INTER-REGIONAL MARKET CLEARING OF A POWER SYSTEM WITH HIGH PV PENETRATION DURING A MID-DAY OVER-GENERATION

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DISSERTATION SUBMITTED IN
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Abstract

With the rapid growth of renewable energy (REs) resources in the electricity sector, the system operators (SOs) are facing some major challenges related to security, market, and operations in power transmission. Since the government policies are providing subsidized and favorable terms; therefore, the investors are highly keen on the installation of REs in the power networks. Altogether, the REs wouldn't be available 24 hours. Hence, the modern and upcoming power markets need to exchange power between different networks or regions (inter-regional) to meet the growing demands. The higher penetration of REs could cause overgeneration into the system due to low demands on the power systems, especially during mid-days. Therefore, inter-regional or inter-power markets strategies are the need in the present power systems to address the market clearing problems during the mentioned situation. In the present work, the locational marginal pricing (LMP) based solution methodology has been proposed to resolve the problem of market clearing in the power system during overgeneration. The objective function for the identified problem has been formulated using optimal power flow technique and solved through Interior Point Method (IPM). The interconnection of IEEE-9 & IEEE-5 bus systems and IEEE-118 & IEEE-57 bus systems have been chosen to create the inter-regional marketplaces. The proposed LMP-based solution methodology has been implemented on these marketplaces. The obtained test results show that the proposed methodology provides an economic and efficient solution for the highly PV penetrated power system.

Keywords: Carbon Emissions, Higher Penetration of Renewable Energy, Inter-regional Power Transmission, Locational Marginal Pricing (LMP), Market Clearing.

Abstrak

Pengendali sistem (SO) menghadapi beberapa tentangan besar yang berkaitan dengan keselamatan, pasaran, dan operasi transmisi tenaga disebabkan oleh pembangunan pesat sumber tenaga boleh baharu (RE) dalam sektor elektrik. Dasar kerajaan yang telah meletakkan terma subsidi dan menguntungkan telah menggalakkan pelabur untuk memasang RE dalam rangkaian kuasa. Secara amnya, RE tidak akan tersedia 24 jam. Oleh itu, pasaran tenaga moden dan masa hadapan perlu bertukar kuasa antara rangkaian atau wilayah (antara wilayah) untuk memenuhi permintaan yang semakin meningkat. Malah, penembusan RE yang lebih tinggi boleh menyebabkan penjanaan berlebihan ke dalam sistem disebabkan oleh permintaan yang rendah terhadap sistem kuasa terutamanya pada waktu tengah hari. Oleh itu, pengembangan strategi pasaran antara wilayah atau antara kuasa adalah diperlukan bagi sistem kuasa semasa untuk menangani masalah pembersihan pasaran untuk menghadapi situasi seperti yang dinyatakan. Dalam kajian ini, metodologi penyelesaian berasaskan penetapan harga marginal lokasi (LMP) telah dicadangkan untuk menyelesaikan masalah pembersihan pasaran dalam sistem kuasa semasa lebihan penjanaan. Fungsi objektif bagi masalah yang dikenal pasti telah dirumus menggunakan teknik aliran kuasa optimum dan diselesaikan melalui Kaedah Titik Dalaman (IPM). Sambungan sistem bas IEEE-9 & IEEE-5 dan sistem bas IEEE-118 & IEEE-57 telah dipilih untuk mewujudkan pasaran antara wilayah. Metodologi penyelesaian berasaskan LMP seperti yang dicadangkan telah diguna pakai untuk pasaran ini. Keputusan yang diperolehi merumuskan bahawa metodologi yang dicadangkan mampu memberi penyelesaian yang lebih jimat dan berkesan untuk penembusan sistem kuasa PV tinggi.

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List of Abbreviations

LMP	Locational Marginal Pricing
SO	System operator
RE	Renewable Energy Resources
PV	Solar Photo-voltaic
AGC	Automatic Generation Control
TSOs	Transmission System Operators
ISOs	Independent System Operators
EMOs	Energy Market Operators
ASEAN	Association of South-East Asian Nations
DSO	Distribution System Operator
ToU	Time of Use
M2M	Market-to-Market Coordination
RTO	Regional Transmission Operator
FTR	Financial Transmission Rights
ASTI	Admissible Set of Tie-line Injections
PVE	Progressive Vertex Enumeration Algorithm
KKT	Karush-Kuhn Tucker
T&D	Transmission and Distribution
TN	Transmission Network
FIDVR	Fault-Induced Voltage Recovery
GEP-UC	Generation Expansion Planning – Unit Commitment
vRES	Variable Renewable Energy Resources
ESS	Energy Storage System
UC	Unit - Commitment
ASI	Apparent Stability Index
PoI	Probability of Instability
IP	Interior-Point

PSOs	Particle Swarm Optimization
PXs	Power Exchanges
RTM	Real-Time Market
DAM	Day-Ahead Market
PoP	Percentage of Penetration
MDTL	Minimum Day-Time Load
MPP	Maximum Power Point
HA	Hourly Ahead
MW	Mega-Watt
FERC	Federal Energy Regulatory Commission

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Chapter1: Introduction

1.1 Background

The global energy transition with the rapid growth of renewable energy (RE) is creating a place in the market and communities, especially solar PV, wind, and hydro. Since renewable energy has been considered economical and environment friendly. Also, consumers and retailers are very keen to purchase electricity at a reasonable price in power system markets with a high share of renewable energy resources. Therefore, government policies, incentives, and advances in power conditioning devices are allowing investors and customers to promote renewable energy resources [1]. Besides these, conventional thermal power generators are having bigger disadvantages in terms of energy price and environment. In the current scenario, coal-fired power plants are the biggest producer of greenhouse gases and radiation in comparison to other conventional plants [2]. Therefore, the energy transition impact could be seen in the power (electricity) sectors more. Henceforth, the REs is playing a vital role in the economy and social welfare of the society. Besides, the major advantages of renewable energy consumption, some challenges need to be assessed such as intermittency in renewable energy productions, voltage stability, overgeneration, rotating inertia, and synchronization. To resolve these issues in the early stages, various forecasting techniques have been developing continuously [3]– [5]. Yet, the higher integration of intermittent generators into the power system may introduce system voltage surges, which may cause damage to the rotating machine connected to the system [6], [7]. It has been observed that the higher penetration of renewable generations may cause over-generation during mid-day. In this case, the system operators need to throttle the variable generators' output during such scenario to ensure the system's security. As a result, it will increase the electricity cost for consumers and reduces the utilization of available low-cost energies [8]. It is notable that renewable power generations are highly intermittent and depend on the weather conditions (i.e. solar PV, and wind energy resources). Therefore, the interconnection of power networks can be considered an alternative solution to utilize available low-cost energy. In addition, these interconnections may also be utilized by the system operators to cater to the energy demands from neighboring networks during the insufficiency of RE power. Far off, different time zones would lead to different load profiles in the interconnected power networks, which could provide demand resiliency [9], [10]. Besides these challenges, the advanced inverters/converters are the centerpieces to incorporate a higher share of variable power generation sources into the electricity system. Modern advance inverters/converters can prevent over-voltages in the system due to higher injection of variable generation sources [11], [12].

The power system operators keep the supply and demand in equilibrium for reliable operations. The equilibrium condition is formed where the supply curve and demand curve intersect each other over the price-quantity plot. The price at the intersection point of the supply and demand curve is known as the equilibrium price [13]. There are mainly three processes to achieve the normal operation: i) Automatic generation control (AGC), (ii) Load following, and (iii) Optimal or economic dispatch. Since the economic dispatch method is less expensive as well as a kind of load following in different time frames i.e. term ahead (at least 48 hours prior), a day-ahead market, half-hour, 15-min, or 5-min markets. Therefore, the economic dispatch operation has been used in the proposed work to obtain the test results. In economic dispatch operation to achieve the power system equilibrium, the objective function (total system costs) must be minimized using optimal power flow techniques (OPF) [14]– [16].

Modern power systems are comprised of financial tools to settle market obligations or contracts. The fundamental tool for the wholesale electricity market is the locational marginal prices. Locational marginal pricings (commonly called LMP) define the cost of energy, congestion, and losses cost at a node in higher voltage transmission systems [17]. In modern power system analysis, the locational marginal pricing (LMP) at the nodes also shows the congestion level in the system. In optimal bidding of electricity in the wholesale market, the least marginal cost generator would dispatch the most power to fulfill the demands. Henceforth, the transmission lines may possess some constraints that lead to the different values of LMPs at the nodes of the network in fulfilling demands. Thus, the LMPs at nodes indicate the price signal for a change in a unit of power. In the modern electricity market, the LMPs is serving as a suitable signal for operators in the market clearing mechanism. The wide use and higher accuracy of LMPs encourage the establishment of new transmission facilities for the most economical delivery of electricity, catalyzing grid upgradations [14], [18]. Further, A fixed amount of power produced with REs is guaranteed by tradable green certificates (TGCs). A system of TGCs' primary goal is to encourage the uptake of green electricity in the electrical market. The producers of power create green certifications. For every predetermined unit of electricity generated from renewable energy sources and added to the grid, producers are issued a certificate. Targets for the sale or consumption of power from renewable sources are given to electricity consumers. These consumers must deliver certificates at a specific time to demonstrate that they met their goals. If they are unable to fulfill their obligations, penalties are established. As a result, consumers are motivated to purchase certificates from producers, and the certificates increase in value. A decrease in the cost of power from renewable sources is expected as a result of producer competition and an increase in the supply of green certificates [19].

In energy or power exchanges, a market-clearing price is the bidding price at which the total demand of buyers satisfies the total costs of sellers in advance of the time albeit physical delivery of energy [20]. This is usually through the day-ahead market (DAM). This market-clearing price is also known as the equilibrium price. The scheduling and prices are declared using market optimization engines, and this price quantity is settled irrespective of the actual performance of market participants. Generally, generators submit one of these three bid prices due to non-convexity: (1) incremental energy, (2) no-load cost – cost at its minimum generation level, and (3) startup cost (to synchronize with the grid). The least-cost set of generators would be selected based on the above three parts of bids to deliver the electricity obeying all the generators and physical constraints of the network [21].

The developments in the power sector happening rapidly. In the series of development, the share of renewable power resources increasing with different supportive environmental and financial schemes over the years (see Figure 1.1); and ISOs/RTOs are establishing inter-regional (cross-border) high-voltage transmission lines; cross-border interconnections are also known as Market-to-Market coordination (M2M). The inter-regional or cross-border (M2M) would enable a far-reaching window of opportunities i.e. demand flexibility, generator choices, higher access to renewable energy resources in the system, etc. [22], [23]. Moreover, the M2M would provide economic benefits to the market participants [24]. Henceforth, this work has analyzed an overgeneration case study considering M2M in the power system. In this work, a network has been considered highly penetrated by solar PV systems and other network has no renewable resources (for a case study purpose). Afterward, different M2M connection methods have been tested.

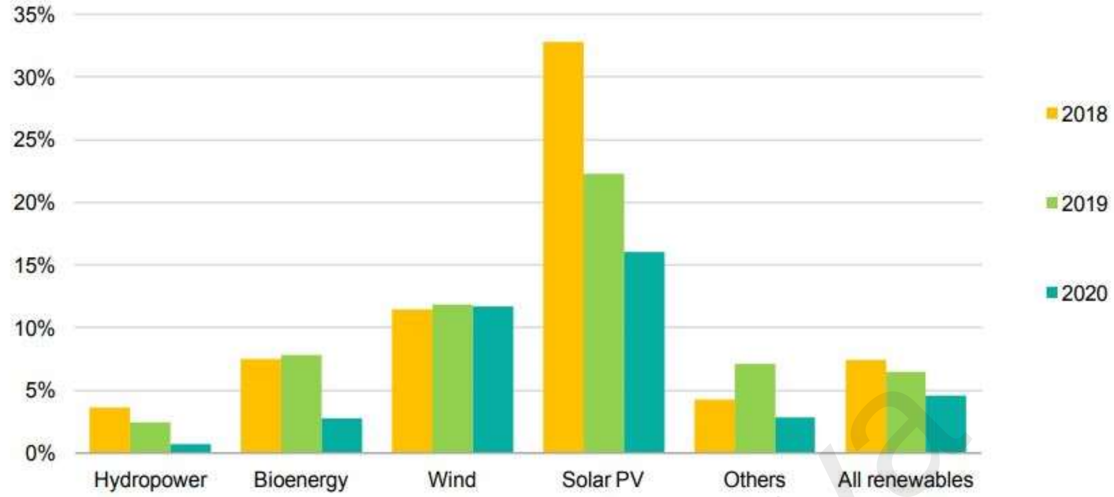


Figure 1.1 Annual growth of renewable power resources, 2018-2020 [25]

1.2 Problem Statement

In this section, the problem statements would be discussed. The first paragraph would discuss the impact of higher penetration of renewable energy resources (REs) into the power networks. In the next paragraph, the impact, and scenarios of overgeneration would be discussed. And the last paragraph of the problem definition will discuss the current market scenarios with higher REs' share and overgeneration scenarios due to REs penetration in the power networks.

The growing energy demand and climate change lead to higher penetration of REs at different scales (small scale to a higher level) into the power systems. Since it is a prominent fact the PV, wind, and other REs resources are highly intermittent in nature. Thus, REs would have impacted over security, reliability, and quality of power supplied in the system. The characteristics of economic dispatch provide higher priority to REs generation units due to the lower marginal cost to meet the supply and demand equilibrium. Further, the residual demands would be fulfilled by conventional generators (i.e. nuclear power plants, coal-powered plants, etc.) which may require running them at their lower limits. Since the generation units with higher marginal costs (conventional generation units i.e. gas plants, coal-powered plants, etc.) must fulfill residual demands and still they would have to operate at their minimum limits. In the event of emergencies, there are standby generators (generally operating in reserve or ancillary market). As a result of the growing power systems scenario, maximum utilizations of available most affordable energy are the major challenge. REs' intermittent nature and availability for certain hours of the day, drive the bidders to bid for conventional generators. Further, to cope with the climate change policy-making and regulating authority implying carbon taxes over generator units in the current electricity & energy market. Therefore, it is also a challenging task to reduce the carbon taxes for the producers, hence the overall revenue will also increase along with a reduction in emissions.

As discussed in the previous paragraph, the overgeneration scenarios due to higher penetration of REs in a power network may raise concerns for Transmission System Operators (TSOs). The overgeneration scenarios have already been arising in the Australian Power Grids [8]. Since western Australia is propertied in REs and the investors have established higher levels of Solar PV and Wind plants. The overgeneration scenarios will increase the voltage of the system and it may rise beyond acceptable boundaries. Hence, the TSO would ask for throttling the REs output. This forceful throttling would increase the electricity prices for consumers. Though, security and safety issues are the major concerns for the Energy Market Operators (EMOs).

Conclusively, an inter-connected market would be analyzed using economic dispatch to find the solutions.

