AN ASSESSMENT MODEL OF DEMAND RESPONSE IN INDIAN ELECTRICITY MARKET

A thesis submitted towards partial fulfillment of the requirements for the degree of

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IN

ELECTRICAL ENGINEERING

By

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CERTIFICATE OF RECOMMENDATION

This is to certify that this dissertation entitled *"*An Assessment Model of Demand Response in Indian Electricity Market" has been carried out by **MOUNADEEP PODDAR**with Roll No. **002010802006** under my guidance and supervision and be accepted in partial fulfillment of the requirement for the degree of Master of Electrical Engineering. In my opinion this thesis, is worthy of its acceptance.

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I certify that except where due acknowledgement has been made, the work is that of the candidate alone. This thesis is a presentation of my original research work and has not been submitted previously, in whole or in part, toqualify for any other academic award. Furthermore, the content of the thesis isthe result of work which has been carried out since the official commencement dateof the approved research program.

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CHAPTER 1

INTRODUCTION

Power is one of the most important components of infrastructure, essential for a country's economic growth and welfare. The availability and development of suitable electrical infrastructure is critical for India's economy to continue to thrive. India's power sector is one of the world's most diverse. Power generation options include coal, lignite, natural gas, oil, hydro, and nuclear power, as well as viable non-conventional options including wind, solar, and agricultural and domestic waste. The country's electricity demand has risen significantly and is likely to continue to rise in the coming years. To meet the country's growing need for power, a substantial increase in installed generating capacity is required. In FY23, India's electricity demand is expected to reach 1,650.59 BUs, up from 1,275.53 BUs in FY21.

No utilities across the world including India wants to increase or reinforced their transmission and distribution corridor and add on thermal and other source of generation until and unless it is required. Day by day the electric consumption is increasing due to daily household usage like air conditioner, fridge, electric vehicles etc. So, electric demand has to be increase in upcoming years and even the demand can be increased exponentially. With this excessive demand of electricity, utilities must ensure that peak demand is reduced as well to avoid commissioning new transmission, distribution corridor and new thermal power plants. Demand Side Management can help the utility to reduce the peak load at a given point of time so that such reinforcement of corridor and new installation can be delayed for few more years. Consumer has a big role in successful implementation of Demand Side Management. Without reduction of load by the consumers in peak hours, the utility alone will not able to manage peak load. Utility has to offer incentive payment to consumers such that more participation may happen in load reduction when it is required. It would be possible in presence of micro grid or smart grid than a conventional utility at low voltage side of electricity network. As of 2020, India was rated fourth in wind energy, fifth in solar energy, and fourth in renewable energy installed capacity.

India is the only country in the G20 that is on track to meet the Paris Agreement's objectives. The power sector in India is undergoing a tremendous transformation that has altered the industry's perspective. India's power demand is still being driven by sustained economic expansion. The Indian government's aim on achieving 'Power for All' has sped up capacity addition in the country. At the same time, both the market and supply sides are becoming more competitive (fuel, logistics, finances, and manpower). India's installed renewable energy capacity was 152.36 GW in January 2022, accounting for 38.56 percent of the country's total installed power capacity. Solar energy is expected to generate 50.30 GW, followed by wind power (40.1 GW), biomass (10.17 GW), and hydropower (46.51 GW). In the first eight months of FY22, 8.2 GW of renewable energy capacity was added, compared to 3.4 GW in the same period in FY21. For FY21, conventional energy generation totaled 1,234.44 BU, with thermal energy accounting for 1,032.39 BU, hydro energy (150.30 BU), and nuclear energy accounting for 150.30 BU (42.94 BU). Bhutan contributed 8.79 BU to the total. With a total installed power capacity of 395.07 GW as of January 2022, India is the world's third-largest producer and second-largest user of electricity. In January 2022, India's coal-based power installed capacity was 203.9 GW, with a target of 330-441 GW by 2040. In 2021, the country's highest power demand was 203.01 GW.

