost, and the laws of supply and demand. The price for reactive electricity should accurately account for the expenses associated with its provision, as well as the advantages it offers in terms of improved system stability and lower losses.

The primary tenet that is used in financial markets is the improvement of profits. If the marginal revenue is equal to the marginal cost (MC), then the profit will be maximized in a market that is completely competitive. Spot pricing, which is the real MC, is responsible for providing the appropriate economic signals and clarifying the situations of both generators and consumers in the power market. Additionally, it ensures that demand and supply are balanced within the power system. Real-time reactive power pricing may be accomplished by the use of the spot pricing concept through the utilization of modified optimal power flow (OPF) [29].

Through the use of the Lagrange multiplier, Baughman and Siddiqi were able to compute the marginal price of active and reactive power on an arbitrary bus of system for the very first time in the year 1991 [30]. On the other hand, due to the variable and unpredictable nature of these prices, the implementation of optimal reactive pricing may not be feasible in practice. In addition, the challenge of balancing MC prices with the obligation to recover expenses is a barrier that must be overcome when using MC pricing. The reactive energy pricing typically must cover the initial investment in transmitting and compensating reactive energy and ongoing operational expenses, both of which are essentially dictated by the value of network losses associated with reactive energy transmission. Hence, the following is the expression for the price of reactive energy delivered by the distribution network R_{C_Q} [20].

$$R_{C_Q} = R_{C_Q}^{T} + R_{C_Q}^{D} \tag{2.1}$$

$$R_{C_Q} = R_{C_Q}^{T} + \{\, r_F + r_{C_Q} + r_P\} \tag{2.2}$$

Here,
$R_{C_Q}^{T}$ =indicates the price of reactive energy utilized by the transmission system,
$R_{C_Q}^{D}$ =indicates the price of reactive energy sent from the distribution system,
$r_F =$ is the fixed portion of the price that is the initial expense of the distribution system's reactive energy transmission and compensation,

$r_{C_Q} =$ is the fluctuating portion that is the value of the distribution network's active and reactive energy losses caused by reactive energy transferred, and
$r_P =$ is the percentage of profit of the distribution system.

There are two types of expenses associated with reactive power: apparent and indirect. Capital expenses of reactive power participants and the costs of producing reactive electricity are examples of apparent costs. Apparent costs are almost proportional to capital costs when it comes to reactive power since, in contrast to active power, its generation cost is little. Opportunity cost and the indirect cost go hand in hand. Because of capacity constraints, a generator would lose out on money from selling active power if it is obligated by the ISO to generate a certain amount of reactive power, even if doing so would reduce its active power. The generator needs to be paid a monetary sum [29].

Implementing nodal reactive power pricing involves creating an alternative pricing framework. The response of generation output cost to reactive power demand is often determined using OPF and is closely linked to the fuel consumption. The primary distinction between active and reactive power expenses is in the variable cost. The production cost mentioned includes the variable expenses associated with generating reactive electricity, which is often low enough that it may be disregarded [29].

3 Market Mechanisms for Reactive Power

The reactive power markets have seen substantial changes because of technical developments, regulatory modifications, and the changing dynamics of global electrical markets. This section discusses the various market processes used to control and determine the cost of reactive electricity. It also provides a thorough analysis of how these mechanisms have changed over the past decade.

3.1 Types of Market Mechanisms

Reactive power market types can be segmented into several types of mechanisms, each with its advantages and operational contexts.

The flowchart titled Figure 3-1 Shows the types of different market mechanisms. It categorizes various market mechanisms into a structured diagram. This flowchart helps in understanding how different market mechanisms are organized and differentiated.

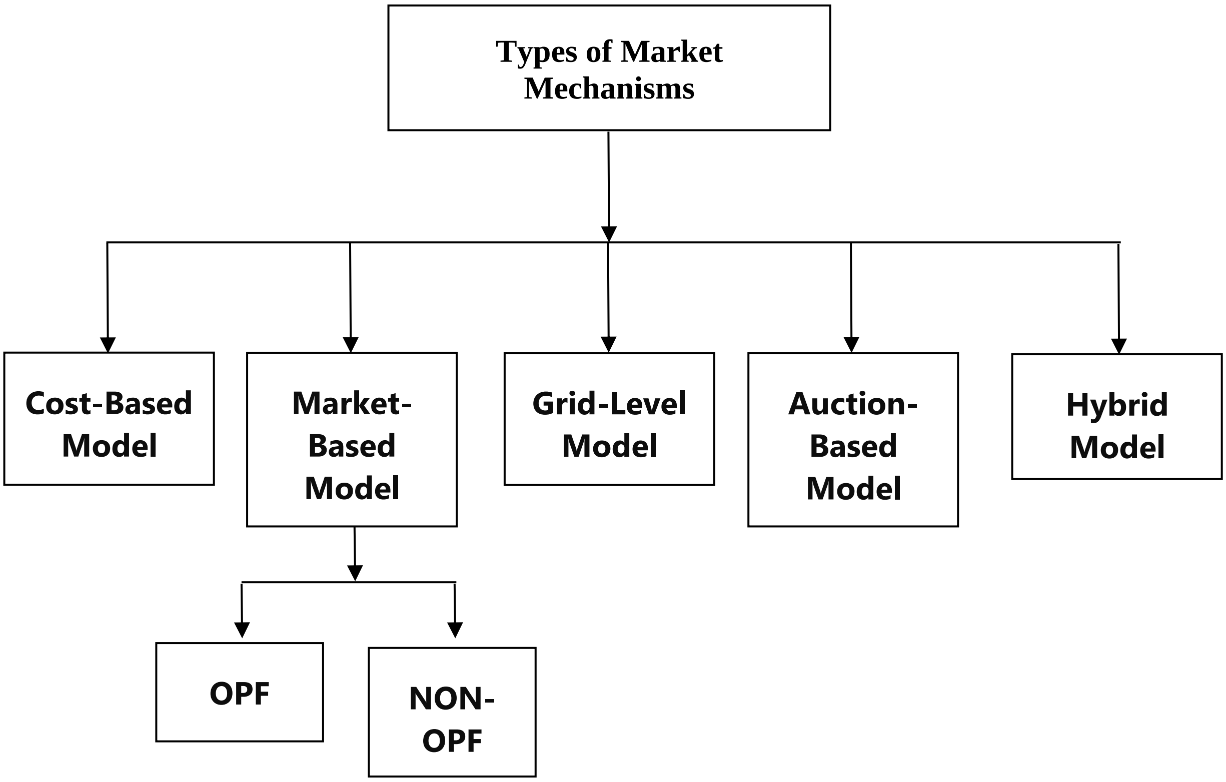

Figure 3-1 Types of Different Market Mechanisms for Reactive Power

3.1.1 Cost-Based Model

Compensation is provided to newly connected components via the cost-based incentive mechanism. This compensation is dependent on the amount of reactive power capacity that the newly connected components make available to the system controller for functions related to voltage management. The use of this strategy provides an incentive for the allocation of resources toward the enhancement of the reactive power capacity at network nodes that have a substantial influence on the voltage of buses that are next to them. It is possible that the overall quantity of incentives that are provided to actors in the power system might be restricted to accommodate the reactive power capacity that the system controller requires in order to deal with predicted operational scenarios. The reimbursement of these expenditures is determined by a cost-based approach that takes into consideration the proportion of capital expenditures (CAPEX) that is allocated exclusively to the provision of reactive power as well as the effectiveness of the control function on offer [31].

The formula for determining the compensation is as-

$$R = W_g * W_q * C_I \tag{3.1}$$

Here,
$R =$ Stands for the sum that will be paid to the supplier of the control service.
$W_g =$ An indicator of how well the voltage control resource is working is the coefficient.
$W_q =$ With this factor, we can calculate the reactive power investment quota.
Lastly, $C_I =$ The capital costs made on the new power plant or installation.