1.3 Objective

The aim of this work is to develop a power system market clearing mechanism using LMPs during overgeneration scenarios due to excessive PV outputs in interconnected networks. The specific objectives of this study are as follows:

- To identify the interconnection nodes of networks in the highly renewable energy penetrated M2M to obtain the minimum market clearing prices (MCPs).
- To minimize the FTRs of interconnected tie-lines of M2M; so the FTR owners or RTOs needs to pay minimum. Henceforth, the tie-line congestion would be minimum too.
- To maximize the revenue of generators in the highly renewable energy penetrated M2M, henceforth the conventional/thermal generators could recover the investments in a long-term market.
- To reduce the carbon emissions and save the taxes (2% with respect to other alternative topologies) against the carbon emissions.

This work will address the mid-day overgeneration issue due to 120% PV penetration of the minimum day-time load on the load bus in the inter-connected markets to minimize the generation cost, FTRs, and MCPs; and maximize the use of renewable energy, generators' revenue, and tax savings against the carbon emissions.

1.4 Research Methodology

The objectives of this work have been achieved using the research methodology (see Figure 3.1) based on the literature review of this topic.

Firstly a literature review has been done for the power systems flexibility and operations, then the power system market and regulations have been done. It has been reviewed that the effect of flexibility parameters and variables over the markets and regulations of the systems. After that, mathematical formulations have been obtained for the economic dispatch optimization of power flow. Then, a mathematical equation for the normal operation (non-M2M) and overgeneration situations during higher PV penetration of PV (M2M) have been obtained. Also, a mathematical equation has been expressed to calculate the carbon emission savings. The LMPs have been obtained using optimization technique in an economic dispatch, using the differences of two nodes LMPs, FTR of the transmission line in between the nodes has been calculated.

1.5 Research Scope and Questions

To identify the scope and answers to research questions, it is important to evaluate the effectiveness of the system under higher penetrations of renewable energy resources (especially PV systems). Moreover, the M2M model has been designed for a novel challenge in modern power systems. The M2M electricity exchange is gaining ground world widely. European countries have the most advanced international electricity exchange systems. Although, it is a major challenge to incorporate higher renewable penetrations and exchange systems for the ISOs/RTOs.

The first question is to elaborate on the main concept: inclination toward the work. And this sparks the first question.

What is the necessity of inter-regional or Market-to-Market Coordination (M2M) in power systems?

The active growth in the energy demand globally and the global warming challenge have enforced the use of renewable energy resources. Now, the policies and government programs have commissioned the private players in the energy market. As a result, some ISOs are planning to go full renewable-powered infrastructure soon. The power systems possess some major challenges with higher renewable penetrations i.e. voltage surge, need for rotational inertia to control the systems' frequency, etc. Notwithstanding these challenges, advanced technologies are backing stable and resilient systems. Nevertheless, the excess power generation only leads to a throttle in the output of clean and affordable energy during their peak. Therefore, the M2M electricity exchange is necessary for future markets. It would also lessen the cyber threat on the grid as most of the grid is interconnected.

Would the Locational Marginal Pricing (LMP) method be suitable to analyze the M2M during overgeneration in a market?

Since the LMP is the marginal price at the location of energy delivery or withdrawal based on the forecasted systems conditions and the latest approved security-constrained economic dispatch solutions. The LMP addresses the congestion, loss, and energy costs as a sum, therefore the spot markets use LMP as price indicators to charge consumers. The full marginal costs for delivering incremental energy demand drive LMP as a key operational instrument in contemporary power systems markets. Therefore, the LMP method would be highly satisfactory to analyze the M2M during overgeneration scenarios in a market and it would also illustrate the future electricity markets (long-term).

How will the performance of M2M during overgeneration be defined?

The performances of power systems are defined by reliability, resiliency, and voltage stability (should be within an acceptable range). Nowadays, social welfares are a superlative priority for the power systems market operators. Therefore, the lowest LMP in the system, lower FTRs, and fewer carbon emissions would define an optimal method for M2M interconnections.

What would be the impacts of this model on modern power systems?

This model would provide long-term M2M establishments along with lower LMPs, FTRs, and low carbon emissions in the power systems. The M2M interconnections would enhance more opportunities for consumers/retailers to opt for affordable generators in the systems. The private players with higher investments in renewable energies will have better business opportunities in the cutting-edge competitive energy markets. Moreover, this M2M model would reduce greenhouse gases by interconnecting large-scale clean energy resources.

1.6 Key Contributions

This work focuses to provide low-cost electricity, identify the mechanism to assure long-term operations of generators, and hedging the funds for the transmission owners. Therefore, the key contributions are as below:

- This proposed a network topology for M2M operations considering the PJM's new interconnection guidelines, and FERC order no. 1000 and order no. 2222 incorporating a higher share of PV units in the market.
- The identified network topology provides the low LMPs in the M2M system, which motivates the consumers to participate in the interconnected market. Irrespective of the generator's location, consumers can receive low-cost electricity.
- The FTRs values have been calculated and have also been compared with the other interconnection topologies. The results show that the FTRs owners will get paid for M2M operations by the recipient RTO (beneficiary).
- It has also analyzed the carbon emission to increase the revenue of the system using carbon emissions pricing and trading in inter-regional connected RTOs.

1.7 Thesis Outline

This thesis has been drafted with five chapters. These five chapters discuss the introduction of the proposed work (i.e. the high share of PV units, increasing energy demand, the future market of electricity and energy, etc.) followed by the literature review of this work. Next, the research methodology has been explained with mathematical formulations. The formulated mathematical explanations have been implemented into MATLAB to test the proposed algorithms to achieve the objectives. And finally, this work has been concluded and stated future work to be performed in the extension of this work.

The literature review has been discussed and reviewed in chapter 2. The second section of the chapter explained the currently ongoing research to maximize the resiliency and reliability of power systems. In a further section, the market and regulations have been discussed followed by the market's financial instruments and types of markets. A brief explanation of carbon trading and carbon taxes also has been done.

Chapter 3 discussed and represented the research methodology (tools and data types) and the mathematical formulations. This section also described the interior point (IP) based on the Karush-Kuhn Tucker conditions optimization technique. The algorithm of the IP technique is also explained.

Chapter 4 discussed the model implementations to test the proposed algorithm in the M2M power system networks. Further, it has also discussed the test results of the illustrative examples. The results and discussions have been represented in tabular and graphical forms.

Finally, chapter 5 discussed the conclusion of the obtained results to validate the proposed algorithm and stated future works to be done in this field.

Chapter2: Literature Review

2.1 Introduction

In this chapter, the literature review of the proposed has been done. This chapter has been divided into several sections which helped to understand the topic in more depth. The second section discusses the flexibility and operations in the current power system markets. It has elaborated on the impacts of inter-temporal parameters on flexibility, and also explained the current findings to improve the flexibility and reliability of the systems concerning generators' inter-temporal parameters. Following the role of inter-temporal parameters, the role of inter-regional markets to ensure flexibility and operations has been discussed in the recent ongoing research. Further, the voltage stability has been discussed and the recent technologies that help the market operators to maintain the voltage magnitudes within the acceptable range. Since the current and future markets are much dependent on the automation and fast communication of information, therefore the role of digitalization also has been explained in the last sub-section of the second section.

Now, in the third section, the power system markets, and regulations have been discussed along with the recent developments. The first sub-section discusses investments in technology and renewable energy resources. After that, the market prices and their clearing have been studied, it also discussed the convergence biddings (CBs) which help to close the DAM and RTM electricity prices in the market. In the next sub-section, the effects of transmission lines on costs have been studied.

In further sections, financial instruments such as LMPs and FTRs have been discussed. Following the financial instruments, types of the electricity market and its structure have been discussed i.e. short-term tasks, long-term tasks, and risk management tasks.

After this, the sixth section discusses the carbon market and the taxes related to it. The seventh section studied the current and ongoing projects in M2M or cross-border electricity trading. And the final section summarized this chapter.

2.2 Power System Flexibility and Operations

The power systems flexibility is defined as the ability of a system to adapt to dynamic and varying conditions, e.g. balancing supply-demand within the different timeframe of electricity trade, and developing generation and transmission infrastructure over a period of years (see Figure *2.1*). The foremost challenges to be assessed near term include incorporating rapid integration of variable generations (VGs), energy price variations and uncertainty, modifications to growing system standards and policies, and adoption of new highly efficient technologies by consumers [26]. VGs i.e. PV and wind can produce low marginal cost energy due to subsidies and the absence of energy costs. Subsequently, thermal power plants would dispatch less power or not at all, lowering their revenues. These two effects in the power system market may hinder the economic sustainability of thermal units and may prompt the owners to shut down the units [27]. Several studies of the current market scenario have identified a challenge that it may convey inadequate capacity under the present power system market, as a consequence of thermal units' closures and lack of investments in new capacities [28], [29].

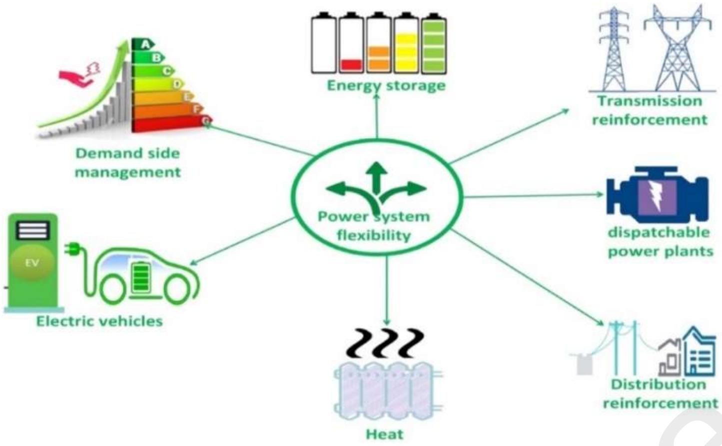


Figure 2.1 Pictorial Presentation of Power System Flexibility's sources [30]

2.2.1 Flexibility and Inter-temporal constraints

Now, the grid expansion in perspective of generation units and their effects on energy price is also a challenge for the power system market players. The modern grids need flexibility with optimal energy prices. Therefore, considering the generation expansion as well as the energy price has been studied in several articles. Real-time flexibility requires fast computation with fast communication of information; also with intermittent generation units in the system, operators need flexible supply by the energy storage system (ESS) and other unit-commitment (UC) constraints (e.g. minimum up/down times, startup, shutdown trajectories, and network constraints) [31]. As the considerations of flexibility in the future/upcoming structures of power systems during the planning phase may result to cope N1-contingencies and financial losses [32], [33]. Further, a study observed that the system factor i.e. operational cost budget, ramping capacity, and transmission line capacity can affect flexibility. Authors in [34], have reformulated and decomposed the flexibility measurement into different indicators i.e. total flexibility (TF), Economic dispatch flexibility (EDF), AGC flexibility (AGCF), Economic dispatch upward flexibility (EDUPF), Economic dispatch downward flexibility (EDDNF), AGC upward flexibility (AGCUPF), and AGC downward flexibility (AGCDNF). The test results have shown that the operational cost budget affected all indicators except EDDNF, and improved ramping capability enhanced the EDF and AGCF. The transmission capacity only contributed to the EDF in the reformulated flexibility indicators.

In the paper [35], the authors used a geometric Brownian motion to evaluate the ramping capability, so can coupe short-time prices in intra-day and day-ahead markets and quantify the net revenues generated by the resilient generators. This method has shown that the revenues have increased (though profits have decreased) in day-ahead and intraday markets. The inelastic prices at the demand level and intermittent resources push systems to replan the supply, tie-line flows, and throttling of RE outputs in extreme cases. Thus, in short-term markets (i.e. intraday and day-ahead markets) policies should be flexible towards the generators' dispatch, tie-line capacity and their allocation, and maximum utilization of RE outputs. Authors in paper [36] suggested frameworks for resilience management that benefit the electric utilities as (1) creating a baseline for resilience management level under extreme weather conditions, (2) increasing awareness and understanding of resilience management practices to fill key gaps, (3) communication between utility and stakeholders, (4) and prioritizing the investment for resilience management and identifying the implementable projects, etc. Further, the loading shedding problem has been solved using failure probabilities of transmission lines in extreme weather conditions. Transmission lines are considered to fail above the failure probabilities threshold, also this method to increase the resiliency of generators helps to minimize economic losses [37]. Further to increase the awareness and economy of the system an integrated online dynamic security assessment system (DSAS) has been developed that intake real-time energy management system (EMS) data combining both bus/branch and node/breaker systems. These data have been used to perform dynamic contingency analysis and calculate real-time power transfer limits covering different geographical areas [38].

2.2.2 Flexibility and Operations in Inter-regional Markets

Since researchers, policymakers, and market operators are continuously modeling and establishing intra-regional and inter-regional markets to enable a future energy market in the interest of mankind and nature. The decrease in the cost of long transmission lines technologies is driving the intercontinental interconnectivity of power grids. The growing economies and power demand of Asian countries impelled inter-regional power trades by establishing sub-sea HVDC lines [10]. Further in prospects of the resiliency of the inter-regional power grid, a study in [39] shows that net zero carbon is not achievable. Therefore, the authors suggested mixed generators (efficient and flexible) in the system, so that the system would be flexible. The authors also suggested hydroelectric generators with solar PV as a summer peak while wind generation as a winter peak for a tie-line power trade, which allows higher penetration of renewable resources. Further, an admissible set of tie-line injections (ASTI) model based on projection theory has been established and implemented to reschedule the tie-line to enforce the intra-regional constraints [40]. In this method, the authors have decoupled the operation of intra-regional and inter-regional systems; henceforth the computational time for the intra-regional system has been reduced. Thus, decoupling the operations of intra-regional and inter-regional systems would lead to more flexibility by reducing the computational time of the systems. In addition to inter-regional market formulation, the selection of nodes is also a challenging task for market operators. Since the characteristics of nodes could change the economy and resiliency of the system, therefore finding the right nodes and optimizing the power flow would enhance the economy as well as the resiliency of the system. A work based on node identification/boundary identification in an inter-regional interconnected system has been proposed in [41]. The work has also studied the existing methods on the tie-line transmission region i.e. maximum transfer capacity, proportionate transmission line limits, multi-parametric programming, and Fourier-Motzkin Elimination. Further, this work modified the multi-parametric programming to perform a fast boundary search using Karush-Kuhn-Tucker (KKT) condition (which avoided the sub-regions).

2.2.3 Voltage Stability

Further to provide the voltage stability, the major challenges are optimum selection and trade-off of various control architectures (including T&D network operators), acceptable parameters setting of controllers, reactive power management, and economical coordination of DERs. Authors in paper [42] proposed control methods to integrate PV/wind power generation units, and fault-induced voltage recovery (FIDVR) and analyzes the measurement-based Thevenin equivalent for voltage stability. In recent developments of digitalization, authors in [43] found that voltage stability margin instead traditional voltage magnitude as a control objective helps the end-user to stabilize the system. A machine learning-based voltage stability test has been executed using an ensemble of machine learning models. It has been observed that the ensemble of machine learning regressions that use different features of inputs, provides higher accuracy of voltage stability [44]. Thus, the increasing intermittency and contingency in the power systems need to mitigate the voltage violations. A volt-VAR (VV) functions inverter has been introduced with a current-controlled inverter, which triggers the sustained oscillation in voltage waveforms [45]. Hence the advanced developments to stabilize the voltage through loadability margin, machine learning methods, or inverters lead to the integration of a higher share of intermittent power resources in the power systems.