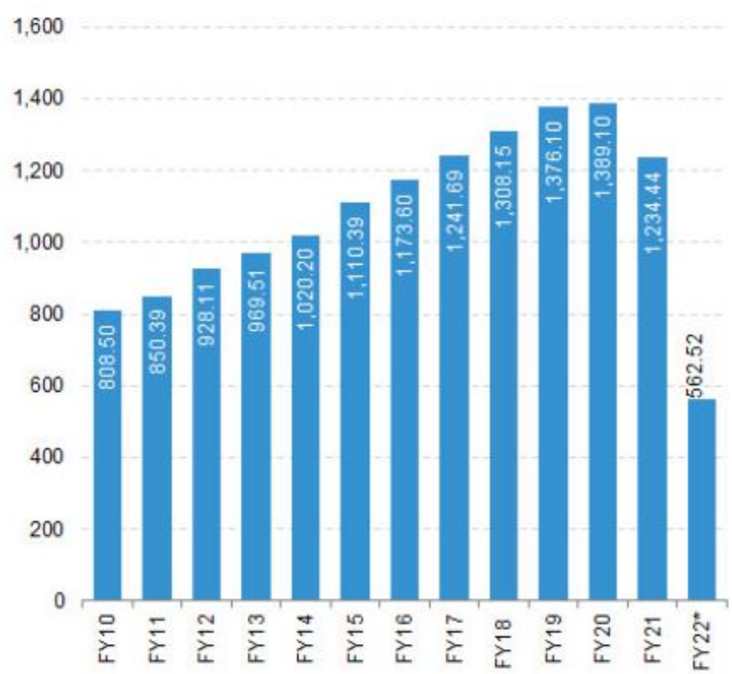

Fig 1.1: Total generation in FY22 in BU (including renewable sources) [1]

The power sector is undergoing a major transformation in terms of both business and operational model, with vertically integrated utilities being unbundled and opened up to competition from private firms around the world. This puts an end to the monopoly era. Running the power system was planned to be a task of esoteric quality from the start. Electricity was seen as a utility at the time. A single organization or utility was in charge of control, which included planning and operational activities. The term "vertically integrated utility" comes from the vertical integration of all tasks. The former power sector setup was defined by the functioning of a single utility that generated, transmitted, and distributed electrical energy throughout its service region. As a result, these utilities had a monopoly in their service region. A monopoly utility was a term used frequently to describe them.

Customers and private businesses profit from the competitive environment, which provides a wide range of benefits. Deregulation of the power business is said to provide a number of key advantages, including:

1. The price of electricity will fall: It is basic knowledge that competitive pricing are lower than monopolist rates. In an ideal competitive system, the producer will endeavour to sell the power at its marginal cost.
2. Choice for customers: Customers will have the option of selecting their retailer. Retailers will compete not only on pricing, but also on the additional services they deliver to their clients. Better strategies, more dependability, and higher quality are just a few examples.
3. Customer focused serviced: Retailers might provide greater service than the monopoly market.
4. Innovation: Electric utilities had no motivation to improve or take risks on innovative ideas that could increase consumer value because of the regulatory process and lack of competition. In a deregulated climate, the electric company will always endeavour to come up with new ways to improve service while lowering costs and increasing profits.

Electricity, as a product, cannot be compared to any other marketable commodity. This is due to its unique qualities, which necessitate the fulfillment of technological limits prior to completing commercial transactions. The need for real-time balance and the difficulty to wheel the commodity via a particular path are two fundamental characteristics of electricity as a commodity (in bulk). As a result, normal microeconomic theory's ideas cannot be directly applied to the power commodity markets. One of the most difficult difficulties in the deregulated era is dealing with network congestion. The transmission network is the channel via which power market transactions are carried out. However, each transmission network has its own set of physical and operational constraints, such as line flow restrictions and bus voltage magnitude limits. Power injection and withdrawal should be configured in such a way that no limits are exceeded. If the network is operated beyond these limits, the entire system may be blacked out.