An example of the computation (3.1) to determine the cost-based compensation method for the increased reactive power capacity, which is briefly discussed above is shown in Figure 3-2 [31]

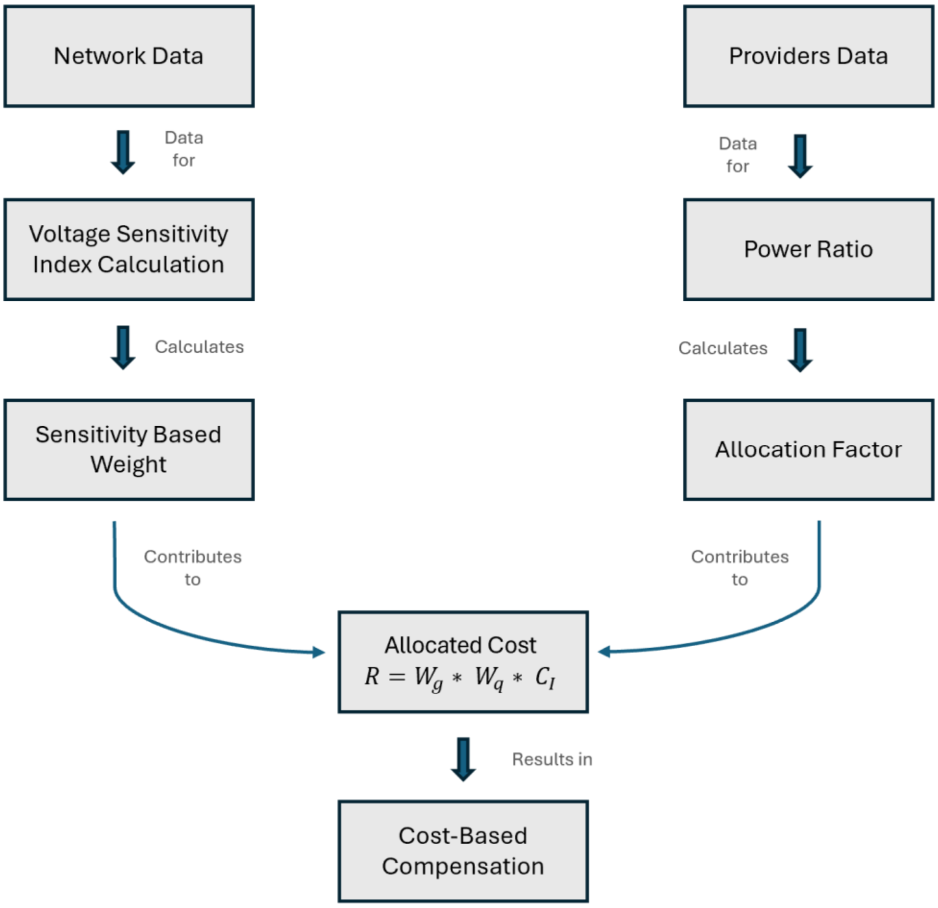

Figure 3-2 Diagrame chart for Cost-Based Model [31].

3.1.2 Market-Based Model

OPF Based

The Optimal Power Flow (OPF) is a comprehensive approach used to calculate the most efficient and stable functioning of power grids, taking into account system limitations and control boundaries [20]. The use of reactive power acquisition began in the early 1990s [21]. Synchronous generators (SGs), which have the capacity to generate reactive power, provide the transmission system operator (TSO) a cost function for reactive power provision. This cost function is either quadratic or linear and represents the expenses associated with providing reactive power. The Transmission System Operator (TSO) gathers all cost functions, inputs them into an Optimal Power Flow (OPF) solver and calculates reactive power set-points that minimize a specific cost function while adhering to a set of restrictions. The Author utilize a security-constrained optimal power flow (SC-OPF) technique to reduce the expenses associated with reactive power pay-as-bid (PAB) consumption and the frequency of switching operations in an alternating manner [32].

Two reactive power markets are proposed by [33]: one for reactive energy, which aims to minimize losses, and another for extra capacity, which focuses on voltage security and helps to avoid reactive power spot price swings. While neither idea is inherently better, [34] note that unit operators tend to favor availability markets while grid operators lean toward utilization markets.

Bhattacharya and Zhong [35], [36] introduced the anticipated payment function in the early 2000s. Because prior articles treated the cost function as a fixed function, the PEF shifts the paradigm to market-focused techniques. An autonomous reactive power supplier may freely specify its anticipated compensation, such as bidding, in a free market. The suggested PEF structure is nonlinear since it is based on reactive power costs Figure 3-3 [26]. The PEF analyzes availability and usage payment, provides for a necessary portion of reactive power that is not compensated, and allows providers to profit. Zhong [37] subsequently add voltage control regions. Voltage control zones are loosely connected power system subsystems. Area-wise uniform pricing allows localized marketplaces with decoupled uniform prices, which better considers locale. A compromise between pay-as-bid and consistent pricing. The technique was previously limited to SGs, but Zhong [38] adds network devices like capacitor banks or static VAr compensators (SVCs).

In Figure 3-3 [26] by assuming the real and reactive power operating point A on the limiting curve below and Q_0 is the payment expectation. Operating point repositioning to a lower value of B_{real} than A_{real} is required if the unit requires more reactive power, denoted as $B_{reactive}$. In order to comply with field heating constraints, the unit will need to reduce its real power generation when reactive power is required. Savings from decreasing generation must thus equal income loss.

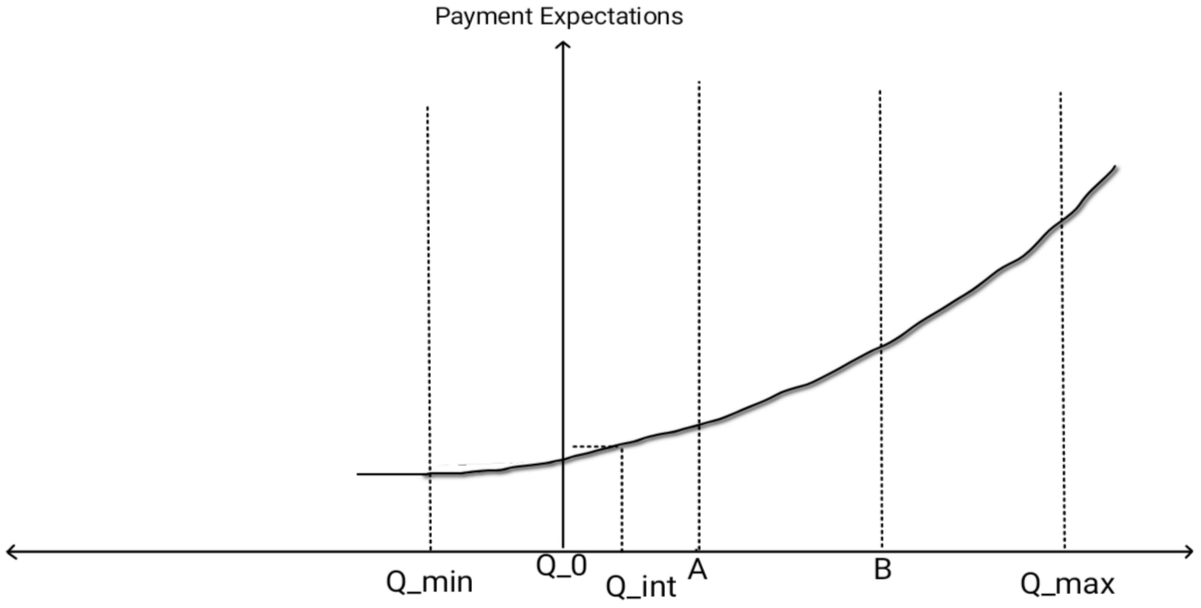

Figure 3-3 Structure of PEF Curve [26].

Non-OPF Based

By analyzing four central solutions—performance compensation, usage compensation, a percentage drop in the distribution price, and an incentive strategy that limits certain power variables—we can determine the minimum required for reactive power in an a small-scale and for sending reactive power to the larger system [39]. Ultimately, they reach the following conclusions: Microgrids are effective because they provide a reliable and flexible power supply for the main grid. Availability compensation and use compensation are used to provide the proper cost.

It is the responsibility of every PV system to ensure that the voltage on the grid remains within the predetermined limits in order to maintain voltage. To begin with, it manages the demand for and supply of its own reaction power. If it is insufficient, it should either reduce the amount of active power it delivers or seek assistance from adjacent devices in terms of reactive power. Reactive power may be transferred from one solar power plant to another. There is a fixed rate for reactive energy, and only solar energy systems are able to transact with one another. It is recommended that potential grid-side expenses be included when prices are determined instead [40]. An other author [41] included a fascinating market procedure independent of OPF. In order to determine the optimal non-uniform pricing signal, the administrator of the grid solves an optimization problem once the reactive power sources submit their bids. Producers are allowed more leeway to utilize the price as a trigger for their own reactions, even if OPF-based procedures are still in place. To prove that the strategy results in honest rivals and net gains, a game-theoretical technique is used. The market is organized area by region using a method similar to [37]. Because active power and voltage may be coupled, voltage-control zones that just address reactive power are insufficient, according to [41]. The locations of voltage-apparent power are instead shown by them.