2.2.4 Flexibility and Digitalization

Since power system security is one of the major challenges in the growing age of intermittent resources and high-frequency electronic devices. The power system security can be defined as the ability of the system to operate and persist stability under any reasonable convincing contingency i.e. outages of generators, transmission lines, transformers, etc. or undesirable system variations, without breaching any operational constraints (such as short circuit, sharp increment in load, bus voltage violations, etc.) [46]. In the digital era of humankind, the power system network needs to be assured with cyber securities along with physical securities of the infrastructures. Figure 2.2 shows the digital architecture of modern power systems, where each asset has been linked with the digital networks (see Figure 2.2). Many approaches and grid standards have been adopted by the ISOs and TSOs to secure the network from cyberattacks and physical losses i.e. ISO: 27001, blockchain technology, zonal management, etc. Further, in an extreme disaster situation, authors in [47] have proposed a zonal method and active power management in branches to cope with the high risk of any disaster. Now to secure the network information system ISOs and TSOs are adopting the supporting platforms for the security test and evaluation of the information system. Digital signature-based identity authentication algorithms have been developed to verify the authenticity of the system user identities. Role-based access control models have been designed based on program manager information (PMI) and according to the characteristics of the power system market [48]. Thus, with the innovation in digital technologies and continuous modification in grid standards to protect the power system from high-risk natural disasters to cyber-attack, power system market players are highly interested in participating in it as well as supporting the green technology to lower emissions.

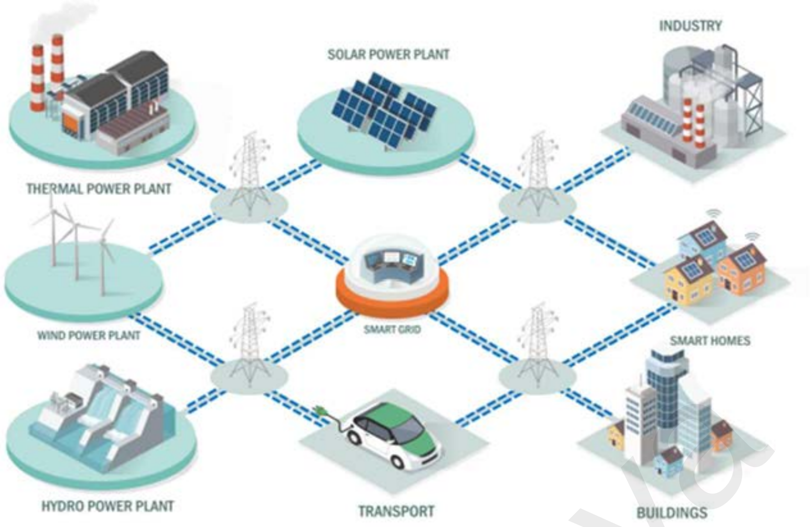


Figure 2.2 Digital Structure of Modern Power Systems [49]

2.3 Power System Markets and Regulations

In a very general way, a power system market can be defined as a system where electricity is capable of being bought, sold, or traded. The electricity markets are being operated from the power exchange system which enables electricity purchases, through bids to buy; sales, through an offer to sell. Now, the electricity market consists of different operators – known as Independent System Operators (ISOs) or Regional Transmission Operators (RTOs). These regions may have different rules, although there are notable mutual principles of market designs and their purposes in the current power market. The market design considers a pool-based market in which there are settlements for future (forward), day-ahead, and real-time/balancing markets, with co-optimization of energy and ancillary services, locational marginal prices (LMP), and financial transmission rights (FTR) markets. The ancillary services are used as a support system when energy markets are unable to provide the required operations [21]. FTRs are cleared in the forward market and are financial instruments to hedge against the differenced locational marginal prices. The power system markets include auctions conducted by market operators to buy or sell the services at various prices. Further to incorporate future growth, and technology and maintain the reliability of power systems the rules of markets always are evolving. Now the variability and uncertainty are not the major challenges for the market operators; since the newer tools have been introduced into the power system market such as advanced scheduling models, balancing authority area cooperation, intelligent operating reserves, operational variable generators' (VGs) forecasting, and new ancillary markets. Besides these newly adopted tools to ensure the reliability and efficiency of markets, the major challenge for power systems markets is to redesign the market so that VGs' efficient use and additional investment could be incentivized [25]– [28].

2.3.1 Investments

Now, authors in [54] have studied a coordinated investment between generation and transmission lines. Since the commercial investments in the transmission capacity of existing power system markets are risky; therefore commercial organizations specializing in power transmission recover their investments by charging on congestions and/or excess power injection charges. The social surplus (sum of the producer surplus and consumer surplus) is the measure of the aggregate benefit of an electricity project, and it could be verified if the overall design of the project fulfills the objective of the wholesale market to maximize the surplus along with efficiency, and consistency. RTO consultations with stakeholders and regulatory agencies can provide more information when evaluating the impact of different projects design- Efficiency or retailer preferred capacity size etc. and the energy prices and distributed welfare effects among the participants in the energy market [54], [55]. The following graphical figure 2.3 (see Figure 2.3) shows the net investment in different energy commodities over the 2019 and 2020 along with the estimated investment in 2021. Further, total investment from 2011 to 2020 and estimated investment in 2021 have been depicted in figure 2.4 (see Figure 2.4).

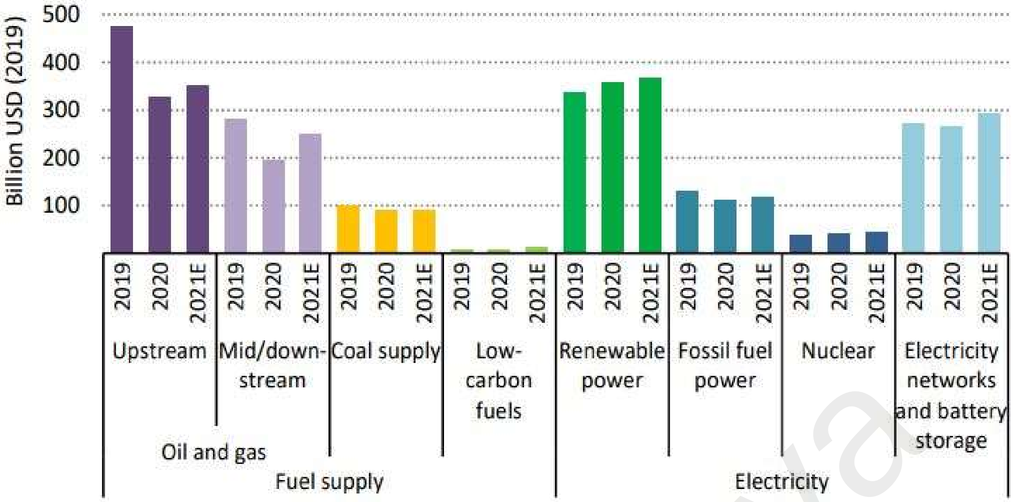


Figure 2.3 Sector-wise Global Energy Supply Investment [56]

Figure 2.4 World-wide Investment in electricity Sector by Technology (2011-2021E) [56]

* EMDE – Emerging Market and Developing Economies

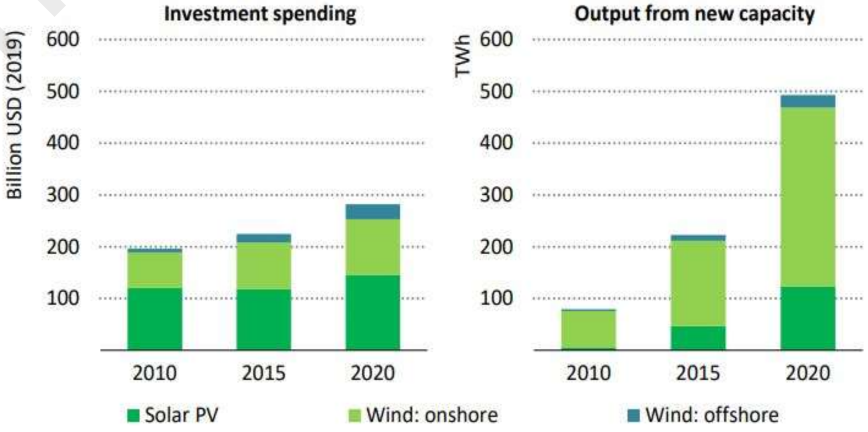


Figure 2.5 Solar PV and Wind Investment and expected generation output (2010-2020) [56]

The above figure shows the total expenditure on solar PV and wind energy technologies in the last decade over the years (2010-2020) along with the output of the newly established capacities (see Figure 2.5). Conclusively, the higher investments in energy commodities whether they are oil & gas or renewable energy resources, have led to producing higher output and contributing significantly to fulfilling the energy demand.

2.3.2 Market Prices and Market Clearing

Now, three steps have been used to settle scheduling decisions in an interconnected power system to imitate the existence of multiple framework operators. Three steps are: (i) exchange forecast data, (ii) decompose unit commitments by generators and (iii) power flow settlements. Authors have observed that the expensive generators can be avoided, average price variances are higher, and higher price-flow divergence in a multi-regional power system using the three steps scheduling decisions [57]. Although, in the development of interregional electricity markets, the operators have major coordination challenges. The imperfect market design and weaker transmission infrastructure are causing trade barriers [58]. Further, authors in [59] have proposed a mixed integer quadratic programming model which computes the profitability of transmission expansion in an inter-regional market. It also identifies the optimum node for renewable energy injections.

Furthermore, an algorithm has been designed to incorporate control reserves into day-ahead markets (DAM), so that the liquidity and stability of ancillary service markets could be improved. Authors in [60] also compared the joint control reserve and separated auctions of energy and reserves. The proposed algorithm by the authors allows to order of joint energy reserves and is guaranteed to allocate with maximum bid surplus considering offered prices to the bidders. The proposed algorithm also helped in handling the non-convex order types to reduce the complexities of self-scheduling for generators. The resulting optimization problems fall into the category of convex MIQP [61]. This can be understood reliably and efficiently using traditional solver schedules that are easily accessible, and for this reason, no specific heuristic or soft computing techniques are needed. Now to minimize the price gaps in a DAM and real-time market (RTM), a sensitivity analysis primarily based totally on a closed-form model has been taken into consideration to explain how the prices of DAM and RTM are affected by convergence biddings (CBs); additionally analyzed further what topological and grid operational situations CBs bring about price divergence [62]. The proposed model has ensured that the profitable CBs close the price gap of the DAM and RTM with congested transmission lines or no congested lines in the system. Thus the power system optimization includes a bi-level optimization, where the upper level maximizes the profit for convergence bidders and the lower level is about the economic dispatch. Coordinated strategic bidding between physical and convergence bids has been adopted for the market participants who submit CBs along with physical assets. The CBs in this coordinated bidding would also be used as leverage by generators to increase the revenue [63]. Furthermore, A new strategy has been planned to convert balancing energy bids submitted as part of the European Central Dispatch System's Integrated Scheduling Process (ISP) (DAM and Intra-day market scheduling) into Replacement Reserve (RR) standards product. The proposed approach includes four advances: (a) local RR capacity maximization process, (b) local mandatory activation process, (c) purely economic local RR clearing, and (d) local conversion process [64], [65].

2.3.3 Effects of Transmission Lines in Markets

Since the transmission lines' parameters also affect the market prices, therefore in paper [66] proposed a structure to evaluate the loss factors by way of analyzing the constant, linear, and piece-wise linear models. Authors introduce a framework for assessing how the inclusion of AC and HVDC transmission line losses in market clearing (nodal pricing and zonal pricing) affects market outcomes; various formulations of loss factors (HVDC conversion and resistance loss, HVAC transmission lines and transformers), and their effects are investigated while maintaining the linear formulation of the market clearing algorithm. The introduction of HVDC loss factors is positive, but it can lead to reduced social welfare. For zonal markets price, this can also occur at all interconnects (inter-regional or intra-regional) due to intra-zonal losses. Further, the system flexibility has been improved by considering distributed energy resources (DER) services procurement through sequential procurement, double-sided auctions, and tailored mechanism. The proposed market clearing mechanisms have been validated with two case studies: (i) short-term operating reserve deployment during DSO congestion services, and (ii) peak load threat case [41]– [44].

2.4 Financial Instruments in the Power Systems Market

In the modern power systems market, financial instruments are playing crucial roles to uplift the infrastructures as well as businesses. The admittance of private players into the market will increase the competition and each business will demand higher profits. There are many financial instruments to settle the transactions among the market participants such as LMPs, FTRs, ARRs, etc. In this work, only LMPs and FTRs have been analyzed for the market clearing mechanism and long-term market growth.

2.4.1 Locational Marginal Pricings

The inter-regional or market-to-market coordination (M2M) needs to analyze the financial factors along with the technical factors. Most of the ISOs are using LMP as their price indicators as well as congestion management indicator. The LMP at a node is price changes due to one unit change of energy at that node. The LMP consists of three components, (i) Energy components, (ii) Loss components, and (iii) Congestion components. The lower the values of LMP indicate less congestion in the system [71], [72]. Further, the consumers would need to pay equal to or more than the value at a node for the energy, it depends on the auctions. Now, in a highly uncertain power generation and load scenario, the authors in [73] propose a power market clearing algorithm based on LMPs. The LMP (ULMP) comprised in the uncertainty has been decomposed into components like the current LMP formulation, reflecting price signals related to variable power generation and load forecast uncertainty levels. This paper also proposed a distributionally strong chance-constrained optimal power flow model (DRCCOPF) that can control the robustness of chance-constrained (CC) in the prediction error for the trade-off between financial problems and network security.

2.4.2 Financial Transmission Rights (FTRs)

Financial transmission rights (FTRs) also have an important role to operate and expand the power systems market. Simply, FTRs are the values paid or received for using any transmission line in the system. The value of FTRs is the difference between the LMPs at two nodes of the transmission line. The FTRs would be paid to the owner by RTO if the FTR value is positive else it would be paid to RTO by the FTR owner which offsets congestion. FTRs and the associated congestion revenues are directly provided to load in a credit to the fact that, because of LMP, load pays more for low-cost generation than is paid to low-cost generation [74]. Under LMP, load pays, and generation is paid locational prices which result in load payments in addition to generating revenues.

2.5 Types of electricity Market and Market Structure

The design of an efficient electricity industry can be done by listing and assigning the important tasks to different entities, and then outlining the frameworks, policies, and incentives to perform the important tasks efficiently and effectively, also to coordinate and cooperate with other entities in the execution of their respective tasks. The general structure of an electricity wholesale market has been represented in figure 2.6 (see Figure 2.6). The wholesale electricity markets are consisting of different sub-markets i.e. capacity, DAM, future, and reserve markets. The important tasks have been distinguished between short-term tasks and long-term tasks. Additionally, 'risk management' tasks have also been listed, which bridges the gap between short-term outcomes and long-term incentives [75], [76].

2.5.1 Short-Term Tasks

- Efficient short-run utilization of available generation units,
- Efficient and effective short-term use of available demand-side resources,
- Efficient and optimum short-run use of available transmission network lines,
- Efficient and quick response to very short-term imbalances in supply and demand.