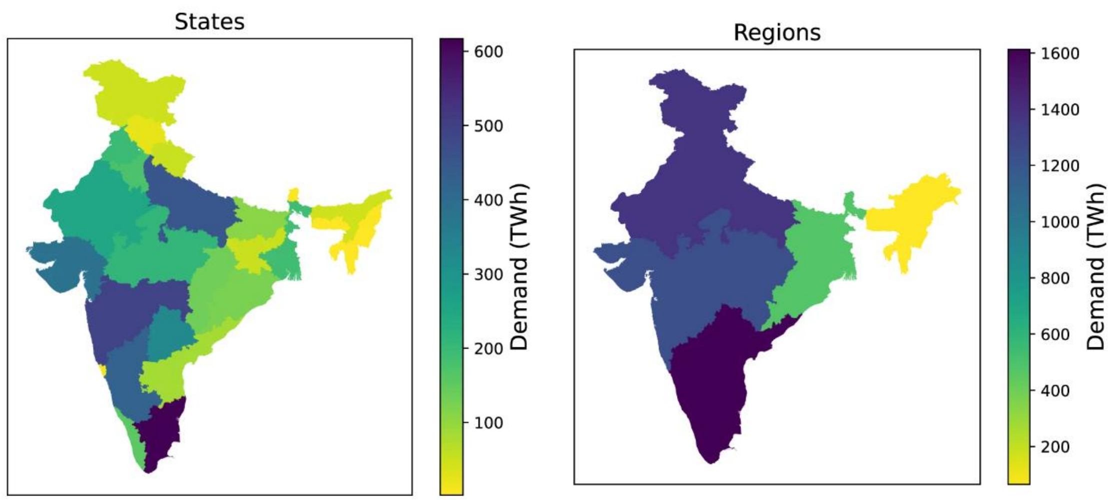

Fig 1.2: Annual electricity distribution at the state and regional level in 2050 assuming constant GDP growth, baseline cooling, and home electric vehicle (EV) charging scenarios. [2]

As a result, the power network cannot be used to organize any random set of transactions. Congestion management is a new problem that has arisen as a result of the restructured power system environment. Congestion can be characterized in a variety of ways, but to put it simply, when some components in a power network appear to be overloaded as a result of a trading arrangement, such arrangement is said to cause congestion on the network. The goal of congestion management is to make the required adjustments in order to alleviate traffic congestion. The commodity market began as a barter system and evolved into the era of electronic trading platforms. In simple terms, a market is a place where buyers and sellers meet to make a deal. Technological advancements have developed to the point where a commodity trade may now be struck with the click of a mouse. This is a virtual market place concept that has the potential to replace a physical market place. Microeconomics is the discipline of economics that studies how individuals and businesses make decisions and interact in marketplaces. Electric energy is treated as a commodity rather than a service in restructured power networks, as it is in vertically integrated systems.

If a market-based solution with economic efficiency is required, congestion management in a multi-buyer and seller system is one of the most difficult challenges. Generation, transmission, and distribution are all under the direct authority of a single utility or a central agency in a vertically integrated utility organization. The generation is dispatched in order to achieve the lowest cost operating for the system. Furthermore, utilizing security constrained economic dispatch as the optimal dispatch option minimizes the possibility of congestion. This practically means that generations are dispatched in such a way that the transmission lines' power flow constraints are not exceeded. In a deregulated system, every buyer seeks to buy power from the cheapest generator available, regardless of the buyers and sellers relative geographic locations. As a result, if all such deals are permitted, the transmission channels evacuating the electricity of cheaper generators will become overburdened. In a deregulated context, transmission congestion management entails developing a set of rules to ensure control over generators and loads while maintaining an appropriate level of system security and reliability. The rules should ensure that market efficiency is maximized across both short and long time horizons. In a deregulated structure, the market must be modeled so that market participants (energy buyers and sellers) can freely transact and play according to market forces, but without jeopardizing the power system's security. As a result, regardless of the market structure in existence, congestion management has become a common practice among power system operators. The dual objectives of congestion management schemes have always been to reduce transmission network disturbance in the market for electrical energy while also ensuring the safe operation of the power system.

In the deregulated electricity system setting, the Locational Marginal Pricing (LMP) mechanism is one of the most often used mechanisms for market settlement. The cost of supplying the next increment of load at a bus is known as the Locational Marginal Price (LMP). The LMP is the sum of the cost of supplying energy marginally, the cost of losses due to the increment, and the cost of transmission congestion, if any, resulting from the augmentation. The LMP is a true indication of energy marginal pricing. Congestion management is implicit in the calculation of LMPs. Due to its inherent efficiency in network capacity allocation; the LMP technique has found widespread adoption around the world when compared to alternative approaches to congestion control.

Many of the successful power markets, such as PJM, NYISO, ISO-NE, CAISO, ERCOT, MISO, and NEMCO, have already adopted a locational marginal pricing mechanism in their systems, while others are moving toward locational marginal pricing. Dr. William Hogan devised the LMP mechanism in 1992, and it was initially used at the Pennsylvania-New Jersey-Maryland (PJM) Independent System Operator (ISO) in 1993. The LMP mechanism, on the other hand, is based on the concept of spot pricing of Schweppe et al. The LMP mechanism is unique in that it handles the complete process of power scheduling from a central location, taking into account system conditions and limits. The essential idea of locational marginal pricing is that when there is congestion and loss in the system, the energy price fluctuates from one location to another.