3.1.3 Grid-Level Model

Regional marketplaces for reactive power, in which a single utility company optimizes the purchase of reactive electricity for its own network. Even so, with the number of big conventional power plants declining, TSOs will have a hard time obtaining reactive power in the future, whereas DERs in distribution networks will offer the majority of reactive power potential. The transmission grid may benefit from the reactive power potential of distribution systems in a number of ways, both technically and economically [42]. Reactive power buying from DERs in adjoining systems must not create local obstructions there [43], so a simple accumulation or central marketplace is not an option.

Such demands reactive power market frameworks that can accommodate multiple grids, as well as cooperation between DER suppliers, local grid companies and purchasing grid owners. If every grid owner launches their own regional market, which can clash with others, then coordination becomes much more challenging. Not only would multi-grid markets greatly expand the number of market competitors, which might help alleviate the issue of market power, but they also offer more service opportunities for the TSO. That would open the door for more reactive power suppliers and maybe more than one client. As a result, local reactive power markets may become less dominant and social prosperity may rise. In most cases, the suggested markets are run by the DSO, which then combines the services with a standardized TSO market. This is referred to as a regional additional service market, as stated in [44]. They go over four different ways that the TSO-DSO interface's ancillary service markets may be run. The literature on the reactive power market, however, does not yet take them into account.

3.1.4 Auction-Based Model

The SO and the supply agents chosen from the market enter contracts for an extended period to establish the auxiliary services market. A yearly auction is held for the whole power system to award contracts for reactive generation and absorption capacity. In order to provide investors with more reliable market indications, these contracts may be extended for more than a year.

If the power system's reactive power capacity requirements are not met by other lengthy agreements, then the auction will take place. In order to allow for the installation of new reactive power capacity or for existing reactive power sources, like generators, to make investments in increasing their available reactive power capacity, the timeframe of the reactive power efficiency auction has been placed to one year. Thus, yearly pricing may effectively communicate market indications. Some American electricity systems, including those in New York, California, and PJM, as well as some European ones, have some experience with yearly agreements for reactive power capacity [18]. Any VAR source may place a bid on providing and consumption VAR capacity items at the annual auction. The ability that has already been provided in previous bidding, however, cannot be bid upon. The bids that have been submitted reflect the agent's lowest yearly revenue target for the VAR capacity quantities that have been provided [9].

In Figure 3-4 a monetary stream of VAR capacity market has been shown where in order to pay some VAR vendors, one will rely on the concept of cost causality. There are two ways that the system is funded: first, load demands cover the remaining amount, and second, generators and transmission lines pay higher VAR capacity fees because of their failure rates. In every system, payments are directly proportional to the average marginal price. Additional VAR supply needs will be levied to market players accountable for equipment unavailability. Extra VAR capacity and line expenses, for instance, will be paid for by generator and transmission owners [9].

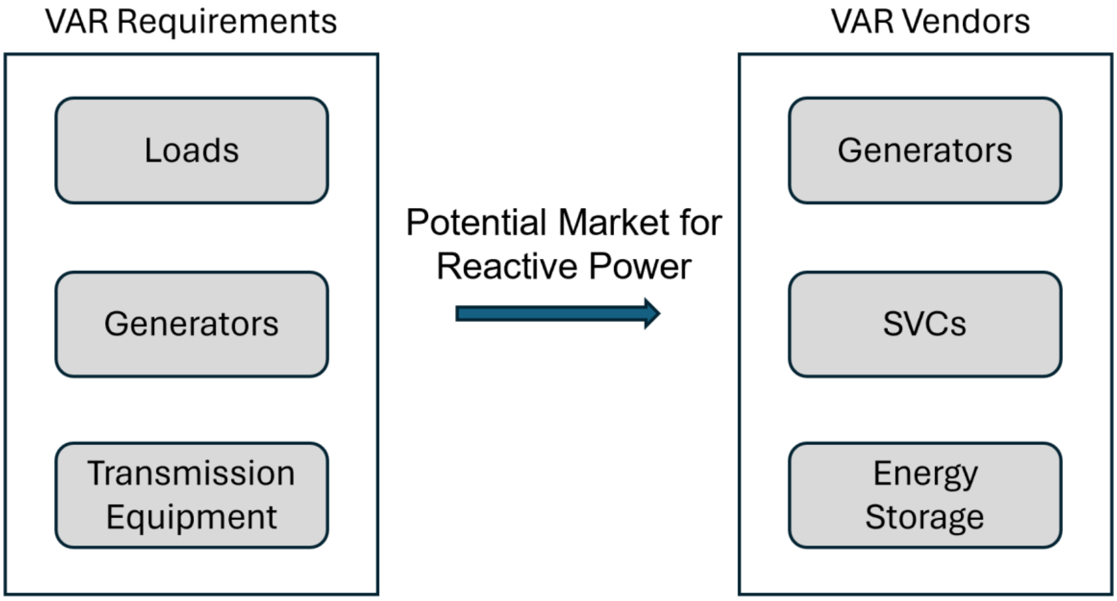

Figure 3-4 Monetary Stream of VAR Capacity Market [9].

3.1.5 Hybrid Model

Renewable energy source integration and grid management complexity have brought reactive power's crucial role to the forefront of power systems' developing environment. Utility companies have long been responsible for managing reactive power without a clear compensation mechanism, despite its critical importance for ensuring stable voltage levels and the power system. But new business models are needed for the transition to decentralized and more dynamic energy systems. A potential solution that combines market-based and cost-based approaches to reactive power is the hybrid market model. This model aims to strike a compromise between equitable remuneration and market efficiency.

Utilities have historically been reimbursed for the expenses they incur while delivering reactive electricity via cost-based methods. Unfortunately, incentives for innovation and efficiency are frequently absent from this approach. However, although completely market-based approaches might promote efficiency, they also run the risk of introducing price volatility and dependability concerns due to their reliance on competitive bidding procedures for reactive power supplies [45].

The goal of the hybrid market model is to combine the best features of both methods:

- **Cost-Based Elements**: Making sure utilities and other providers are not discouraged from participating by setting baseline remuneration that covers the costs of delivering reactive electricity.
- **Market-Based Elements**: Bringing in competitive mechanisms to boost system efficiency by incentivizing providers to innovate and save costs.

3.2 Evolution of Past Decades

Across various locations, the adoption rates of reactive power market mechanisms have shown diverse trends over the last decade. The development of smart grids and real-time monitoring systems has facilitated the implementation of more flexible and market-oriented procedures. There has been a clear trend in Europe and North America to include reactive power into wider energy market frameworks, promoting more competition and transparency in pricing. Regulatory developments have also had a crucial impact. For example, the incorporation of renewable energy sources, which are less reliable and more unstable, has required the implementation of market mechanisms that are more adaptable and quicker to respond. Countries including the USA, UK, and many European countries have modified their markets to accept alternative energy sources, while still guaranteeing voltage stability and system dependability.

3.2.1 Market-Based Compensation Schemes

Reactive power assistance is usually compensated for by generators via market-based methods. The goal of this strategy is to make reactive power services more accessible by allowing many suppliers to enter the market and provide them at varied rates depending on supply and demand.

This article [46] takes a look at a reactive power market that uses consolidated compensation as its foundation. In such a market, there must be a system in place to incentivize market players to provide reactive power services and make sure they get enough money to continue in operation.

As a result, there are two distinct segments within the reactive power market: the capacity-based segment and the quantity-based segment [36]. Because of the reasonable distribution of reactive power sources in a capacity-based market, the investment cost of these sources is considered alongside their distribution and capability. Analyzing the implicit cost of reactive power sources and rearranging their outputs according to the system reactive power need is what quantity-based markets are all about. Consequently, the system's overall fault-enduring capability is enhanced.

Key Features

- Pricing models: Prices for reactive power can be set through auctions or based on predetermined tariffs that reflect the cost and value of providing reactive power in different regions and times.
- Eligibility and participation: Open to various entities, including traditional power plants, renewable energy sources, and other grid resources capable of voltage support.