2.5.2 Long-Term Tasks

- Efficient investment in electricity production systems
- Efficient investment in power consumption resources
- Efficient investment in transmission lines

2.5.3 Risk-Management Tasks

- Some sort of assurance to generators to provide average price over a year or more,
- Financial certainty or assurance to traders for physical unavailability in the event of transmission or distribution congestion limits,
- Providing risk-management tools based on the prices for balancing services.

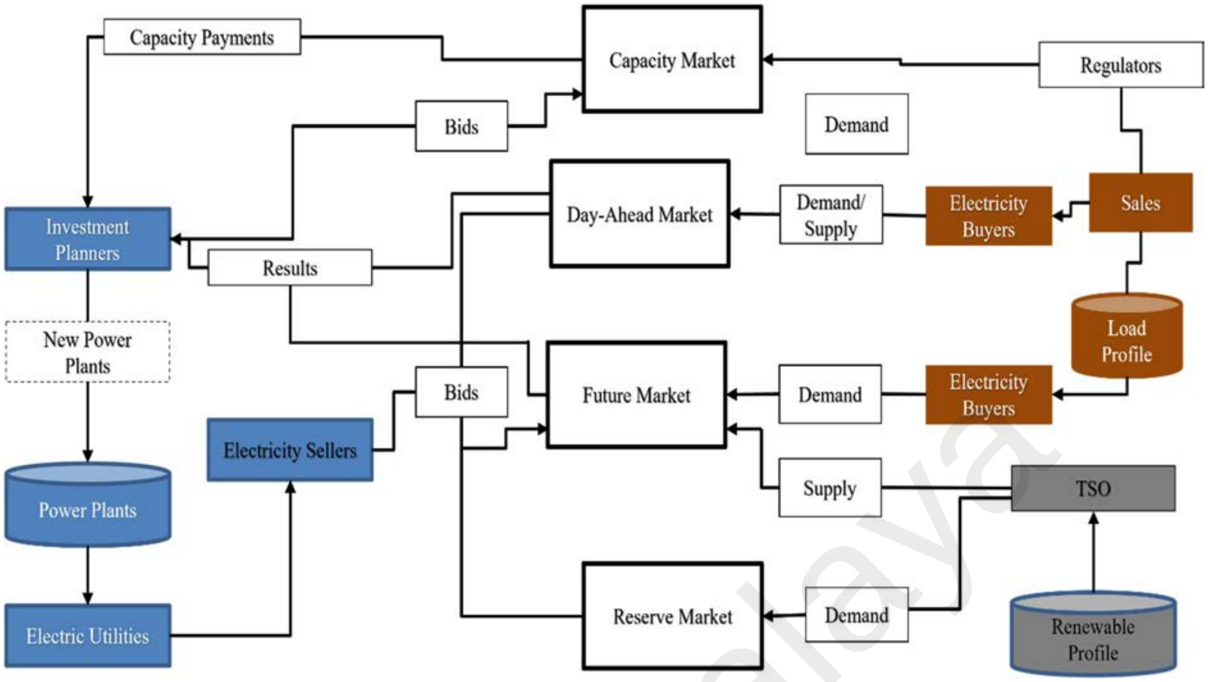


Figure 2.6 Structure of a wholesale electricity market

2.5.4 Types of Markets and Definitions

- ***Capacity Market*** **–** This type of market is used by some wholesale electricity markets to pay for resources available to respond to emergencies.
- ***Day-Ahead Market*** **-** DAM is a physical electricity trading market for delivering any / part / all of a 15-minute time block within 24 hours of the next day from midnight.
- ***Future Market*** – The future market of electricity enables the trading of commodity contracts at a specific price which would be delivered in the future at a specific time/period.
- ***Reserve market*** **–** The reserve market capacities are available when any contingencies occur, such as disconnections of transmission facilities or generator units from the grid.

2.6 Carbon Markets and Taxes

Now, the cutting-edge power systems markets are also including the carbon emissions price and the prices may vary under different circumstances. Carbon trading would bring flexibility that ensures emissions reduction taking the least expenses to do so [77]. The robustness in carbon price promotes investments in green energy and low-carbon technologies. There are two approaches for pricing, one is a carbon tax (price), and another is capacity trade (quantity target) (see Figure 2.7 & Figure 2.8). Although, the prices flow through the wholesale energy market irrespective of policy (tax or quantity). In the capacity trade (cap-and-trade), prices are determined based on the set quantity reduction of the emissions and the stricter capacity will yield higher prices. While in the tax policy, the prices depend on various assumptions including domestic and global benefits and prices of carbon [78]. Moreover, the increasing global warming challenges have administered the carbon emissions pricing on conventional generators. Carbon trading is the agreement for a trade of credits to emit CO_2 among different regions comprised of international agreements aimed at gradually lowering global warming. According to the international energy agency (IEA) report, the average emissions from conventional power generators are 475g CO_2/kWh (0.475ton CO_2/MWh) and have been priced as a tax at \$40/ton including all financial remunerations [79]. In this work, the over-generated power due to PV systems would be the saving in emissions. Therefore, the excess power generating network would receive the cost of emissions that have been precluded in the other network. Henceforth, the FTRs owner will get paid or charged by the RTOs.

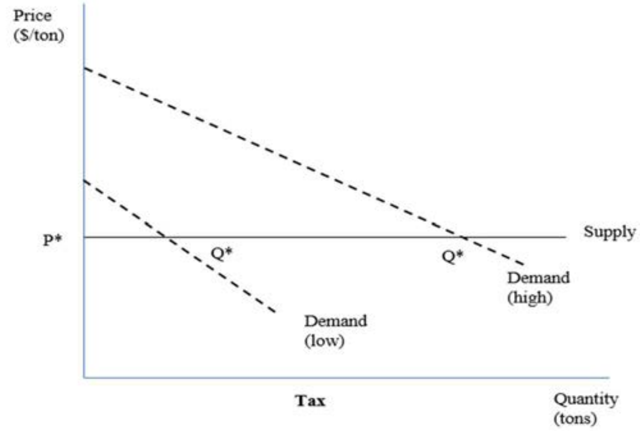


Figure 2.7 Tax-based price vs quantity relation

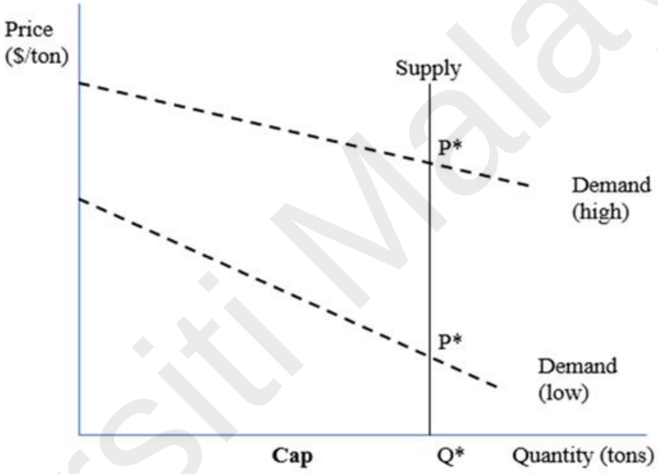


Figure 2.8 Cap-and-Trade based price vs quantity relation

2.7 Current Market Scenarios for Inter-regional Power Exchange

The current inter-regional or trans-power markets are in the development phase. Only European nations (especially Western and Southern Europe) have an exchange of power with different Independent System Operators (ISOs) and TSOs (i.e. Energy Exchanges of different European Nations), and it's only because of their geographical and political associations with each other. Now, there are many inter-regional and trans-power market programs to expand the power transmission network. In southeast Asia, the Association of South-East Nations (ASEAN) has planned to exchange power through ten countries (Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Philippines, Singapore, Thailand, and Vietnam). The major challenge for the power exchanges is to define the pricing system; since most of the ISO, TSO, or Distribution System Operators (DSOs) define the pricing of electricity based on time of use (ToU), critical peak.

2.8 Summary

The flexibility and operations in a power system consist of many factors such as inter-temporal parameters of generators, supply-demand balancing, voltage stability, and fast communication along with fast computations. Researchers and market operators have been continuously developing algorithms to minimize the inter-temporal constraints to enhance the systems' resiliency and reliability. Additionally, with the use of modern technologies inter-regional market clearing i.e. sharing forecasted data, generation scheduling, and financial settlements have been easier. Therefore, the supply-demand equilibrium has been maintained throughout the operations. The voltage stability in the short term is feasible with the help of advanced voltage controlling devices (power electronics devices).

The electricity reformation happening rapidly with higher investment in technology and infrastructures. The open market enables strategic investment and every participant looking forward to making profitable businesses. Therefore, the wholesale market getting competitive and need to resolve the major challenges such as minimizing the price gap between DAM and RTM, local RR capacity maximization, etc. The optimal allocations of transmission lines would also lead to a profitable business in the power system market.

Financial instruments are contracts between parties. In this work, LMPs and FTRs have been considered. LMPs consist of energy prices, loss prices, and congestion prices, further it has been decomposed in terms of active power and reactive power prices. The analysis of LMPs would lead investors and market operators to continue the businesses in the long term. Further, FTRs help to hedge-fund the transmission lines' cost to trade the electricity.

Chapter3: Research Methodology

3.1 Introduction

This chapter explains the research methodology of this to obtain the solutions such as economic dispatch, LMP values, FTRs, Voltage Profile, and carbon emission tax savings. The second section has explained the data types, and tools used in the work to test the M2M models during overgeneration scenarios due to higher PV penetrations. The third section discusses the mathematical formulation of the problem, following it the formulae of LMPs, FTRs and carbon emission savings in terms of prices have been expressed. The last section of this chapter discusses the Interior Point optimization technique based on KKT conditions. Further, to test and validate the proposed algorithm and network topology (see Figure 3.1), this work has illustrated two interconnected models of IEEE bus systems.

3.2 Data Types and Tools

This work is an under-researched topic in power system markets and establishes a cause-and-effect relationship by analysis of case studies. A dedicated power system library MatPower [79]– [81] would be used to study the steady-state operations, planning and analysis, and market-based optimal flow. The MatPower library requires MATLAB to execute the optimizations or power flow analysis. Secondary data would be used in this work to perform optimization and test the case studies. The type of data that has been used is qualitative and quantitative. Further, to analyze the results and statistical computation Microsoft Office Excel also has been used.

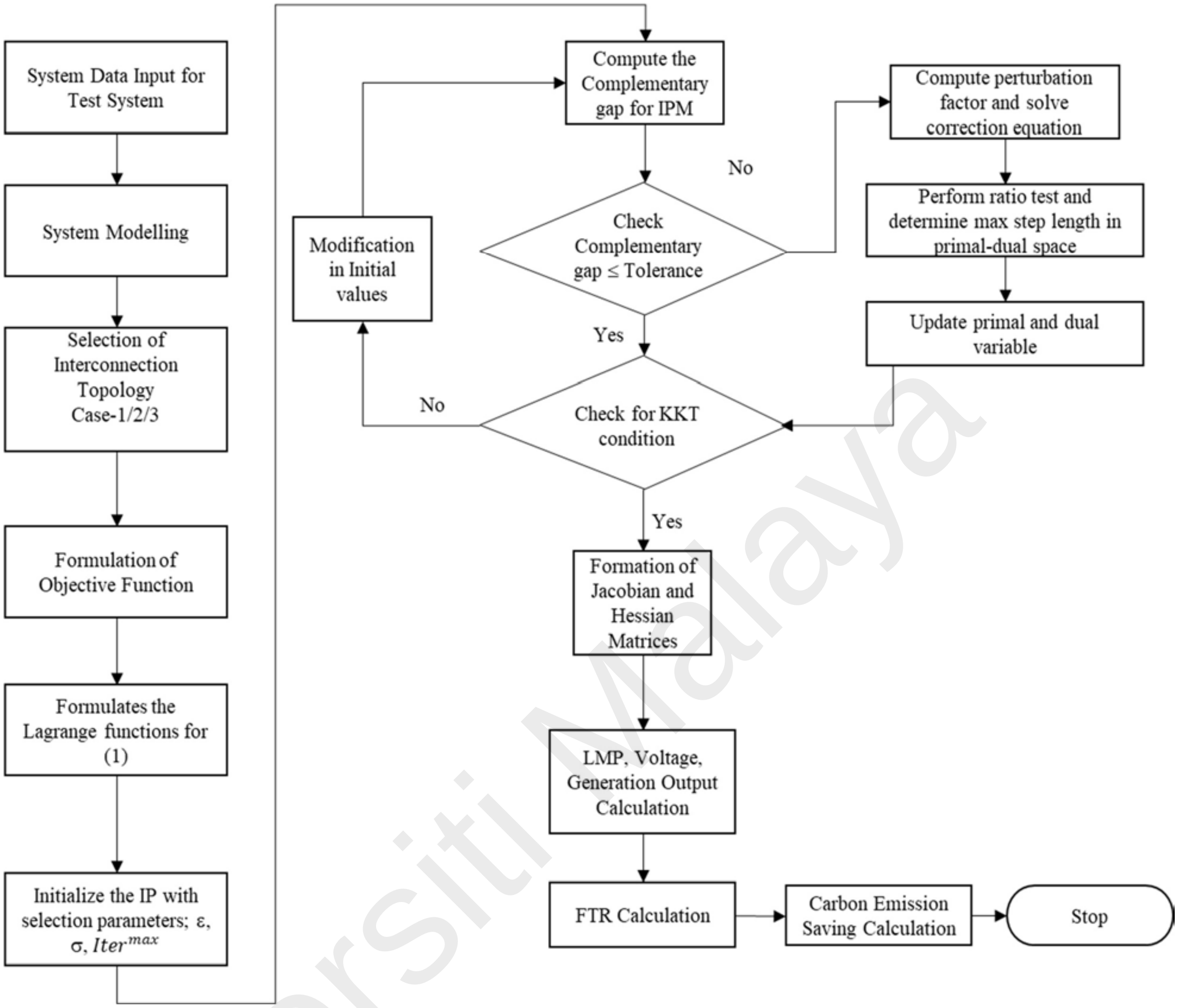


Figure 3.1 Flow Diagram of proposed Algorithm/Method

3.3 Formulation of Objective Function

This work has dealt with the market clearing price in an inter-connected power system (M2M), and the nodal pricing system has been adopted to fulfill the supply and demand. Therefore, economic dispatch would be the first step, and identifying a novel network topology to lower the LMP (nodal pricing) would be the second step in M2M clearing.