Locational marginal pricing is a centralized market clearing mechanism in which the (ISO) is in charge of determining power dispatch schedules and energy prices. Network constraints must be considered while scheduling generators, loads, and bilateral transactions, unlike the system uniform pricing (i.e., unconstrained bidding) approach. Because network restrictions are taken into account during the market clearing process, the market equilibrium cannot be determined only by the intersection of a cumulative supply curve and a cumulative demand curve. Instead, power dispatch plans and energy prices are created using an optimization method that takes into account network and power flow constraints. A single settlement or two settlement LMP market is possible. A single settlement market's scheduling is done only in the day-ahead mode, whereas a two settlement market's scheduling is done in both the day-ahead and real-time modes. A real-time market is essentially a market that operates within the hour. The real-time scheduling and settlement is then broken down into time blocks. Real-time scheduling in PJM, for example, is done in 5-minute time chunks. At the start of each time block, the real-time scheduling begins with the state estimation solution. The state-estimation solution provides the real injection and withdrawal by each generator and load at the current moment. It should be noted that the above settlement time frames are not rigid and may alter based on market conditions. When used for energy pricing, LMP can give helpful price signals that can be used to locate acceptable locations for new generators, load centers, and transmission lines. The LMP mechanism encourages the most effective and optimal use of system resources as generation and transmission. Nonetheless, despite the LMP mechanism's high economic efficiency, vigilance must be exercised before it is implemented.

1.1 LITERATURE REVIEW

The phrase Demand Side Management arose from a logical evolution of utility planning techniques in the late 1980s in the United States [18]. According to India's Ministry of Power, “Demand Side Management is used to describe the actions of a utility beyond the customer's meter, with the objective of altering the end-use of electricity – whether to increase demand, decrease it, shift it between high and low peak periods, or manage it when there are intermittent load demands – in the overall interests of reducing utility costs” [19].

Installation of new transmission, distribution corridor and capacity expansions need large capital investments and timely approvals to develop new power plants, and there has been an increase in inflation and a decrease in capital availability [13, 14, 15]. India's installed electric power capacity has steadily increased throughout the years. However, the increase in demand for electricity has outpaced the increase in existing capacity. Increased electricity supply generates significant tax revenue for the government [16]. However, effective revenue collection by electric utilities to pay their supply costs is missing due to huge investments necessary for capacity increases, transmission, and distribution, as well as a lack of capital and revenue recovery [17]. In such a case, effective electricity usage may be a less expensive option to providing reliable electric power delivery. Activities altering customers' power consumption behavior with the goal of changing the load curve profile, developing energy efficient appliances and equipments, promoting energy conservation measures, and so on are examples of demand side actions [4].

Demand Response (DR) is a demand-side management strategy in which electricity end-users are urged to help reduce peak load on the system by changing their typical energy consumption patterns. End-users receive pricing or service incentives in exchange. As end-users transfer part of their loads from peak hours or high market pricing hours to off-peak hours or low market price hours, this process is intended to reduce overall system peak load. Demand response has a few challenges before it can be widely used in the current electricity grid. One of them is the issue of a utility business controlling and monitoring power functionality remotely, which would necessitate widespread public awareness. Customers must actively participate in the dynamic market, so a minimum level of knowledge is required. The most severe obstacles, however, will arise as a result of technological gaps at the utility, aggregator, and customer's location. Any disaster recovery strategy will necessitate a certain level of infrastructure [3]. Demand Side Management (DSM) is a strategy for reducing energy consumption by altering consumer energy consumption patterns through financial incentives and/or behavioral modification through education [5, 6].

In the United States, independent system operators (ISOs) have gradually adopted the centralized bid-based pool concept as market architecture. They've continued to accommodate self-schedules while building and working toward a centralized pool-based method that doesn't jeopardize their goal of lowest-cost grid operations. This has given the ISOs room to gradually improve the market architecture in order to encourage more participants to use the energy market instead of submitting self-schedules [7]. Currently, all power transactions are resolved financially at the market clearing price (MCP), whether they are part of the day-ahead energy market or self-scheduled [8]. As a result, buyers who self-schedule effectively become price takers because they must settle at prices cleared in the day-ahead market. Bilateral contracts usually do not deal with the dispatch of available resources, but rather with the allocation of economic rents from spot markets and the risks of lower-than-expected capacity factors between parties.

Even a slight fall in demand can result in a significant reduction in system marginal costs of production in a competitive energy market where all generators are paid the market-clearing price under a uniform price auction structure. Although these peak pricing episodes are brief, they add to the consumer's average cost per kWh. Demand response (DR) in restricted electrical networks can dramatically reduce peak energy costs and can potentially operate as a check against generators abusing their market power. DR has the ability to improve the energy market's long-term efficiency [9].