3.2.2 Cost Based Reimbursement

Utilities or operators compensate generators for reactive power expenses in cost-based systems. To make sure the payments are fair and appropriate, this approach generally uses regulatory frameworks.

The cost of reactive power for actual power transit from various sources is evaluated using a cost-saving structure. Each generator is compensated for its reactive power assistance based on the difference between its cost of supplying reactive power and the cost of reactive power required for actual power sales. Recovering loading side costs involves factoring in the location and quantity of reactive load. As an essential competitor in the reactive market, the independent reactive compensator will be compensated based on its actual costs [47].

Key Features

- Cost recovery: Generators are compensated for the actual costs of providing reactive power, including capital and operational expenses.
- Regulatory oversight: Typically managed by national or regional regulators who oversee the fairness and adequacy of the compensation.

3.2.3 Dynamic Pricing Model

To better represent its actual worth and cost, this system employs dynamic pricing of reactive electricity in response to real-time grid circumstances and demands. The active and reactive related issues are identified using a decoupled formulation, which is used to construct this approach. In order to encourage agents of the power markets to participate, this article examines a model for the reactive power pricing computation. An OPF has been put in place to address the reactive power subproblem; this OPF takes into account the reactive power generation costs and actively seeks to minimize active losses in the objective function. Researchers used a nonlinear programming approach to solve the OPF and get the marginal cost prices of active and reactive power [48].

Key Features

- Real-time adjustments: Prices adjust in real-time based on grid conditions, demand, and the availability of reactive power.
- Demand-responsive: Encourages providers to adjust their reactive power output in response to price signals.

3.2.4 Auction-Based Scheme

Auctions are used to procure reactive power, where providers bid to offer their reactive capacity. The lowest-cost bids are typically accepted, promoting economic efficiency.

This research [49] presents a dynamic model that considers network limitations and utilizes an auction-based local market clearing mechanism for energy management in a power plant. In order to accomplish this goal, a comprehensive array of resources was taken into account, including both renewable and conventional distributed generators, energy storage systems, and flexible loads. In addition, the power plant has the capacity to participate in the purchase and sale of electricity in the day-ahead energy market on behalf of distributed energy resources (DERs) with the aim of minimizing its operational expenses. The results indicate that the power plant operator may increase its expected profit by implementing an effective strategy for allocating resources and arranging market activities. Furthermore, implementing the recommended local auction-based approach not only led to a reduction in customers' power costs but also facilitated the participation of small-scale distributed energy resources (DERs) in the day-ahead electricity market, while safeguarding them from market uncertainties.

Key Features

- Competitive bidding: Providers submit bids to supply reactive power at a specified price.
- Cost-effectiveness: Aims to minimize the cost of reactive power procurement for the grid operator.

3.2.5 Decentralized Mechanisms via Distributed Energy Resources (DERs)

As distributed energy resources such as solar panels and storage systems become more prevalent, new models have arisen that include these resources contributing to local reactive power management. Facilitating peer-to-peer energy trading within an active distribution network may promote the equitable distribution of benefits among numerous prosumers and enable the effective integration of distributed renewable energy. However, it is essential to ensure that the distribution voltage limitations are met in order to safely carry out energy transactions in the physical system. The P2P trading ecosystem consists of many local energy marketplaces that are launched by the prosumers. Within each local energy market, there is a single vendor and a small number of possible purchasers. Thus, in accordance with the fundamental principles of microeconomics [50], both the supplier and the buyers possess a certain degree of market power that enables them to affect the price [51].

Key Features

- Local management: Reactive power is managed locally at the distribution level, reducing the need for centralized compensation.
- Technology-driven: Advanced inverters and smart grid technologies enable DERs to participate actively in voltage support.

3.3 Comparison of Different Market Mechanisms

The comparison of market mechanisms for the reactive power section details the popularity, overlaps, and distinctions among different mechanisms. This addition will enhance understanding of the dynamics and preferences in reactive power markets.

3.3.1 Most Popular Mechanisms

- Market-based model: This idea has gained widespread popularity, especially in regions that have liberalized their electrical markets, such as the European Union and some regions of the United States of America, such as California, North America, and PJM. These models are popular because of their ability to properly describe the current state of the market and to motivate rivals to participate in behaviors that are efficient. In addition, they have the potential to accurately represent the market.

- Cost-Service Compensations: On the basis of the expenses that they have incurred in the process of supplying reactive power, suppliers are compensated for their services when this technique is used. In addition to operational expenses, these costs also include investments. The ability of providers to pay their bills is ensured because of this, which in turn encourages the delivery of reactive power that is consistent and reliable. There are numerous sections of Asia and Africa that have traditional utilities that are vertically integrated, and this concept is common in those places.

3.3.2 Least Popular Mechanism

- Auction-Based Approach: In general, auction-based procedures are deployed in very particular settings or as part of trial initiatives. They are not as widespread as other alternatives. When it comes to auction systems, their limited usage is sometimes attributed to the difficulty of establishing and maintaining them, as well as the need for a solid legal structure to oversee them. There is a need for reactive power in order to regulate the voltage levels at certain points within the power system. In contrast to active power, which can be transported across great distances, its influence is tightly concentrated in a single location. In light of this, the demand for reactive power is unique to certain locations and periods, which makes it difficult to implement an auction strategy that is universally applicable. The compensation of reactive power is controlled in many locations, and it is possible that it is not susceptible to the forces of the market. Rather than being reimbursed via competitive market pricing, utilities are frequently compensated through cost-based systems, which reduces the motivation for holding an auction-based market. Consequently, for auction mechanisms to work well, they need a strong trading environment. However, this environment is less practical in this context owing to the lower magnitude of the demand and the more specialized nature of the demand.

3.3.3 Overlapping Mechanism

- Hybrid Approach: Despite the fact that reactive power requirements might significantly shift in response to changes in grid circumstances. For the purpose of ensuring dependability and stability, hybrid models enable operators to take advantage of market processes to acquire reactive power at a cost-effective rate, while still preserving the flexibility to intervene directly. By incorporating some market-based incentives, such as payments for available capacity or performance-based remuneration, operators are able to successfully manage costs while simultaneously encouraging investments in reactive power resources.

Frequently, hybrid models are a combination of techniques that are focused on market forces and cost considerations. As a result of their efforts to strike a balance between the predictability of cost recovery and the efficiency of market dynamics, these models are earning a growing amount of popularity. An example of overlap is when a market first employs a cost-based strategy for baseline compensation, but then permits market-based incentives for increased reactive power supply during peak hours or in confined zones. This is an example of how overlap might occur. The PJM Interconnection in the United States of America and the National Electricity Market (NEM) in Australia are two examples of hybrid models that are currently being implemented [5].

Figure 3-5 below shows a pie chart of the different market mechanisms discussed above where it comparatively presents a percentage analysis -

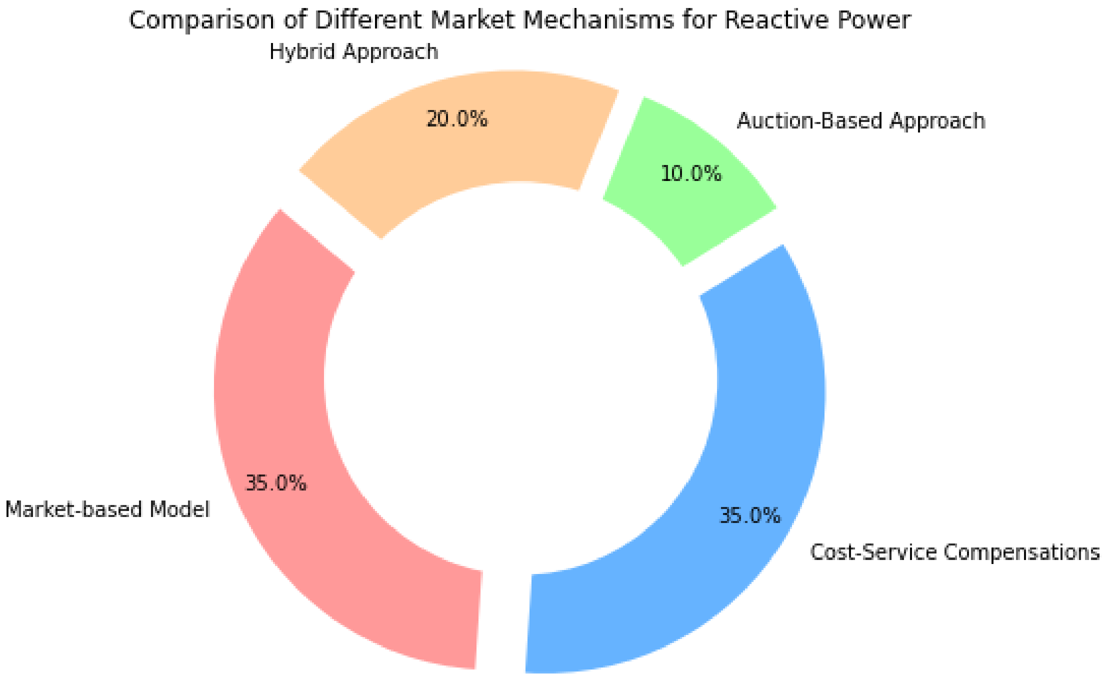

Figure 3-5 Comparisn of Different Market Mechanisms

4 Pricing Strategies in Reactive Power Market

The strategies employed to price reactive power are crucial for ensuring the operational reliability of power systems and for motivating investment in reactive power resources. This section explores various pricing methods, provides examples from different global markets, and offers a comparative analysis of these strategies.