Moreover, the inclusion of PV units alters the conventional objective function which incorporates the fixed operating costs of the PV units. Henceforth, the mathematical representation of objective function (equation 3.1(b)) with systems' constraints has been shown below:

Conventional Generators' marginal cost function:

$$min\, f\left(P_{g_i}^{Conv}\right) = \sum_{u=1}^{U}\sum_{i=1}^{N_g}\left\{(C_i+\alpha)\left(P_{g_i}^{Conv}\right)\right\} \tag{3.1(a)}$$

Generators' marginal cost function incorporating PV units:

$$min\, f\left(P_{g_i}^{Conv}, P_{g_i}^{PV}\right) = \sum_{u=1}^{U}\sum_{i=1}^{N_g}\left\{(C_i+\alpha)\left(P_{g_i}^{Conv}\right) + {C_i}^{PV}\left(P_{g_i}^{PV}\right)\right\} \tag{3.2(b)}$$

$$\sum_{u=1}^{U}\left\{\sum_{i=1}^{N_g}\left(P_{g_i}^{Conv} + P_{g_i}^{PV}\right) - \sum_{i=1}^{N_l} P_{d_i} - P_{loss}\right\} = 0 \tag{3.3}$$

$$P_{g_i}^{Conv^{min}} \le P_{g_i}^{Conv} \le P_{g_i}^{Conv^{max}} \tag{3.4}$$

$$Q_{g_i}^{Conv^{min}} \le Q_{g_i}^{Conv} \le Q_{g_i}^{Conv^{max}} \tag{3.5}$$

$$P_{g_i}^{PV} = P_{g_i}^{pv^{MPP}} \tag{3.6}$$

The upper and lower limits of generators, bus voltages, and transmission line capacities are security constraints.

$$V_i = I_i Z_i + V_{ref} \tag{3.7}$$

$$V_i^{min} \le V_i \le V_i^{max} \tag{3.8}$$

$$P_{g_i}^{Conv} + P_{g_i}^{PV} - P_{d_i} = \sum_{k=1}^{N} |v_i||v_k|(\, G_{ik}\cos\theta_{ik} + B_{ik}\sin\theta_{ik}) \tag{3.9}$$

$$Q_{g_i}^{Conv} + Q_{g_i}^{PV} - Q_{d_i} = \sum_{k=1}^{N} |v_i||v_k|(\, G_{ik}\sin\theta_{ik} - B_{ik}\cos\theta_{ik}) \tag{3.10}$$

Case A- If normal condition i.e. a power system case where the total supply meets the total demand in a network.

$\sum_{u=1}^{U}\left\{\sum_{i=1}^{N_g}\left(P_{g_i}^{Conv} + P_{g_i}^{PV}\right) - \sum_{i=1}^{N_l} P_{d_i} - P_{loss}\right\} = 0,$ no Tie-line interconnection and line limits can be represented as

$$S_{ik,t}{}^{U} \le S_{ik}{}^{U^{max}}\ and\ S_{T_l} = 0 \tag{3.11}$$

Case B- In the case of overgeneration *i.e.* a power system scenario where the total supply exceeds the total demand in a network due to higher PV outputs and low demands.

$\sum_{u=1}^{U}\left\{\sum_{i=1}^{N_g}\left(P_{g_i}^{Conv}+P_{g_i}^{PV}\right)-\sum_{i=1}^{N_l}P_{d_i}-P_{loss}\right\}>0$, the Tie-line interconnections included in the formulation and line limits can be revised as

$$S_{ik}{}^{U} \leq S_{ik}{}^{U^{max}};\ i \in g^{PV}, k \in d\ and\ S_{T_l} \leq S_{T_l}{}^{max} \quad 3.12$$

Equation (3.11) is showing the direct interconnection of identified PV units to the identified load buses.

where,

U = Total number of interconnected networks,

N_g = Total number of generators,

N_l = Total number of loads,

N = Total number of buses/nodes,

C_i = Fixed cost of Conventional generators at i bus,

$C_i{}^{PV}$ = Fixed cost of PV units at i bus

α = Cost coefficient of Conventional generators,

$P_{g_i}^{Conv}$ = Active Power of conventional generator at i bus,

$P_{g_i}^{PV}$ = Active Power of PV units at i bus,

P_{d_i} = Active Load Power at i bus,

Q_{d_i} = Reactive Load Power at i bus,

P_{loss} = Active Power Loss,

$P_{g_i}^{Conv^{min}}$, $P_{g_i}^{Conv^{max}}$ = Lower and Upper Active Power limits of conventional generators at i bus,

$Q_{g_i}^{Conv^{min}}$, $Q_{g_i}^{Conv^{max}}$ = Lower and Upper Reactive Power limits of conventional generators at i bus,

$P_{g_i}^{pv^{MPP}}$ = PV output for maximum power point at i bus,

V_i = Voltage at the ith bus,

V_i^{min}, V_i^{max} = Lower and Upper limit of voltage at the ith bus,

G_{ik}, B_{ik} = Transmission line constants between ith-kth buses,

θ_{ik} = Phasor Angle difference between ith-kth buses,

${S_{ik}}^{U^{max}}$ = Total transmission capacity of ith-kth buses between U networks,

${S_{ik,t}}^{U}$ = Transmission flow of ith-kth buses between U networks,

3.4 Locational Marginal Price (LMP) Calculation

Since the necessary condition for the optimality of power flow is that the partial derivative of Lagrange function w.r.t state variables (voltages and angles) should be zero. This condition produces the equation to calculate the locational marginal price (Lagrange multiplier) for any bus i, in the system.

$$\lambda_i = \frac{\partial C_s(P_s)}{\partial P_s} - \frac{\partial P_{loss}}{\partial P_i}\frac{\partial C_s(P_s)}{\partial P_s} - \frac{\partial \mathcal{H}^T}{\partial P_i}\mu \qquad 3.13$$

The first term is the energy component, the second is the loss component, and the third one is the congestion component.

The LMP values need to be studied through the various M2M network topologies for the longer term, where the networks provide the lowest energy prices.

3.5 Financial Transmission Rights (FTRs)

FTRs are the financial mechanisms that permit the holder to the difference between LMPs at two defined nodes. A source and sink nodes with the quantity of power (MW) are the parameters of the FTRs. The holder of an M (MW) FTR from the source node to the sink node (P_{ij}) is permitted to receive:

$$FTRs = P_{ij} * \left(LMP_j - LMP_i\right) \qquad 3.14$$

For the $LMP_j > LMP_i$, the FTR holder is paid by the RTO. And for $LMP_j < LMP_i$, the FTR holder must pay the RTO.

3.6 Carbon Emissions Saving and Pricings

The recipient RTO would save the carbon emissions equal to the overgeneration due to PV systems in the dispatcher RTO minus the transmission losses in tie-lines times to the general average production per unit energy (per MWh). And the total cost for this carbon savings is the product of total CO_2 emissions from fossil fuel generators and cost per ton (varies with different countries' environmental policies). In this work the internal carbon emissions distribution and financial management of individual RTOs' have not been considered, therefore the power flows within the tie-lines have been considered in the analysis of carbon trading.

$$TotalCO_2(ton) = (P_{OG} - Tl_{loss}) * {}^{CO_2(ton)}/_{MWh} \qquad 3.15$$

$$Cost(CO_2) = TotalCO_2 * {}^{\$}/_{ton} \qquad 3.16$$

3.7 Interior Point (IP) Method and Karush-Kuhn-Tucker (KKT) Condition

The power system formulation to optimize the problem is a non-linear problem. Therefore, *Karmarkar's Interior Point (IP)* has been used to solve the formulated non-linear problem. The polynomial-time algorithm characteristics of Karmarkar's IP method provide fast-optimal solutions with a lesser number of iterations and make it one of the most efficient techniques [83]. Also, the IP method is effective for extremely large LPs. The concept and algorithm of the interior point method (IP) are as follows:

Let, the problem is formulated as

$$\begin{aligned} &Min\ c(x) \\ &Subject\ to,\ d(x) = 0 \\ &el \leq e(x) \leq eu \end{aligned} \quad 3.17$$

where *c(x)* is an objective function, *d(x)* is a set of nonlinear equality constraints (Power balance) and *el ≤ e(x) ≤ eu* is a set of nonlinear inequality constraints. For optimal power flow (OPF) solution with interior point method, Lagrange function is formulated for equation (3.16) redrafted as

$$L_h = c(x) - r^T d(x) - s^T[e(x) - l - el] - t^T[e(x) + u - eu] - \mu \sum_{i=1}^{r} ln\, l_i - \mu \sum_{i=1}^{r} ln\, u_i \quad 3.18$$

Where *r, s,* and *t* are the Lagrange multipliers for equality and inequality constraints respectively; l_i and u_i are the resilient variables; μ *is* the boundary parameter. The Karush-Kuhn-Tucker conditions are first-order derivative tests (also known as first-order necessary conditions for optimality) for a solution in non-linear programming to be optimal, provided that some regularity conditions are satisfied. The Jacobian and Hessian matrices have been formed to uncomplicate the power flow solutions. The Jacobian matrices are used to calculate a matrix with a higher number of variables whereas the Hessian matrices are used for the faster conversion of the solutions. Forthwith, the equation (3.17) is verified based on KKT conditions and obtains Jacobean matrices J_c, J_d, and J_e and Hessian matrices H_c, H_d, and H_e of *c(x), d(x),* and *e(x)* respectively. Further, a decomposed linear equation for (3.16) is obtained by using a reduced Newton method.

A. Karush-Kuhn-Tucker (KKT) Condition

A general optimization problem has been considered for a first-/second-order condition,

Min *c(x)*

s.t. $d_i(x) \leq 0$, $i = 1, 2, \dots, m$

$e_i(x) = 0 \quad , i=1, 2, \ldots, r.$ 3.19

If the given problem has x^* a local minimum also it is a substantial point of the constraints; then it exhibits unique vectors μ_i^* (i= 1, 2, …, m) and λ_i^* (i= 1, 2, …, r), called KKT multipliers [83], such that

$\nabla c(x^*) + \nabla d_i(x^*)^T \mu^* + \nabla e_i(x^*)^T \lambda^* = 0,$ 3.20

$\mu^* \geq 0,$ 3.21

$d_i(x^*) \leq 0,$ 3.22

$e_i(x^*) \geq 0,$ 3.23

$(\mu^*)^T d_i(x^*) = 0.$ 3.24

The above conditions (3.19) -(3.23) are known as KKT conditions. These prerequisite conditions must be fulfilled to achieve the optimal solutions to the formulated non-linear problem. Moreover, the KKT conditions are adequate for convex objective functions and affine constraints to obtain global optimality.

B. Solution Algorithm

IP-OPF-based solutions have the following main steps:

1) Initialization: Choose initial values and parameter values for the formulated objective function.
2) Formulation of objective function's Jacobean and Hessian matrix equality, and inequality constraints: $J_c, J_d, J_e, H_c, H_d,$ and H_e [84].
3) Formulation of linear system equation using a predictor-corrector strategy to solve the linear system for (3.16). If convergence criteria are satisfied, then break; otherwise, go to step 2.

Initially, the tolerance value is 1 × 10−6, and the centering parameter is in the range of (0, 1) for the IP method. The number of iterations is not specified for optimization [84].

Chapter4: Model Implementations, Results & Discussion

4.1 Introduction

The IEEE bus systems have been adopted widely to research or analyze new concepts/ideas of power systems. These IEEE models consist of loads, generators, transmission lines, and other required electrical components. Since the IEEE-9 bus system provides the most desirable system stability for small test systems and the IEEE bus system is based on the PJM-5 bus system (small test system) for power systems economic analysis. Further, the results from smaller networks need to be validated over larger networks; therefore IEEE-118 bus system and IEEE-57 bus system have been considered due to the larger loads, generation capacities, and transmission capacities. Henceforth, the tests' results have been examined using two system models; one is modified IEEE-9 and IEEE-5 bus systems, and the second one is standard IEEE-118 and IEEE-57 bus systems [24], [25]. The network that has a higher share of PV energy would allocate the maximum power to PVs due to low cost during the rescheduling of generators [85]. The over generation will occur when the sum of total PV generations and the conventional generators' minimum limit are more than the demand at the time. The carbon emission prices for the conventional generators have been considered uniformly ($40/ton) for the convenience of the study, it may vary under different circumstances. The PV penetrations have taken 120% MPP of minimum day-time load (MDTL). Each case has been tested for one period.

The maximum output could be expressed as follows for the respective percentage of penetration (PoP):

$$MPP\ P_i = PoP * MDTL\ at\ load\ bus\ i \qquad 4.1$$

where, P_i is the active power output of PV units at bus *i* and *PoP* is 120% of MDTL.

4.2 Case Studies

Case 1: PV units to Identified Load Buses

This case has been analyzed by interconnecting identified PV units directly to the identified load buses. This M2M interconnection would save further investments in the infrastructures. Also, it would enhance supply-demand equilibrium in the system.

Case 2: Network 1's fictitious bus (F1) to Network 2's Slack Bus

The fictitious bus has been constituted in the transmitter network (having excess power) to aggregate the PV outputs. This node is interconnected with the slack bus of another network. Since the slack bus of another network may provide more resiliency to the system during higher penetrations of PV units.

Case 3: Fictitious Bus 1 to Fictitious Bus 2

This case has been analyzed by introducing fictitious buses on both sides (networks). Further, identified PV unit outputs are aggregated over the transmitter's fictitious bus; and the identified loads have been aggregated over the receiver's fictitious bus.

Assumptions Made in this work:

- Every bus voltage magnitude is around 1 pu (per unit).
- The voltage angle differences across the transmission lines are negligible.
- The generation capacities are sufficient to fulfill the total demand (including both networks).
- The cost analysis has only assumed the real (active) power.
- Highly PV penetrated network has excess power generation.