Even simple real-time pricing, according to the Brattle Group, could yield yearly advantages related to disaster recovery in the tens of millions of dollars, with further potential impacts on capacity and investment needs [10]. By providing better price signals, technology, and information, and then allowing market participants to respond to these price signals, DR participation can be improved. In order to realize the potential of DR and energy efficiency, studies have revealed the necessity for advanced metering infrastructure (AMI) and building automation controls [9].

DR is used as part of demand-side management (DSM) strategies in regulated vertically integrated markets to postpone network upgrades and expenditures in restricted networks [11]. DSM investments by utilities have decreased dramatically since deregulation in the early 1990s, as utilities in restructured markets do not have financial incentives to invest in DSM in deregulated markets. Recent research has also found that in deregulated markets, historically poor participation in time-differentiated pricing programs, as well as low short-run price elasticity of demand can result in potentially severe social welfare losses. By combining administered DR programs with centralized energy spot markets, welfare losses from low DR levels could be greatly reduced [12].

The PJM Interconnection, L.L.C. (PJM) runs a centrally dispatched, competitive wholesale electric power market with installed generating capacity of 186,593 megawatts (MW) and 1,045 members, including market buyers, sellers, and traders of electricity, in a region with more than 65 million people in all or parts of 13 states (Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, and Tennessee Virginia, West Virginia) and the District of Columbia [22].

On the basis of all generation offers, demand bids, increment offers, decrement offers, and bilateral transaction schedules submitted to the PJM's day-ahead market, the hourly clearing prices for the following operating day are calculated [20]. Regardless of their operating condition, all generators must submit offers in the day-ahead market (e.g.: maintenance or unplanned outages). Generators who self-schedule must also submit their MW schedules to the day-ahead market. Buyers must submit their hourly demand bids for the next operating day in MW quantities at specific places that they are willing to acquire [21].

Buyers can also submit price-sensitive demand bids, which include the price as well as the number of MWs and the location. After all of the submissions have been received, the prices are determined using the Locational Marginal Pricing (LMP) approach, which takes into account three factors: the system energy price, congestion price, and loss price. For the day-ahead

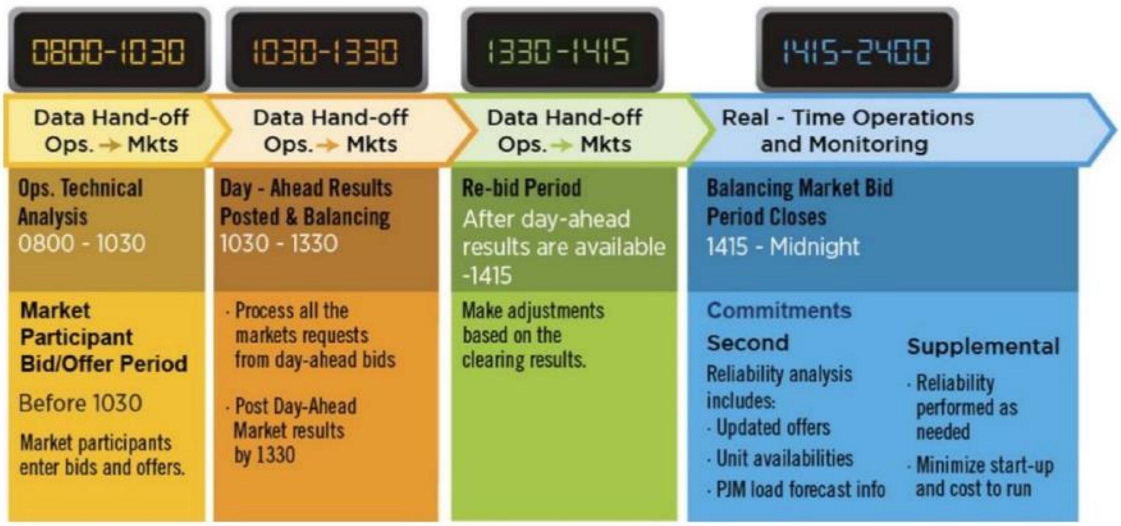

Fig 1.3 PJM market timeline [20]

market, PJM's scheduling concept is as "to schedule generation to meet the aggregate demand bids that results in the least-priced generation mix, while maintaining the reliability of the PJM RTO" [20]. The day-ahead schedule is created using the lowest-cost, security-constrained resource commitment and dispatch for each hour of the next operating day [21]

1.3 OBJECTIVE

There are multiple objectives behind carrying out the thesis on Demand Side Management and Demand Response.

1. To observe the effect by Analyzing the already successfully executed DSM scheme like PJM wholesale market model and theoretically applying the same on Indian power market is the main objective.