4.1 Performance Based Pricing

The performance-based pricing structure sets a benchmark for the amount of reactive power that may be loaded or generated within a control region. The system operator establishes these rules, clearly defining the obligations and constraints for both providers and load clients. No fee or credit is applied when the demand for reactive electricity falls within the permissible range. The system operator controls the immediate functioning of reactive power generation by setting the required voltage levels. To effectively manage system needs and provide operational flexibility, it is necessary to establish a penalty system for breaking performance criteria and a credit system for providing more reactive power capacity. The expenses associated with reactive power generation may be recuperated via two methods: allocating the cost responsibility to either the generators or the loads. The system operator must take into account the technical feasibility, power factor-based limitations, zonal-based norms, and economic indicators for the increase of reactive power [52].

Traditional transmission service requirements have always relied on reactive power performance criteria. However, the suggested technique may necessitate the reevaluation of generator reactive power costs and their incorporation into the transmission rate base. The implementation is simple but necessitates the packaging of reactive power services with other services supplied by the generator. If the usage or generation of reactive power remains below acceptable limits, no additional fee for reactive power is applied [52].

4.2 Location-Based Pricing

Transmission customers should be given the option to provide either a part or the whole of the required generation-related reactive power for their transactions. Nevertheless, it is not feasible for transmission customers to provide reactive power along transmission channels. In order to tackle this problem, it is advisable to promote the establishment of a regional market for reactive electricity, which would include the participation of power providers, consumers, and other relevant entities. Generators may get recognition for their ability to provide reactive power, while load users might be billed based on the overall reactive power needs resulting from their demand for electricity. Implementing a zonal-based fee may streamline the management of this levy. Should the transmission client want to independently provide reactive electricity, they must ensure coordination with the transmission provider [52].

Load consumers bear the financial burden, and the need for reactive power may be calculated using the RPAF principle for each transaction or load demand. Customers have the ability to get the necessary capacity for reactive power within a specific local region or zone without any restrictions. The remuneration to power producers and the pricing system for consumers should be established according to their reactive power requirements and the geographical significance of reactive power losses [52].

In order to avoid any manipulation of the reactive power market, it is possible to establish a pricing mechanism based on a reactive power capacity that is measured over a longer period of time. This measure aims to deter the practice of short-term gaming by allocating resources to other generations, hence mitigating the influence of local generators on the reactive power market. Market-based solutions are becoming common and are likely to become dominant as markets develop and local market power concerns are resolved[52].

5 Challenges and Opportunities of Reactive Power Market Mechanisms

5.1 Cost-Based Mechanism

The cost-based model, which takes into account the actual expenditures that are incurred by the producers or suppliers, is the one that is responsible for determining the price of reactive energy. The majority of the time, these costs include both operational expenditures (such as fuel and maintenance) and capital expenditures (such as investments in infrastructure and technical advances as well as other enhancements). There is also the possibility that the price structure may include a substantial profit margin. It is usual practice for regulators to keep an eye on this model in order to ensure that prices are reasonable and acceptable, and that they accurately reflect the cost of production without taking into account any additional markups.

Challenges:

- Accuracy of Cost Allocation: Determining the exact cost of providing reactive power can be challenging, potentially leading to inaccurate pricing that does not reflect true costs.
- Limited Incentives for Efficiency: Since payments are based on reported costs, there may be little incentive for providers to reduce costs or improve efficiency.

Opportunities:

- Predictability: Provides a stable, predictable framework that can facilitate budgeting and financial planning for both providers and regulators.
- Simplicity: Easier to implement and understand compared to models relying on market forces, making it a preferred choice in less competitive environments.

5.2 Market-Based Mechanism

The prices of reactive energy are not determined by cost reimbursement under the market-based approach; rather, they are determined by the competitive market dynamics that take place in the market. This strategy is based on the assumption that the market for electricity is liberalized, which would make it possible for several providers to offer reactive power and compete with one another in terms of price and quality. There are a number of factors that influence prices, including supply and demand, the availability of alternative resources, and the requirements of the grid. Prices are liable to vary as a consequence of these factors.

Challenges:

- Risk of Market Failure: If not properly regulated, the market may fail to provide sufficient reactive power, especially during critical times, due to its non-profitable nature.

- Barrier to Entry: New entrants may find it difficult to compete in established markets, leading to potential monopolies or oligopolies.

Opportunities:

- Dynamic Pricing: Allows for dynamic pricing which can more accurately reflect the current market situation and grid needs.
- Market Efficiency: Promotes more efficient market operations as providers strive to be competitive, potentially driving technological advancements and cost reductions.

5.3 Auction-Based Mechanism

The auction-based technique, which includes a bidding mechanism, is used in the process of contract distribution for the supply of reactive power. It is possible to determine the price at which suppliers are prepared to offer reactive power by looking at the bids that are filed by the providers. The grid operator or regulator ensures that cost-effectiveness is maintained while also serving the critical supply demands at the same time by selecting the bids that are the lowest. This model may be used on its own, or it can be included into a market structure that is more extensive that is more complete.

Challenges:

- Speculative Bidding: Providers might engage in speculative bidding, which can lead to volatility and inefficiency in reactive power provision.
- Short-term Focus: The competitive nature of auctions may encourage providers to focus on short-term gains rather than long-term stability and investments.

Opportunities:

- Cost Efficiency: Can drive down prices through competitive bidding, ensuring cost-effective procurement of reactive power.
- Market Entry: Opens the market to multiple providers, potentially increasing supply, and innovation.

5.4 Grid-Level Mechanism

Reactive power is especially included in the centralized management of the energy grid within the scope of this structure to begin with. It is often regulated by a grid operator or a regulatory body, which is responsible for ensuring that enough reactive power is maintained in order to maintain voltage levels and overall grid stability. This control is typically carried out by means of a grid operator. The reliability of the system is given a greater priority in the model than the dynamism of the market.

Challenges:

- Resource Allocation: Efficient allocation of resources can be challenging, as central management may not always respond quickly to local changes in demand or supply.

- Innovation Stagnation: Heavy regulation may limit incentives for innovation and efficiency improvements among providers.

Opportunities:

- System Reliability: Enhances overall system reliability by ensuring a consistent supply of reactive power where and when it is needed most.
- Integrated Planning: Allows for better integrated planning and response strategies across different types of power and grid contingencies.

5.5 Hybrid Model Mechanism

Using components such as market-based pricing, cost-based pricing, and regulated cost recovery, a hybrid model is able to produce a balanced approach by integrating parts of the separate models that have been described before. This combination allows the hybrid model to develop a more comprehensive strategy. This specific model is capable of reacting to the individual needs and conditions of a grid or market, and it may also contain flexible regulatory structures in order to fit the ever-changing dynamics of the market.

Challenges:

- Regulatory Complexity: Managing a hybrid system requires sophisticated regulatory frameworks and can lead to increased administrative costs and complexity.
- Conflicting Mechanisms: Different components of the hybrid model might conflict, requiring careful coordination and management to ensure system harmony.

Opportunities:

- Versatility: Provides the versatility needed to adapt to both market conditions and regulatory changes, potentially offering the best of both worlds.
- Optimal Resource Allocation: By leveraging multiple mechanisms, it can more effectively match supply and demand, optimize resource allocation, and promote stability and efficiency across the grid.