The pictorial representation of the proposed M2M model has been shown below:

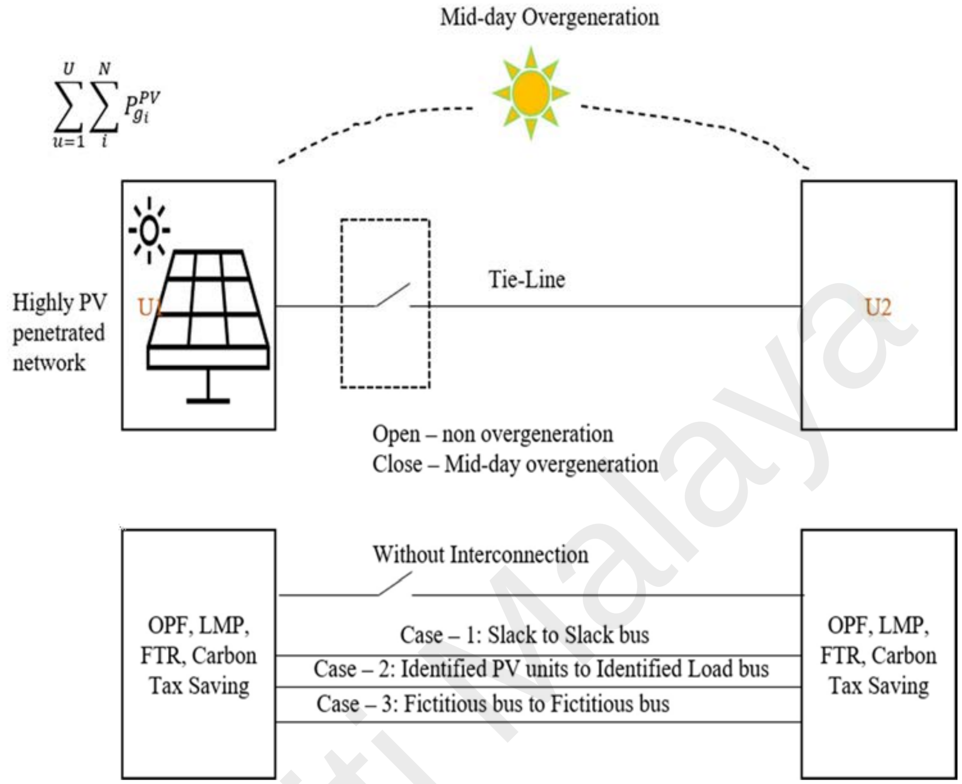
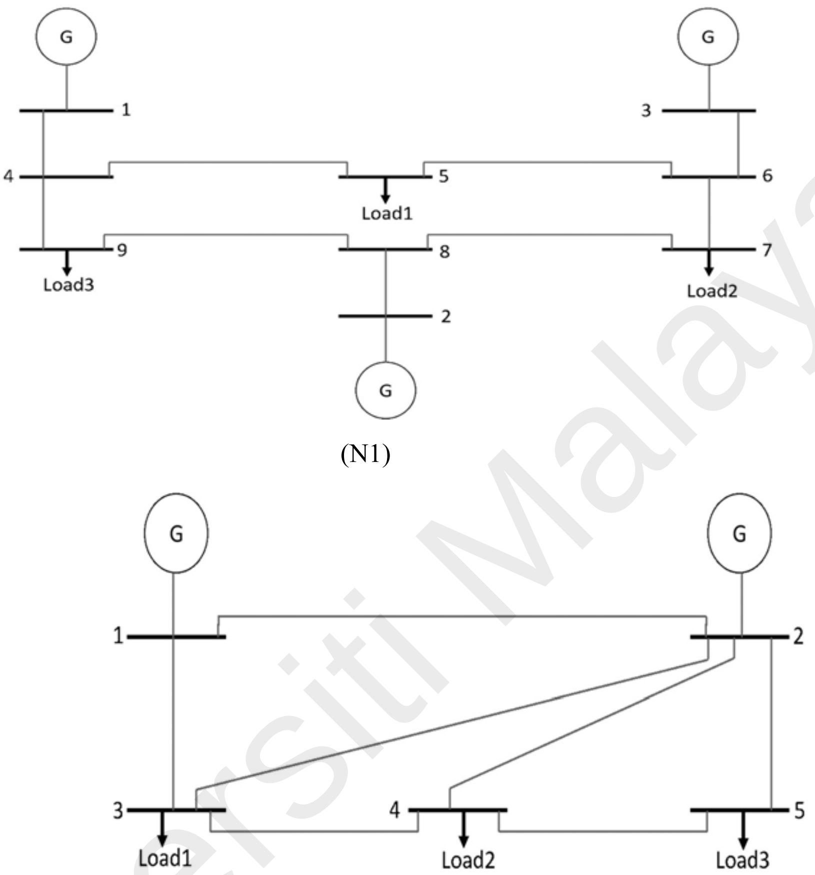


Figure 4.1 Graphical representation of proposed market model and method

4.3 Model Implementations

Illustrative Example 1: IEEE-9 Bus System and IEEE-5 Bus System

The M2M studies have been performed on a smaller system considering modified IEEE-9 and IEEE-5 bus systems. The prototypical IEEE-9 bus system consists of three conventional generating units, three loads, and nine transmission lines; and the IEEE-5 bus system consists of two conventional generating units, three load buses, and seven transmission lines. Further, the modified IEEE-9 bus system has been penetrated with the PV units, which is the same as the prototypical IEEE-9 bus system but incorporates PV units at load buses. The Marginal costs of generators and load profiles at different nodes have been shown in Table I (see Table 4-I) and Table II (see Table 4-II) respectively. The cost of conventional generators is the same as prototypical IEEE-9 and IEEE-5 bus systems as per the MatPower library [79]– [81]. The fixed cost of the PV unit has been selected at 20$ as per IEA data [85]. In this model system, the load profiles have been considered similar in both networks. Figure 4.2 shows the IEEE-9 and IEEE-5 bus systems (see Figure 4.2).



(N1)

(N2)

Figure 4.2 IEEE-9 (N1) and IEEE-5 (N2) Bus system Network

Table 4-I: Generation Cost Function in Modified IEEE-9 and 5 Bus Systems

Systems	Generator No.	Bus No.	Marginal Gen. Cost Function $/h
IEEE-9 BUS SYSTEM: N1	G1	1	$5P+0.11P^2+150$
	G2	2	$1.2P+0.085P^2+110$
	G3	3	$P+0.1225P^2+125$
	PV1	5	20
	PV2	7	20
	PV3	9	20
IEEE-5 BUS SYSTEM: N2	G1	1	$6P+0.2P^2+150$
	G2	2	$6P+0.2P^2+100$

*P is the active power of generators.

Table 4-II: % Loading on Load Buses

Type of Loads	L_1	L_2	L_3
Industrial	60%	Nil	Nil
Commercial	20%	30%	10%
Municipal	10%	20%	Nil
Residential	10%	50%	75%
Agricultural	Nil	Nil	15%

The diverse load profiles affect the power factor of the system. Subsequently, the reactive power scheduling will vary in the power system to assist the voltage profile of the system during all cases analyzed in the work. In this example, L1 is load bus 5 in IEEE-9 and load bus 3 in the IEEE-5 bus system. Similarly, L2 represents bus 7 and bus 4 in IEEE-9 and IEEE-5 bus systems respectively. And L3 is bus 9 and bus 5 in IEEE-9 and IEEE-5 bus systems respectively. The load profiles (active and reactive power) have been shown in figure 4.3 (see Figure 4.3). The PV units' active power generation in the hourly-ahead (HA) market at different load buses for 120% MPP penetration of MDTL in the modified IEEE-9 bus system has been shown in figure 4.4 (see Figure 4.4).

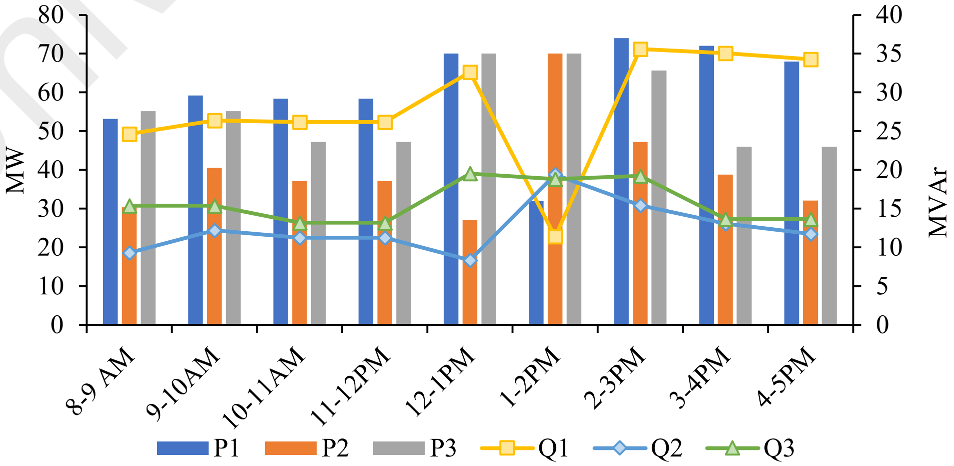


Figure 4.3 Active and Reactive Power Demand Profiles for IEEE-9 and IEEE-5 bus systems

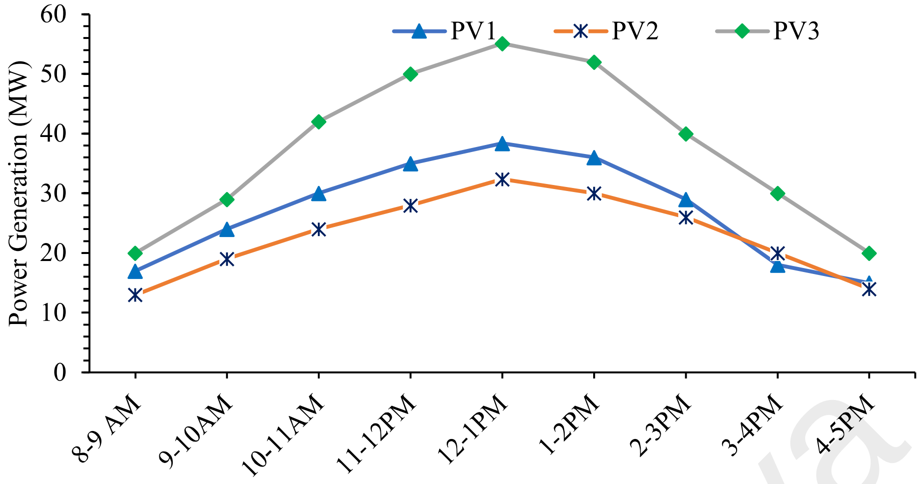


Figure 4.4 PV systems output (MW)

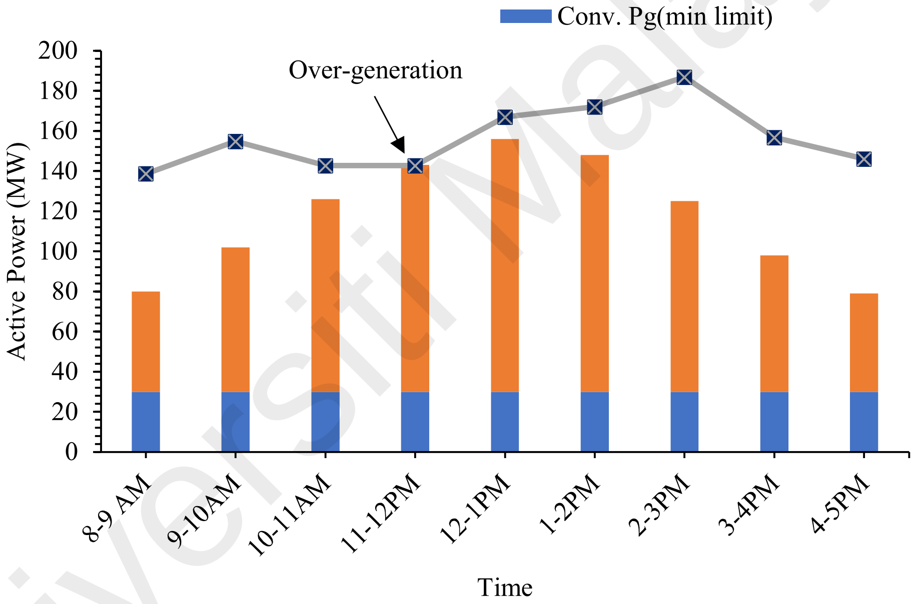


Figure 4.5 Minimum Possible Generation vs Total demand

The minimum possible generations and total demand in the hourly-ahead market in the modified IEEE-9 bus system (N1) have shown in figure 4.5 (see Figure 4.5). In the hour 1100-1200, the figure indicates that the overall least possible generations have surpassed the entire demand. The difference between total generation to total demand is 0.225 MW (0.16% of total demand), and it is a large gap in smaller power systems networks. This means an over-generation scenario (excess power), and the market operators must interconnect the N1 to N2 (M2M) to utilize clean and affordable energy at its maximum.

Illustrative Example 2: IEEE-118 Bus System and IEEE-57 Bus System

The results of the first example have been carried out on IEEE-118 and IEEE-57 bus systems. The prototypical IEEE-118 bus system contains 19 conventional generation units, 91 loads, and 177 transmission lines; while the IEEE-57 bus system contains 7 conventional generators, 42 loads, and 80 transmission lines. Moreover, the modified IEEE-118 bus system contains 42 PV units at the load buses along with the same other specifications of the network.

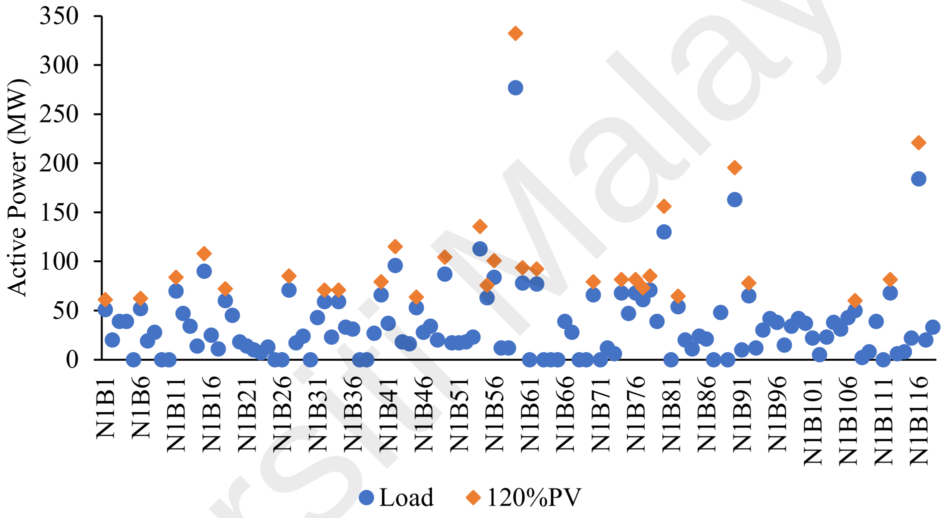


Figure 4.6 Active Power Demand and PV outputs in IEEE-118 Bus System

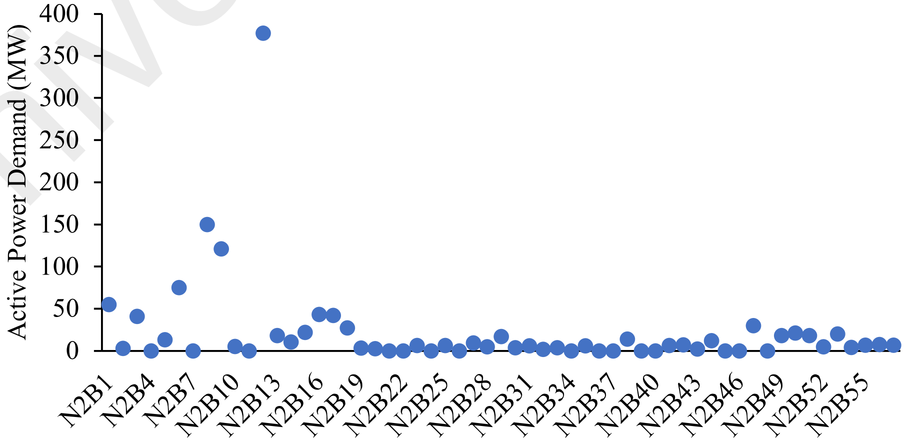


Figure 4.7 Active Power Demand in IEEE-57 Bus System

Figure 4.6 shows that the total active power demand is less than the minimum conventional generators' limit (20 MW considered for each conventional generator) and total PV active power output (see Figure 4.6). Therefore, the excess power must be transmitted to the other networks. The active demand at each node of the IEEE-57 bus system during the overgeneration period has been shown in figure 4.7 (see Figure 4.7).

4.4 Results and Discussion

In this section, obtained results from the optimization of different case studies have been presented in graphical as well as tabular form.