2. To assess the concept of LMP in Indian market is an objective. Locational Marginal Price (LMP) has been already introduced by many power markets outside India like PJM successfully. LMP may have a huge impact on Indian power market.

3. To understand the demand side participation in controlling peak load through a conceptual mathematical model. More and more customer participation is required for successful implementation of Demand Response in India. Price incentive based DR can be a useful strategy here.

4. To introduce the incentive price trigger in DR scheme. The variation in net social welfare with the change in DR parameters through different case studies can give a better understating of the market.

CHAPTER 2

THEORY

2.1 DEMAND SIDE MANAGEMENT

In response to the effects of energy shocks on the power utility business, the idea of Demand Side Management (DSM) was developed in the 1970s. After the OPEC countries cut off oil supplies to countries that backed Israel during the Arab-Israeli War in October 1973, energy difficulties exploded. To punish western supporters of Israel, Arab allies inside OPEC countries stopped delivering oil to them. The oil-producing countries removed the boycott in early 1974, but the price of oil skyrocketed. Consumers had to spend more money on energy and less on other items as a result of increasing energy prices, and company activity has decreased. In order to lower electricity demand, utilities had started offering incentives to consumers who reduced their electricity usage, resulting in the creation of Demand Side Management.

Demand Side Management (DSM) has long been regarded as one of the most important interventions for reducing energy needs while maintaining continuous development. DSM has risen to unparalleled significance in recent years, and it has become a key part of practically all central and state missions promoting energy efficiency. DSM interventions have helped utilities in reducing peak electricity demand as well as deferring large investments in production, transmission, and distribution networks. Because of rapid changes in weather, a surge in economic growth, line damage, and other reasons, electricity demand can fluctuate wildly. Sharp oscillations might cause power outages in extreme instances. Because power demand may peak at a time when renewable energy supply is unpredictable, the shift to renewable energy has a role in these oscillations as well. The changing energy scenario necessitates a more flexible energy grid. Fortunately, utilities have a great instrument to control peak-load demands, allowing them to provide service while still saving customers money.

2.1.1 WHAT IS DSM?

Demand Side Management (DSM) is a demand-control approach used by electric utilities to encourage customers to change their electricity usage patterns and levels. A Demand Side Management program takes place on the user's premises and includes monetary incentives to encourage consumers to buy energy-efficient equipment, as well as lower pricing if they agree to reduce their usage during peak demand periods. It's a win-win situation, when customers agree to minimize their energy use during peak demand (and hence pricing) and shift their consumption to times when energy is more plentiful, the utility benefits from a more consistent supply, and the customer benefits from lower prices. The increasing need for public utilities as a result of rising population and higher living conditions has raised the energy demand for services offered by metropolitan municipal governments. Electricity is consumed by the municipal sector/urban local bodies for a variety of utility services such as street lighting, water pumping, sewage treatment, and other public buildings. Around 30% of the Indian population now lives in cities, and continued migration from rural regions is putting extra strain on urban local governments. The municipality sector's energy consumption is characterized by frequent variations and rising peaks in power load curves in the early hours owing to water pumping and in the evening hours due to street lighting. The inefficient use of electricity, caused by a lack of widespread adoption of energy efficiency technology and demand side management (DSM) activities, has resulted in a significant increase in the amount of energy consumed by municipalities. The Municipal Demand Side Management initiative can increase the overall energy efficiency of Urban Local Bodies, potentially leading to significant reductions in electricity consumption and cost savings for ULBs.

Demand-side management (DSM) programs are electric utilities' planning, implementation, and monitoring operations aimed at encouraging customers to change their electricity usage levels and patterns. Most DSM initiatives used to have the primary goal of providing cost-effective energy and capacity resources to help defer the need for new power sources, such as producing facilities, power purchases, and transmission and distribution capacity upgrades. However, as the business changes, electric utilities are turning to DSM to improve customer service. Only energy and load-shape altering operations conducted in response to utility-administered programs are referred to as DSM. It excludes energy and load-shape changes that occur as a result of the machine's normal functioning.

Demand-side management (DSM), also known as energy demand management or demand-side response (DSR), is the process of reducing a client's energy demand using a variety of tactics, including behavioral changes through awareness and financial advantages. The goal of DSM is to prevent consumers using more energy during peak hours or shifting their energy use to off-peak hours such as weekends or late at night. This may not always imply a reduction in overall energy consumption. Instead, it focuses on decreasing the need for unnecessary investment in power plants or networks in order to satisfy optimal demands, such as storing energy during off-peak hours and discharging it during peak hours. DSM's most recent method for reducing power usage is to aid grid operators in stabilizing intermittent generation from solar and wind sources, particularly when energy demand and renewable energy supply do not coincide.