6 Reactive Power Market Across the Continents

Because of variations in regulatory frameworks, market maturity, technical breakthroughs, and energy consumption patterns, the reactive power market, an essential component of electrical power systems, varies greatly among continents. The reactive power market on different continents is summarized here:

America: The market for reactive power is strongly developed in North America, notably in the United States and Canada. This is mostly because of the severe rules and standards that are in place to ensure the quality and dependability of the electricity. In the U.S., reactive power is managed by regional transmission organizations (RTOs) and independent system operators (ISOs) for example, via the use of ancillary services markets. Compensation for providers of reactive power is usually based on pricing structure validated by the Federal Energy Regulatory Commission (FERC). These tariffs can include payments for the capability to provide reactive power as well as actual provision. With a rising integration of renewable energy sources, which provides new problems and possibilities in reactive power management, the primary focus is on ensuring that the system remains stable and limiting the number of losses that occur during transmission [5].

Australia: Australia is taking preventative measures to control reactive power, which is particularly important given the country's growing dependence on occasionally impacting power quality renewable energy sources like as solar and wind. Policies enacted by the Australian Energy Market Operator (AEMO) promote the use of technologies that provide reactive assistance and maintain grid stability, and they supervise the management of reactive power. Markets for Frequency Control Ancillary Services, Network Support and Control Ancillary Services, and System Restart Ancillary Services are the three main types of reactive power ancillary services identified by AEMO [53].

Asia: Asia exhibits a diverse reactive power market landscape, with mature markets in Japan and South Korea, and rapidly developing ones in China and India. The expansion of both transmission infrastructure and renewable energy capacity, particularly in wind and solar, drives the need for effective reactive power management. In India, the Central Electricity Regulatory Commission (CERC) has established regulations that include reactive power management [54]. China, for instance, has been implementing significant grid modernization projects to enhance its reactive power capabilities [55].

Europe: The reactive power market in Europe is known for its robust regulatory framework, which focuses on the integration of renewable energy sources while ensuring the stability of the power system. The European Network of Transmission System Operators for Electricity (ENTSO-E) has a crucial role in ensuring consistency and uniformity in operations and standards across Europe [26]. Germany, France, and the UK possess sophisticated systems for controlling reactive power, which often include dynamic compensation technologies such as STATCOMs and SVCs. The management of reactive power differs across countries, but typically, transmission system operators (TSOs) are accountable for maintaining the equilibrium of reactive power. In comparison to the United States, the demand for reactive electricity in the market is not as prominent. Typically, it is regulated by methods set by the government rather than being driven by competitive markets.

7 Reactive Power Market Proposition for Norway

7.1 Introduction

The regulation of voltage levels in electrical power networks relies on reactive power, an integral part of these systems. Energy systems can't efficiently transmit electricity over long distances without these voltage levels. Particularly relevant in Norway, where extensive power transmission networks are required to connect remote hydropower sites to larger cities due to the country's hilly terrain, is this. Because of how the power grid is designed, reactive power must be carefully managed in order to keep the transmission system stable and efficient. Utilities use a wide variety of compensators and regulators to control reactive power and maintain system reliability. Norway has a well-developed electricity market where reactive power is sold alongside other electrical commodities. In this field, Statnett the Norwegian Transmission System Operator is a major participant which is authorized by The Norwegian Water Resources and Energy Directorate (NVE).

The Norwegian reactive power market is following the trend of decentralization and market forces seen across most of Europe. In the past, traditional generators were the go-to for regulated reactive power regulation and voltage support. The structure and service provided determine the compensation for these generators, which can be nothing at all or a defined amount over time. Still, reactive electricity providers are seeing an uptick in demand for alternatives provided by the market. The increasing use of renewable energy sources and the tightening of environmental regulations are driving this change.

There has been an increasing trend toward the formation of regional reactive power markets as of late. In these markets, the stability of the grid's voltage is ensured by cooperation between the transmission system operator (TSO) and the distribution system operator (DSO). Distribution service providers (DSOs) in these markets may meet transmission system operators' (TSOs') requests for reactive electricity by drawing on grid-connected resources. Agents in the market compete to provide these services within a nearly real-time context. Keeping to the constraints of the grid, this model seeks to maximize the common good. It does this by using advanced procedures like alternating current optimal power flow (AC OPF) and by supporting various bid types.

7.2 Revolutionary Approach for Reactive Power Compensation

The growth of carbon-neutral energy power production has resulted in an upward trend in the use of grid-edge distributed energy resources (DERs), namely distributed generation (DGs). This has caused some disruption in the conventional methods of power distribution, device management, and market remuneration systems. Historically, grid stability and power quality have been maintained by huge, controlled generators operating at the transmission level. Nevertheless, this novel approach is required for the developing grid. Reactive power control in the transmission grid is often accomplished by modifying the power factors of large synchronous generators. Nevertheless, resources that use inverters, like distributed generators

(DGs) outfitted with adaptive inverter systems, have the ability to rapidly and inexpensively modify their power factor (PF). These Distributed Energy Resources (DERs) provide distinct grid flexibility provided their ability to generate reactive power can be synchronized, since reactive power transmission is inefficient. Novel approaches for controlling a diverse array of power factors are required for the developing power network.

Figure 7-1 is the suggested technique aims to equalize the reactive power of the main grid, which is essential for voltage stability and to provide loss-free power transmission. The decentralization of grids enables the efficient use of distributed energy resources (DERs) to provide reactive power support throughout the distribution system. This allows for more flexibility in power factors and the use of distributed control units. This might potentially serve as a replacement for traditional reactive power suppliers, which have limits in terms of power factor and are expensive to operate. However, in order to provide responsive power, Distributed Energy Resources (DERs) need to be incentivized to do so.

In Figure 7-1 a comparative approach shows how existing high reactive power flow can be minimize through a proposed reactive power flow model through transmission and distribution system.

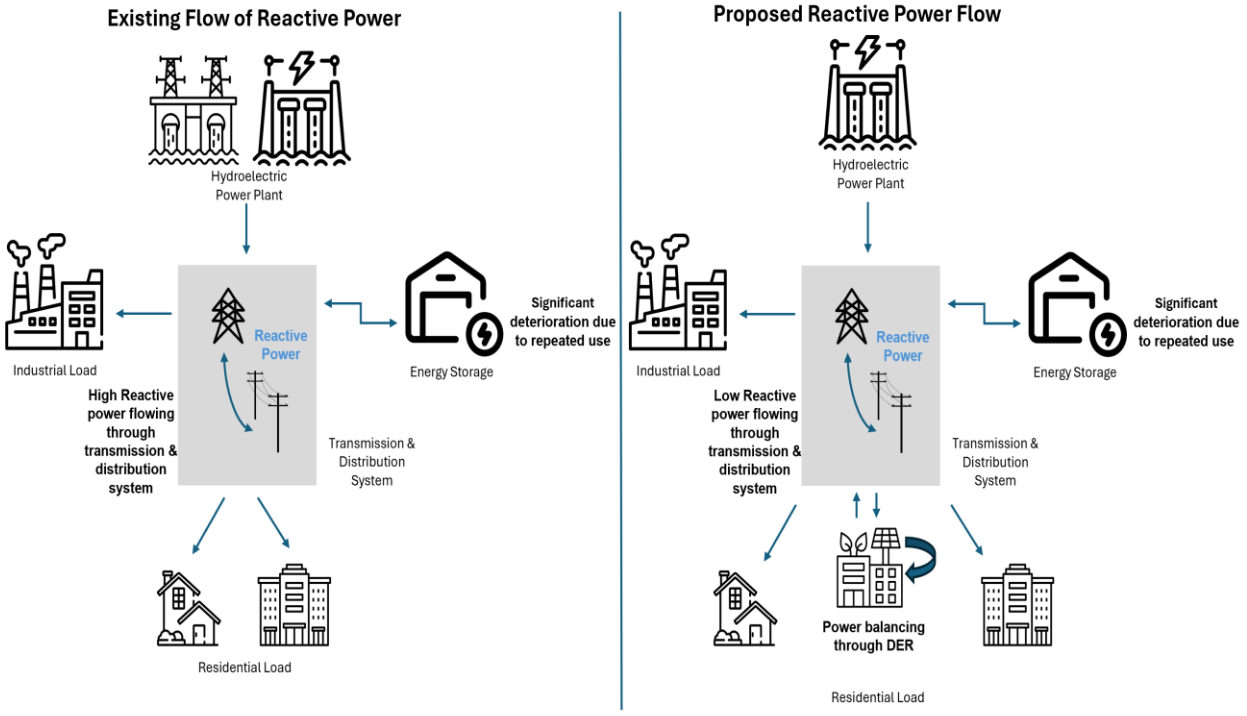

Figure 7-1 Decentralized Mechanism for Reactive Power Flow

7.3 Decentralize Market Mechanism & Pricing

Efforts to lower minimum power bids have not yet resulted in reactive power markets in the United States or Europe. Distributed generation (DGs), which provide a great deal of operational flexibility for very little money, are not considered supplementary services in Europe. The renewable energy transition presents an opportunity to use these DGs in order to provide essential grid services. Deep grid integration of DGs can only be achieved with a market mechanism that accounts for the geographical and temporal variability in their reactive power capacities and values them accordingly. In order to accommodate grid physics and increase the penetration of distributed energy resources (DERs), this may be achieved using methods based on optimum power flow (OPF). These methods allow for the simultaneous calculation of prices corresponding to actual and reactive power injections.