Illustrative Example 1: IEEE-9 Bus System and IEEE-5 Bus System

Figures 4.8 and 4.9 are showing the voltage profiles and active power generation profiles respectively at their corresponding nodes (see Figure 4.8 & Figure 4.9). Figure 4.10 is showing the generators' cost and the carbon emission prices in different proposed network topologies. It can be observed that the direct interconnection of identified PV units to identified load buses of another network will provide a cost-effective power generation in an M2M system. Also, this network topology will save lots of carbon emissions. Henceforth, this topology would increase the net revenue of the generators.

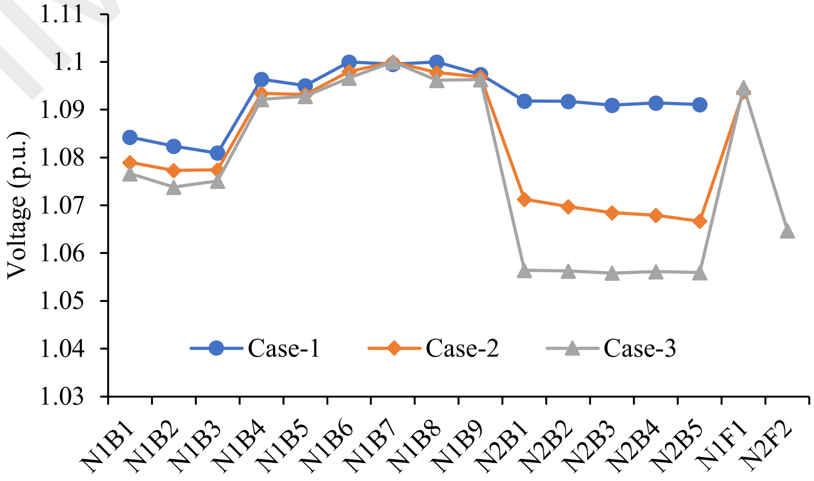


Figure 4.8 Voltage Profile for all three cases

Now, the LMP values among the proposed topologies have been shown in figure 4.11 (see Figure 4.11). This graphical representation shows that the LMPs are lowest again for the direct interconnection of identified PV units and loads of corresponding networks. The obtained results show that the voltages are higher for direct interconnections of PV units and loads, the values are within an acceptable range though.

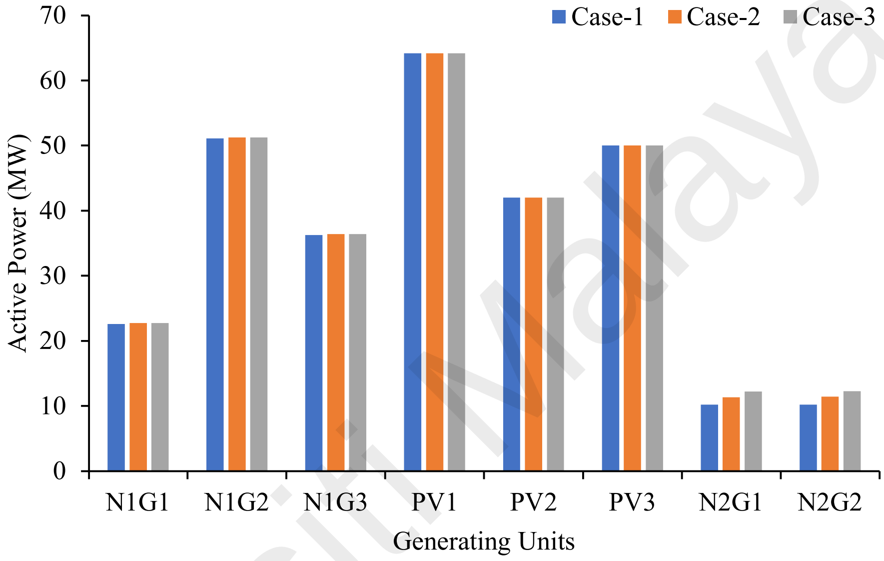


Figure 4.9 Active Power (MW) Generation Profiles

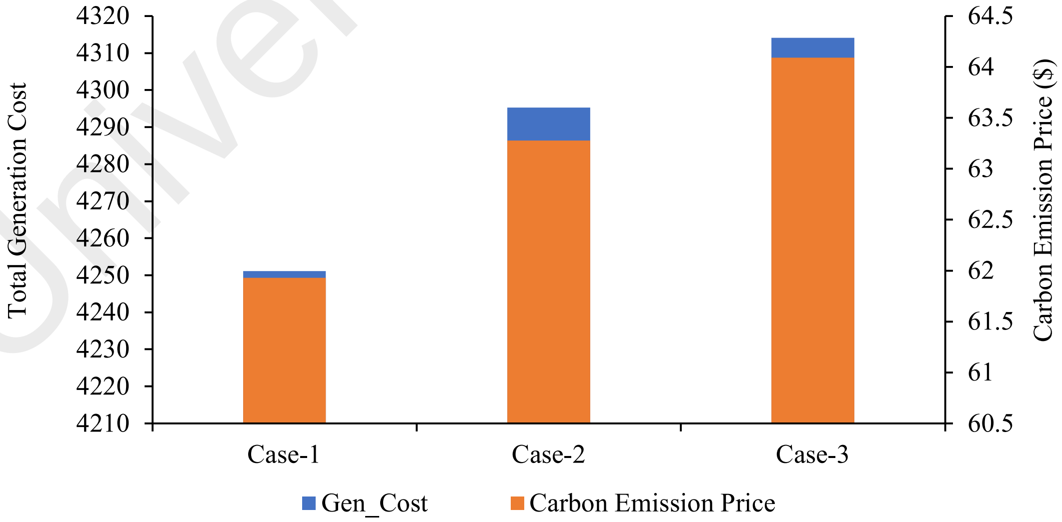


Figure 4.10 Total Generation and Carbon Emission Costs ($)

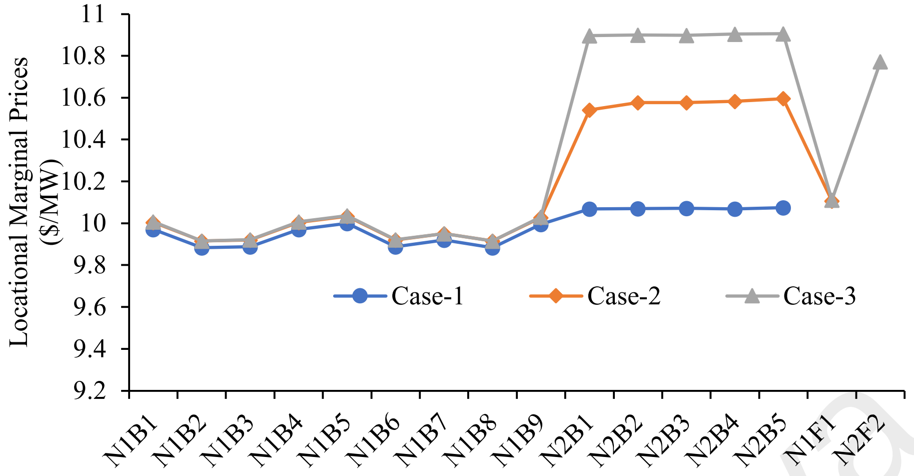


Figure 4.11 Locational Marginal Prices (LMPs) in different cases

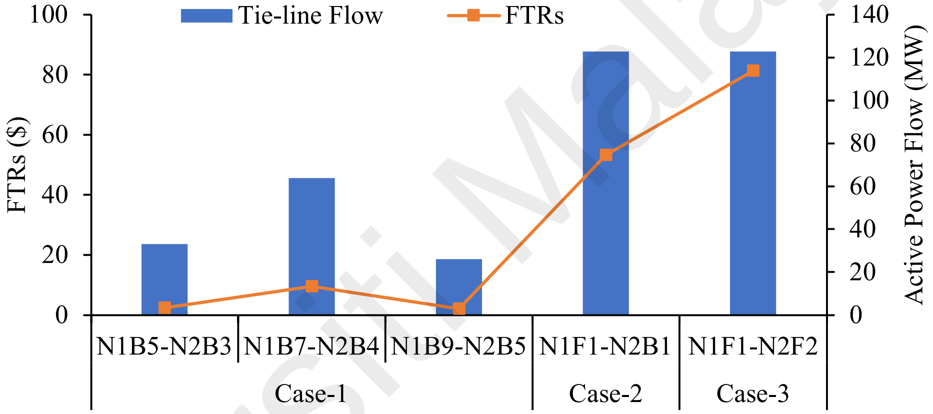


Figure 4.12 Active Power flows and FTRs values for Inter Tie-lines

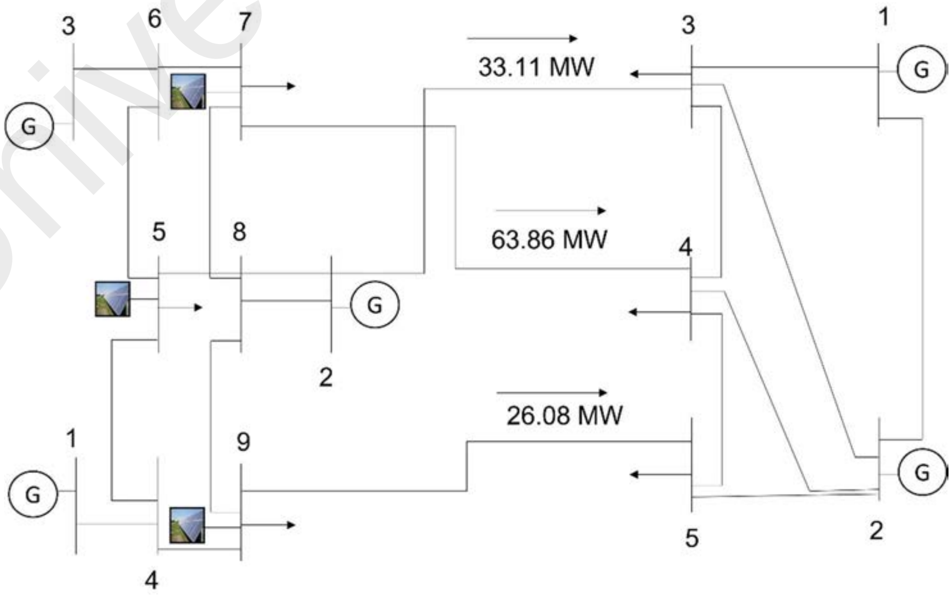


Figure 4.13 Direct Interconnection of IEEE-9 and IEEE-5 bus systems with tie-line flow

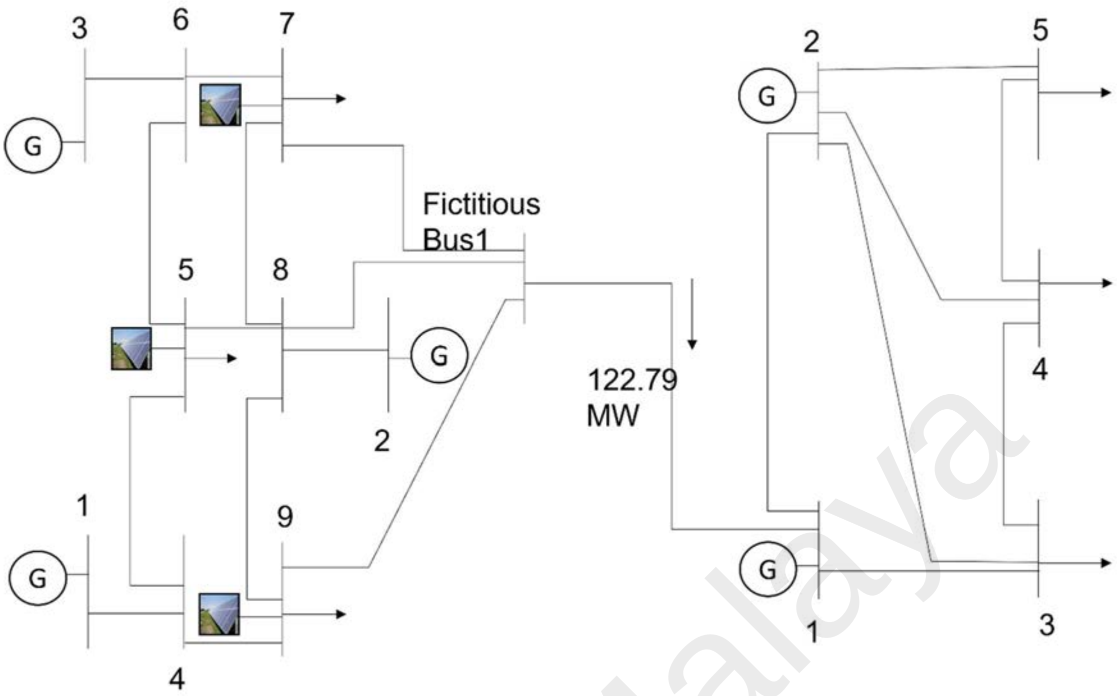


Figure 4.14 Fictitious Bus of IEEE-9 to slack bus of IEEE-5 bus systems interconnection with tie-line flow

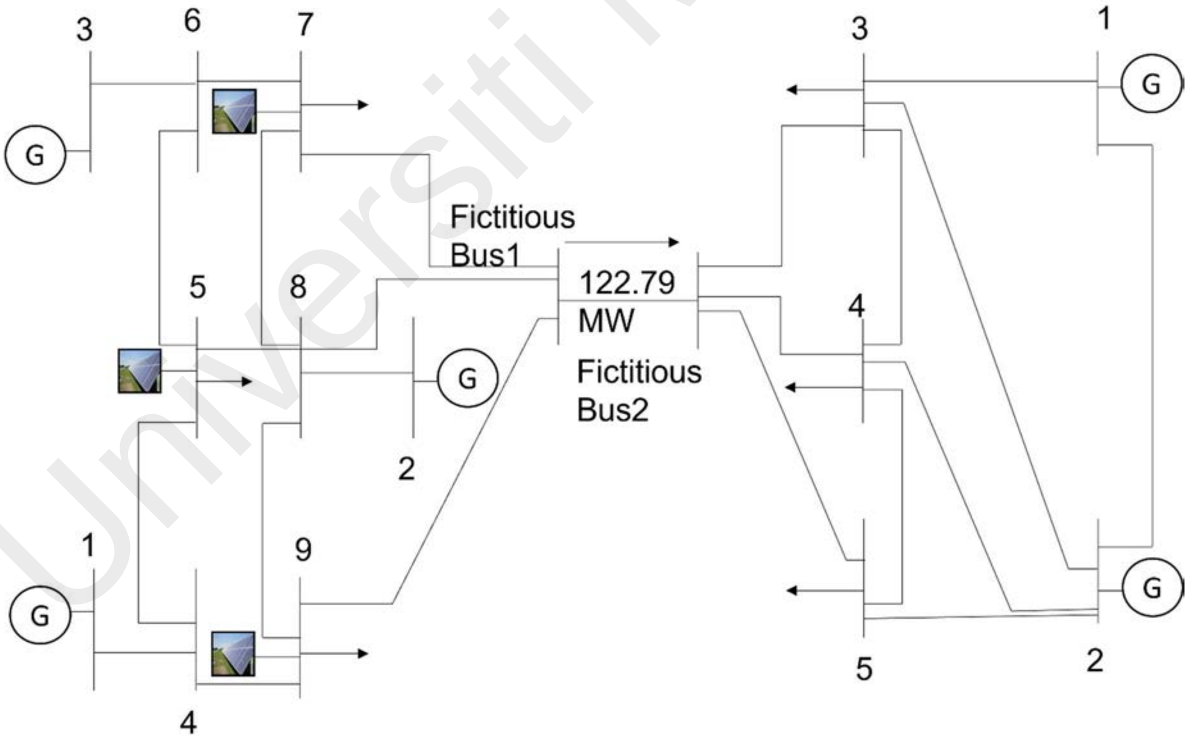


Figure 4.15 Fictitious Bus of IEEE-9 to Fictitious Bus of IEEE-5 bus systems interconnection with tie-line flow

Furthermore, figure 4.12 shows the FTRs values are positive, hence FTRs would be paid to the holder by RTOs (see Figure 4.12). And it is much lesser with the direct interconnections of identified PV units to identified loads than the other two methods of M2M interconnections. Figure 4.13 (see Figure 4.13) represents the direct interconnection of identified PV units to identified load bus interconnection of IEEE-9 bus systems (N1) and IEEE-5 bus systems (N2) with the tie-line flows. The total transmission power flow through tie-lines is the same for all the cases though. Similarly, figure 4.14 and figure 4.15 are depicting the case 2 and case 3 M2M interconnections (see Figure 4.14 and Figure 4.15).