2.1.2. DSM PROGRAMS

Three most important Demand Side Management programs are:

a) Energy Efficiency: This is a sort of DSM in which we consume less energy to perform the same tasks, such as a permanent decrease in demand by replacing inefficient equipment. Energy efficiency is described as a long-term conservation approach that uses energy-efficient procedures to save energy and minimize demand. House appliance efficiency enhancement and weatherization are two examples of energy-efficiency schemes. Weatherization entails shielding a structure from the elements, such as wind and sunshine, as well as modernizing structures to reduce energy use and losses. Implementing energy-efficiency program can reduce on-peak demand and average power system costs while also deferring the need to enhance power system capacity. Among the energy-saving measures are:

1. Using energy-efficient buildings and appliances to reduce energy usage and encouraging consumers to be more energy conscious.

2. Improving and maintaining electrical equipment on a regular basis by recovering heat waste, improving maintenance methods, using contemporary equipment with optimum designs, and implementing cogeneration.

3. Increasing the efficiency of power transmission and distribution networks through the use of (1) distributed generation; (2) advanced control systems for voltage regulation, three-phase balancing, power factor correction, and data acquisition and analysis in supervisory control and data acquisition systems; (3) modern technologies for data acquisition, such as low-loss transformers, smart metering, and fiber-optics; and (4) high-transmission voltage.

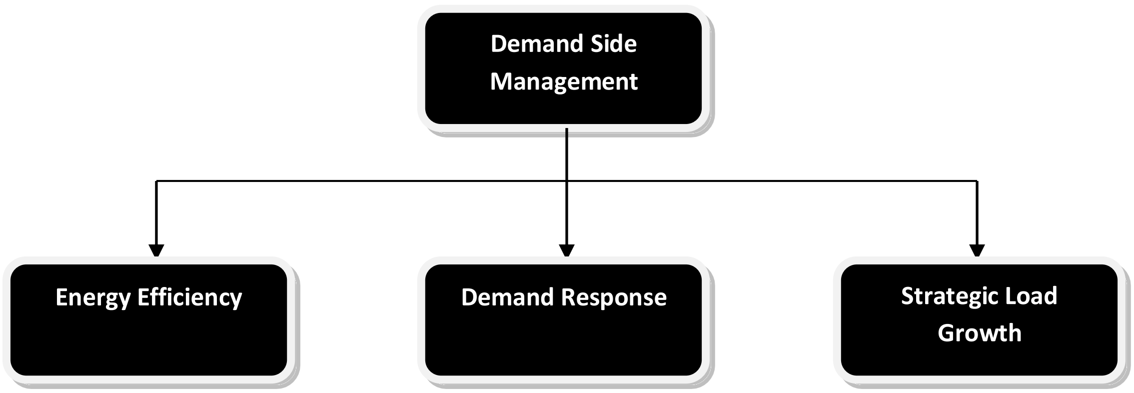

Fig 2.1: Major Types of Demand Side Management Program

b) Demand response: Any proactive or reactive techniques to reduce or shift demand are included in this category. Demand response (DR) programs not only help to defer high supply costs by reducing peak consumption, but they also help to change the net load structure (which is the total load minus wind and solar power generation) while integrating all types of renewable energy. DR refers to all changes made to a utility customer's electricity consumption patterns with the intent of altering the timing, total power consumption, or intensity of spontaneous demand. DR techniques include a variety of activities taken by the client at the electric meter during high charges or network congestion during peak periods. Given that one of the benefits is that it affects load directly. Other DSM techniques are gradually being replaced by DR program in the new DR is conducted using either valley filling to boost loads during off-peak times peak clipping to lower loads during on-peak periods or load shifting, which combines valley-filling and peak-clipping activities.

c) Strategic Load Growth: Strategic load expansion is described as an increase in electrical energy load caused by utilities through dual fuel heating, heat pumps, thermal storage (thermal energy is stored during off-peak times for use during on-peak times), and promotional rates. Because of the general increase in electricity consumption, strategic load expansion is often unavoidable, especially with the introduction of electric vehicles and contemporary power systems, as well as air conditioning in warm nations.