A reactive power market that permits variable payments based on an OPF technique is proposed in this study. Market schedules and pricing are determined using a framework based on limited optimization. By include DG penetration, the suggested model broadens the scope to include each DG as an inverter-based resource with reactive power capabilities and variable PF. Support for reactive power from flexible consumption or storage devices is also taken into account, albeit they may be accommodated by extending the market structure. Furthermore, it takes into account an imbalanced distribution grid via the use of a current injection (CI) model and provides analytical backing for the reactive power price that emerges from this model in relation to industrial demands.

It can develop a distribution grid reactive power energy market for priority aligned DGs. A linear CI model of the imbalanced distribution grid is used to solve the problems of market dispatch and price clearing. The market's implications in the important areas of price volatility and supporting consumer investment choices, as measured by this market's flexibility and performance across a variety of scenarios, such as DG penetration and inverter PF. This suggested market can create the following characteristics.

- Make use of the extensive PF operating range and huge reactive power capabilities of DERs deployed widely.
- Reduction of grid loss via the use of nearby DERs.
- Ensure equitable compensation for distributed energy resources (DERs) in exchange for their contributions to the grid.
- Encourage the ongoing implementation of DERs by establishing reliable revenue sources and broadening market accessibility.

An imbalanced distribution grid is the starting point for the reactive power market, which seeks to calculate the best power dispatch for both active and reactive power concurrently. It is possible to incorporate a Q-RMP for completion, and an OPF technique might be used to find a solution to this issue. There is a temporal and geographical variation in the pricing of active and reactive electricity at the local level, which provides more precise economic signals for distributed energy resource (DER) management and equitable service-based compensation. The implementation of reactive power compensation at the transmission level is accomplished via a variety of mechanisms, and monetary incentives are necessary in order to guarantee electrical power supply and grid capacity. Tariffs are intended to be payments to asset owners that are either fixed or variable; but, if the incentives are not constructed properly, they might result in reactive power shortages or surpluses, which would result in monetary losses for utilities and customers.

Here is an overview of the pricing strategies of the priorities for the developing grid, as outlined by proposed market with new approach and capabilities in Table 7-1 where traditional methods of reactive power compensation did not include generators running at power factors (PFs) of 0.95, resulting in the cancellation of tariffs. Reactive power pricing was established outside this range in order to recoup equipment expenses and prevent losses. Nevertheless, this method is very responsive to the power factor (PF) range and becomes insufficient when the PF fluctuates, rendering it inappropriate for the modern power grid that is seeing a significant rise in the integration of Distributed Energy Resources (DERs) with fluctuating power factors [56].

Existing Method		Proposed Method	
Q- Pricing Approach	Present Constraint	Q- Pricing Approach	Proposed Capabilities
Stable Tariff	To react appropriately, stable tariffs are unable to offer effective signals.	Flexible Tariff	The fluctuation of Q prices over time provides a signal for distributed energy resources to adjust their behavior in accordance with the necessary needs of the system.
Tariff Based on Expence	The DERs that do not contribute significantly to the high production costs of Q are excluded.	Tariff Based on Facilities	The price of Q is established using an Optimal Power Flow (OPF) algorithm.
Price Neutral for PF	For existing markets, price neutralization for PF (0.9-1) shouldn't be done since it is inappropriate.	Anti Price Neutral PF	Consider remunation for PF

Table 7-1 Proposed Pricing Strategies with New Approach & Capabilities [56]

7.4 Operational Regulation in Norway

The National Utility power Company (NVE) is tasked with overseeing adherence to the Energy Act and enforcing laws to ensure the efficiency of the power market. NVE has been granted authority to promulgate laws pertaining to several aspects of the energy sector, including network regulation, tariffs, power system planning, supply quality, metering, billing, supplier switching, neutrality, non-discrimination, system operation, and the responsibilities of the transmission system operator. To establish and run a marketplace for the exchange of physical electricity, one must get a marketplace license. Now, Nord Pool Spot is the only organization authorized to possess such a license. The marketplace's objective is to enhance the effectiveness of price determination in the electricity market by supporting efficient trading systems and regulations. Generator and supplier firms function under a framework of open competition, but transmission system operator and distribution companies operate as natural monopolies and are subject to regulation by NVE. NVE has difficulty in establishing an efficient power market while dealing with vertically integrated enterprises that engage in both monopolistic and competitive operations [57].

The electrical balance regulation and its implementation are as follows [57]:

- Settlement rules are established to guarantee that transactions between Transmission System Operators (TSOs) are conducted in compliance with consistent standards.
- As per the correction of disparities. By ensuring conformity with European rules throughout member states, all market actors will be subject to the same terms and conditions for energy provision. This will lead to a greater use of the balancing market. The settlement of the imbalance is conducted at a national level.
- The allocation and exchange of balancing capacity across zones is regulated by regulations. The TSOs may pool their resources to purchase and use balancing capacity thanks to these rules. This allows the TSOs to benefit from reserves that are beyond their control.
- Balancing Responsible Parties and their regulations lay forth the ground rules for balancing services on a national scale. To ensure that all participants in the balancing markets are bound by clear and equitable regulations, certain rules have been put in place.

As before, NordREG will keep the EU's CEP implementation in sync by coordinating regulatory changes. Efficiently implementing European network standards and guidelines will also be a primary priority. The updated 2022 NordREG Strategy, which intends to provide clear directions for the evolution of the energy markets in the Nordic and Europe up to 2030, is outlined in the annual report from NordREG. There are three guiding concepts that make up the approach [58].

These are-

- Accurate indications for price
- People who actively engage in purchasing
- A flexible structure that allows for a sustainable future and proficient markets for electricity

NordREG's strategy is backed by a plan of action that establishes the necessary actions to achieve the goal objectives developed in the Strategy, both in the short, medium, and long term.

The legalization of energy market adjustments in the Nordics nations by the end of 2023 necessitates the implementation of national policies that need cooperation across the Nordic countries for comprehension and execution. Table 7-2 are the NordREG for 2024 [58].

1. Monitor and manage the execution of the revised regulations related to the improvements of the electricity market, decarbonization of hydrogen and gas markets, modification of the REMIT rules, and renewal of the energy efficiency directive.
2. Establish fruitful authorization processes for suggestions for localized criteria and techniques.
3. Establish a well-coordinated regulatory supervision to ensure the prompt and effective adoption of the Nordic Equilibrium Model, enabling a timely link to MARI and PICASSO.
4. Maintain the successful execution of European network regulations and norms.
5. Enhance the synchronization of Nordic perspectives and engagement in CEER (Council of European Energy Regulators) and ACER (Agency for the Cooperation of Energy Regulators). Particularly in the European argumentation over the modifications to the Electricity Market Model.
6. Maintain collaboration and synchronization of efforts related to the shared Nordic end-user market and economic situation for buyers in the Nordic wholesale electricity markets.
7. Collaborate and synchronize efforts related to adaptability concerns, with particular emphasis on the renewable energy legislation.
8. Establish and uphold regular and active communication with Nordic Transmission System Operators (TSOs) about matters of significance for the national economy.
9. Enhance the dissemination of data and optimal methodologies across Nordic National Regulatory Authorities (NRAs) and foster a shared comprehension as the foundation for concrete decision-making.
10. Enhance managerial and operational collaboration within NordREG.