Illustrative Example 2: IEEE-118 Bus System and IEEE-57 Bus System

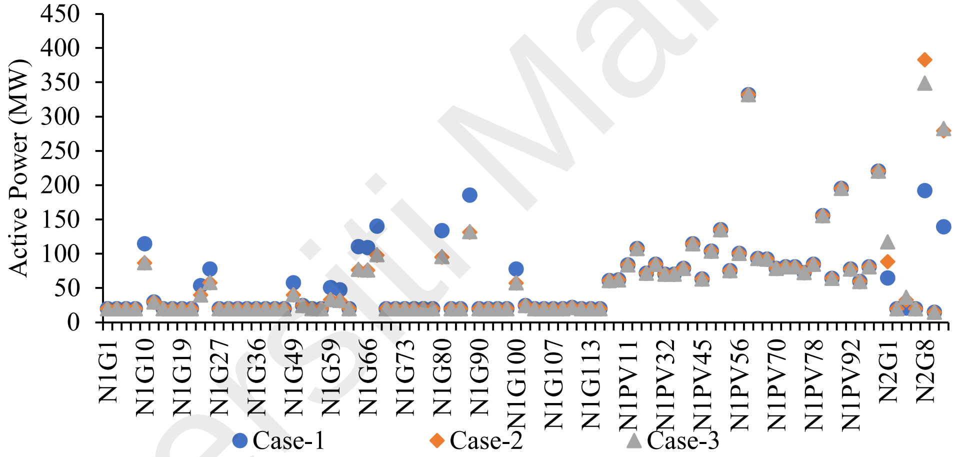


Figure 4.16 Active Power Generation Profiles

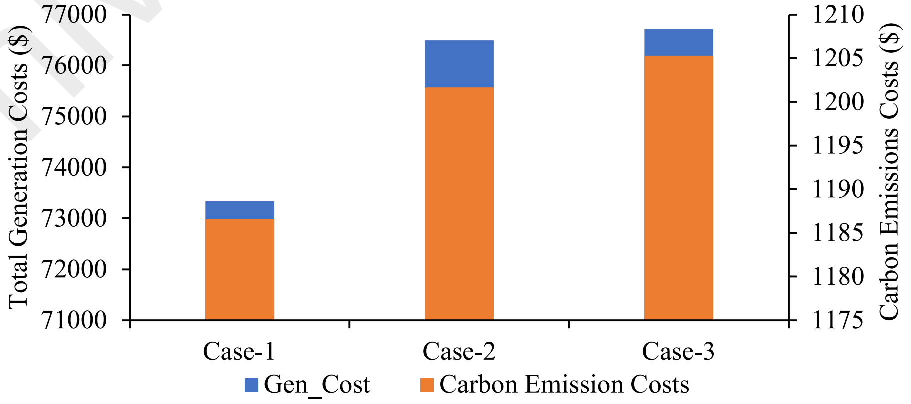


Figure 4.17 Total Generation and Carbon Emission Costs ($)

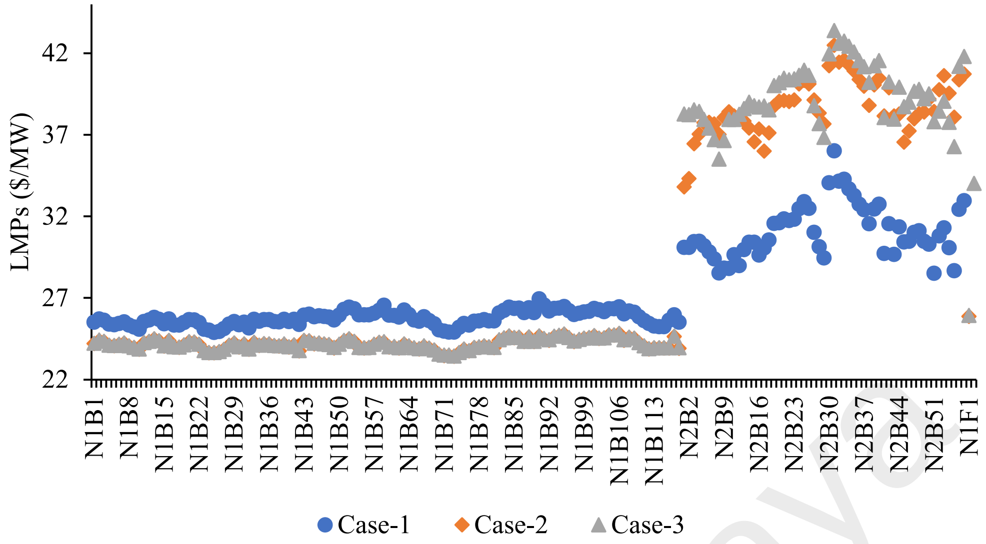


Figure 4.18 Locational Marginal Pricings at different nodes for all cases

In this test result, figure 4.16 shows the similar active power generation profiles of generators at their corresponding nodes (see Figure 4.16). Moreover, figure 4.17 is revealing that the economic effect (generator costs & carbon emission savings) of these three types of interconnections (see Figure 4.17). The direct interconnection of identified PV units to identified load buses committed lower production in the non-PV network. As a result, the carbon emission is lower in case 1 than in case 2 and case 3. The direct interconnection of identified PV units to identified loads of the other network is much more economic than the others. The LMPs values are nearly similar for all the cases in the larger power system (see Figure 4.18). Further, the voltage profiles of M2M for IEEE-118 and IEEE-57 bus systems, validate the results from the previous test model (IEEE-9 and IEEE-5 bus systems) and are within the acceptable range. Also, the voltage profiles are similar for the three test cases (see Figure 4.19). Here, the FTRs value is positive and least for the direct interconnections of identified PV units to identified loads (see Figure 4.20). The positive value of tie-line flow signifies that the power flows from PV (REs) rich network to the REs deficit network.

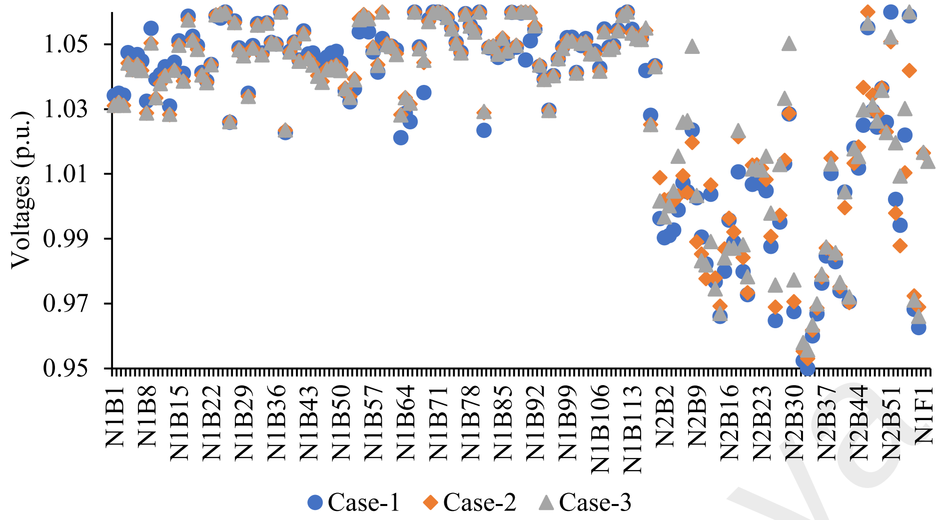


Figure 4.19 Voltage Profiles for different cases

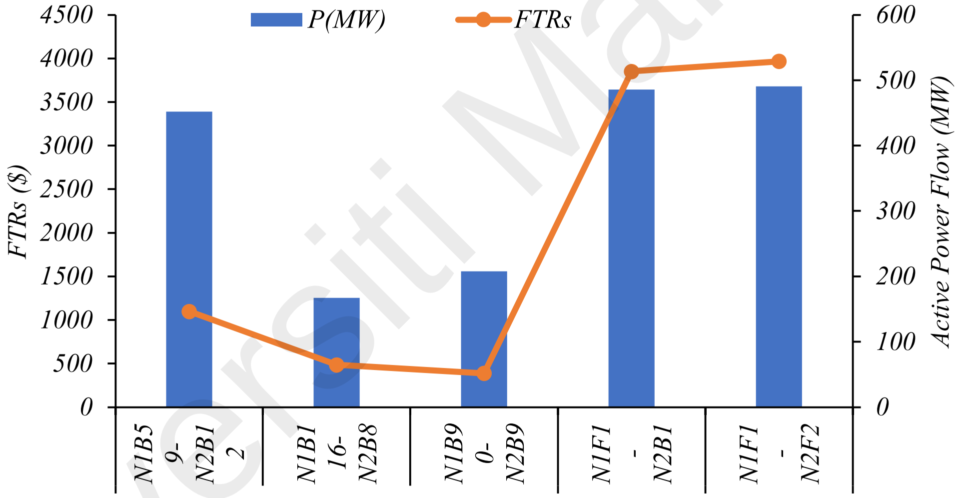


Figure 4.20 Financial Transmission Rights and Active Power Flow to Inter-Tie lines

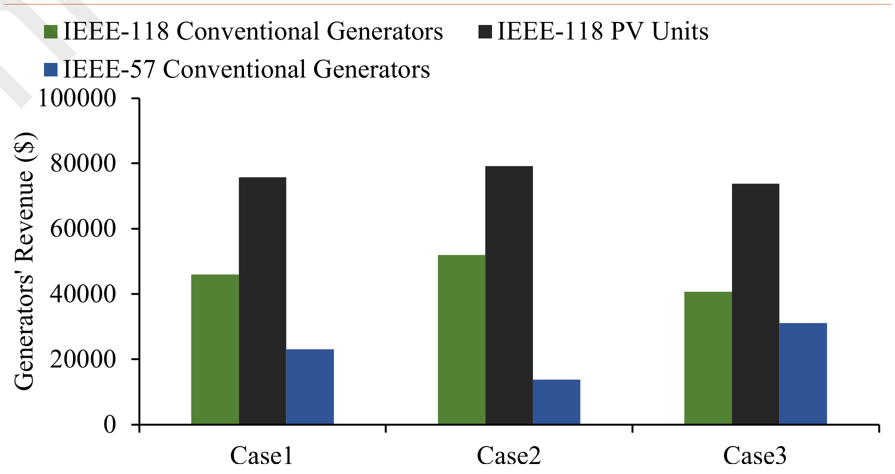


Figure 4.21 Generators’ revenue ($) for different Interconnections

In inter-connected power system markets, the proposed analysis suggests the direct interconnection of PV units to improve the revenue of the generators with the higher implementation of PV units in the system (see Figure 4.21). The revenue generated by the conventional generators in the receiving network is low though. Notwithstanding, the carbon emission savings (carbon tax savings) is higher for the direct interconnection of identified PV units to identified load buses, Table III (see Table 4-III).

Carbon Emission Savings ($) in the Receiver network:

Since the same volume of power has been traded to the other network, therefore the traded carbon emission prices would be the same for all three method interconnections. Now, the traded carbon emission prices ($40/ton) for both illustrative examples have given in the following Table III.

Table 4-III: Traded Excess Power and Carbon Emission Savings in the receiver network

	Excess Power (MW)	***Carbon Emission Savings in N2 ($)***
Example 1 (IEEE-9 & IEEE-5) bus systems Interconnection	0.225	4.275
Example 2 (IEEE-118 & IEEE-57) bus systems Interconnection	191.8	3644.2

Chapter5: Conclusion

5.1 Conclusion

The ISOs/RTOs are constantly looking for extension/interconnection with other ISOs/RTOs; therefore incorporating the FERC order no. 1000 and order no. 2222, this paper has tested the different interconnection methodologies for better operations and economics of the markets. The proposed method provides an M2M interconnection incorporating the FERC order no. 2222 to penetrate the system with higher PV units. It has also developed an interconnection method to support the PJM's interregional connection policies with fundamental financial analysis. A comparative study has been brought up to analyze the financial tools i.e. LMPs, FTRs, and carbon taxes. It also provides the model for improved results for the M2M interconnections. Hence, this work has identified a new method of direct interconnections of PV units to load buses in an interregional power system market.

The voltage profiles are within the acceptable range. The voltage stability and supply-demand balance in the M2M networks show the improved flexibility and reliability of the system during the overgeneration scenarios due to the higher share of PV units in the system. Also, the transmission line flows show that there is no congestion in the transmission lines. Hence the proposed algorithm provides a smooth operation in the M2M.

In other words, this method will lower LMPs, higher carbon emission savings, and minimize FTRs to be paid to FTR holders. In smaller power systems, the voltages would be somewhat higher but for higher systems voltage profiles would be nearly similar in all cases. Moreover, this analysis has identified a long-term M2M power exchange system that will save the costs of new infrastructure. The major limitation of this work is the non-consideration of the financial obligations of the market players in M2M. In future work, the dynamic-state analysis and extensive carbon trading policies considering the financial obligations in real-time would be studied to intercept the potential challenges.

5.2 Future Works

This work provides an interconnection topology for the inter-regional or cross-border (M2M) to trade electricity with higher penetration of PV systems. This work can be extended in future work to study the following objectives as mentioned below:

1. Since the power system markets consist of many players, therefore the financial obligations among these players would be studied; also the formulation of algorithms to resolve the conflicts for transparent transactions and to increase the total social surplus.
2. Extensive carbon trading and market policies would be analyzed under different circumstances of the power system markets such as 100% renewable installations in one market, green corridors in power systems, increasing nuclear power plants, and contingent situations.
3. Inter-zonal LMP analysis and its deviation with the voltage sensitivity indices would be studied to minimize the consumers' costs.

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