Table 7-2 Operation Regulations of Norway (2024) [58]

8 Conclusion

This paper has explored the complexities of different reactive power market mechanisms and pricing strategies, highlighting the evolution of these mechanisms over the past decade, their operational challenges, and the varied approaches taken by different regions. Through comparative analysis, identified popular, less popular, and overlapping market mechanisms, each reflecting the specific needs and capabilities of their respective power systems. For Norway, a market-based model combined with performance-based pricing appears to be the most viable mechanism for reactive power pricing. Norway's high penetration of renewable energy sources, particularly hydropower, such a model can provide the flexibility needed to accommodate the variability and decentralization of power sources by the integration of distributed generation system into the grid. To establish noninterrupted real and reactive power flow decentralize mechanism is more appropriate. DER may have a lead to maintain the pricing strategies for real and reactive power. It is feasible to capture the value of distributed energy resources (DERs) and control them via the use of economic signals, variable payments, and prices that fluctuate between regions. Moreover, Decentralized marketplaces incentivize DER participation in part by providing a steady stream of income via the daily deployment of locational marginal pricing for reactive electricity which are crucial in a market with significant renewable energy contributions.

Further Study Recommendation:

The distinctive Norwegian energy environment and the wider consequences of integrating DERs into existing power networks must be considered when making research recommendations for a decentralized reactive power market in Norway via Distributed Energy Resources (DERs). Presented below are several suggestions for future studies.

1. Assessment of Grid Stability and Reliability: Examine the effects of Distributed Energy Resources (DERs) on the stability and dependability of Norway's electrical system. This encompasses the examination of frequency and voltage regulation, as well as the contribution of Distributed Energy Resources (DERs) in bolstering the resilience of the power grid against disruptions and blackouts.
2. Economic and Regulatory Framework Development: Explores economic models for a decentralized reactive power market, including pricing mechanisms, incentives, and tariffs, and assesses the existing regulatory framework to propose modifications for a market-based approach to reactive power management.
3. Environmental Impact Analysis: Perform research to analyze the environmental effects of expanding the deployment of Distributed Energy Resources (DERs) for the purpose of providing reactive electricity. Specifically, concentrate on assessing the emissions during the whole lifespan of the DERs, the use of land, and the efficiency of resource utilization.
4. Consumer Participation and Behavior: Examine methods to include residential and business users in the reactive power market. This includes investigations of customer behavior, motivation, and obstacles to engagement in such a market.
5. Impact on Renewable Energy Integration: Analyze the impact of decentralized reactive power markets on the integration of renewable energy sources such as hydroelectric power, wind and solar in distant and rural regions of Norway.

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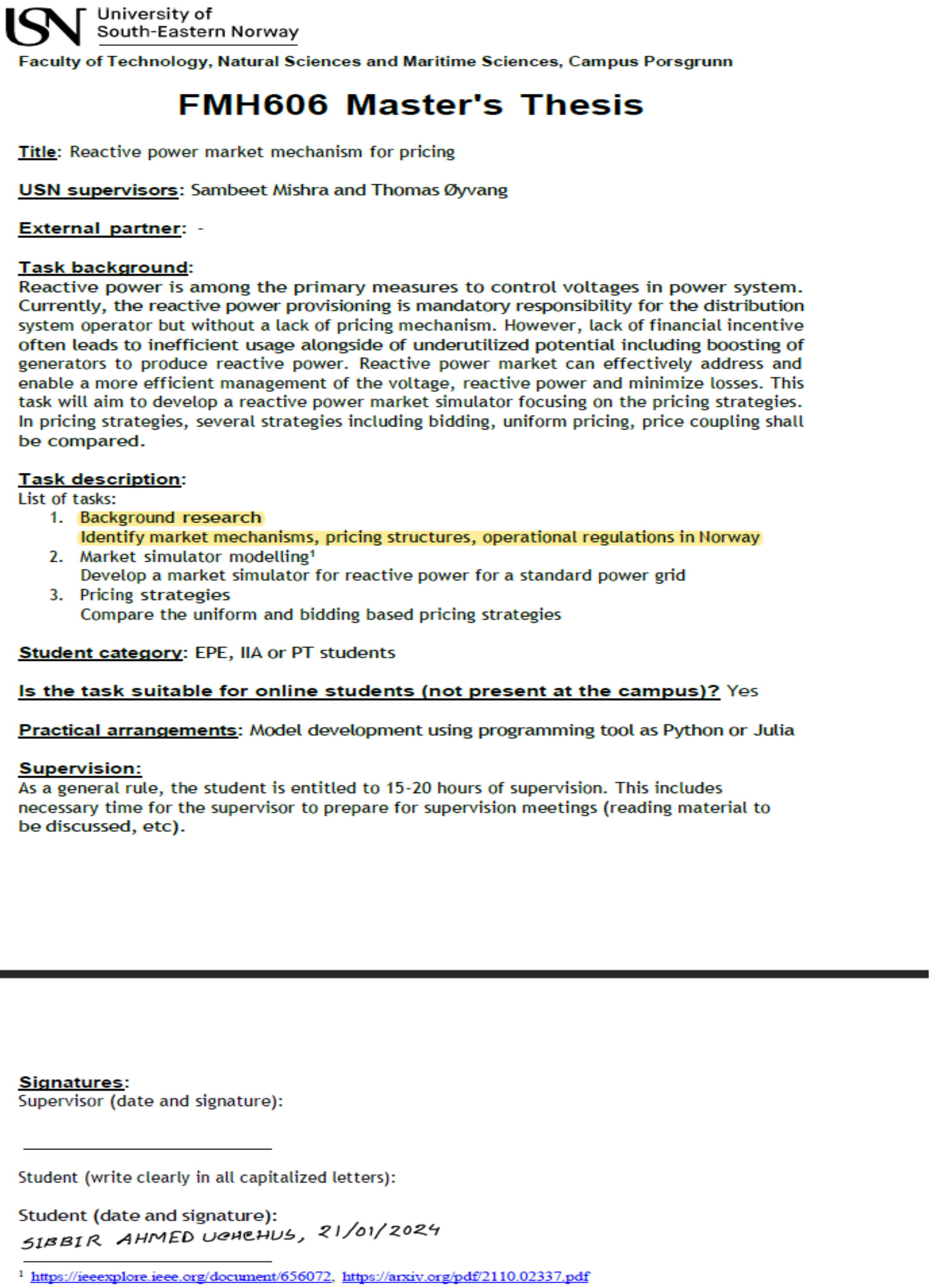
Appendices

Appendix A - Master's Thesis Topic Description



University of
South-Eastern Norway

Faculty of Technology, Natural Sciences and Maritime Sciences, Campus Porsgrunn

FMH606 Master's Thesis

Title: Reactive power market mechanism for pricing

USN supervisors: Sambeet Mishra and Thomas Øyvang

External partner: -

Task background:
Reactive power is among the primary measures to control voltages in power system. Currently, the reactive power provisioning is mandatory responsibility for the distribution system operator but without a lack of pricing mechanism. However, lack of financial incentive often leads to inefficient usage alongside of underutilized potential including boosting of generators to produce reactive power. Reactive power market can effectively address and enable a more efficient management of the voltage, reactive power and minimize losses. This task will aim to develop a reactive power market simulator focusing on the pricing strategies. In pricing strategies, several strategies including bidding, uniform pricing, price coupling shall be compared.

Task description:
List of tasks:

1. Background research
   Identify market mechanisms, pricing structures, operational regulations in Norway
2. Market simulator modelling[1]
   Develop a market simulator for reactive power for a standard power grid
3. Pricing strategies
   Compare the uniform and bidding based pricing strategies

Student category: EPE, IIA or PT students

Is the task suitable for online students (not present at the campus)? Yes

Practical arrangements: Model development using programming tool as Python or Julia

Supervision:
As a general rule, the student is entitled to 15-20 hours of supervision. This includes necessary time for the supervisor to prepare for supervision meetings (reading material to be discussed, etc).

Signatures:
Supervisor (date and signature):

Student (write clearly in all capitalized letters):

Student (date and signature):
SIBBIR AHMED UGHEHUS, 21/01/2024

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[1] https://ieeexplore.ieee.org/document/656072, https://arxiv.org/pdf/2110.02337.pdf