There are other kinds of Demand Side Management as follow:

a) Dynamic demand: Dynamic demand is the practice of delaying equipment running cycles by a few seconds in order to generate load set variety. The goal of dynamic demand is to monitor the electric grid's power factor, as well as its properties, and to administer loads individually at irregular intervals during peak hours to balance the entire system load with production, reducing serious power disorder. Because the operational cycle is only a few seconds late, the end user, i.e., the client, has minor effects.

b) Distributed Energy Resources (DER): On-site generation (OSG), distributed energy and generation, and decentralized/district energy are all terms for electrical production and conservation accomplished by a variety of tiny devices connected to the grid. DER, in contrast to huge renewable power plants, is more decentralized, adaptable, and near to the load. They typically have a capacity of no more than 10 MW. A smart electric grid interface can be used to control and coordinate the DER. Dispersed storage and generation allow for the aggregation of electricity from diverse sources, reducing environmental changes and improving production safety.

DSM can also be divided into different implementation scales:

a) National scale: On a national scale, energy efficiency is just as important as DSM initiatives. Legislation and standards in a variety of industries, such as machinery, housing, transportation, construction, and appliances, can help to enhance efficiency across the country.

b) Utility-scale: When demand is high, utilities can control storage water heaters, air conditioners, and pool pumps across vast areas to balance supply and demand.

c) District /neighborhood scale: This is also known as community scale. Central heating/cooling systems have been utilized to manage peak loads in regions with harsh winters or summers. Another method to put DSM into practice on a larger scale is to build a Net Zero Building or community.

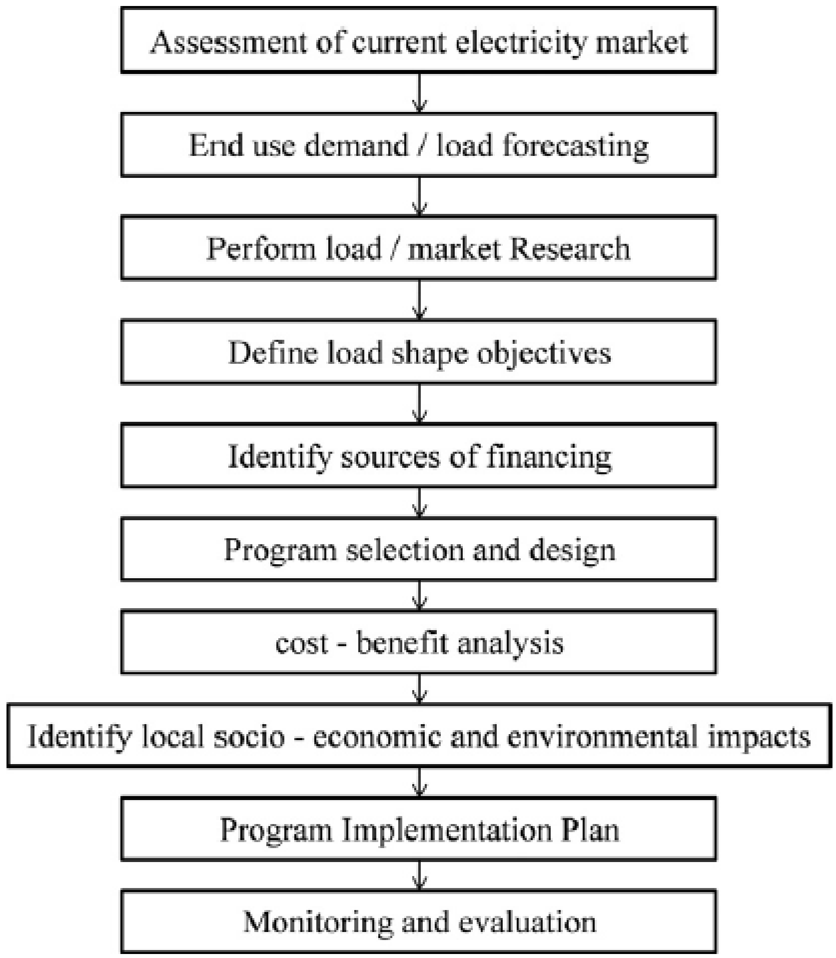

Fig 2.2: Flowchart for the steps to be conducted to implement DSM program successfully in India [4]

PV systems installed by experts are one option to apply DSM on a household/personal business scale. Solar energy's utility allows for a reduction in electric grid energy usage. Energy efficiency measures, storage water heaters, PV operations, air conditioners, building performance, and energy storage systems are all examples of systematic DSM approaches that may be implemented at the household/business level.

2.1.3 DSM STRATEGIES

Load characteristics of a particular day experiences two peaks generally. One is evening peak and another one is day peak. For easy understanding of DSM strategies, load curve is considered with one peak only.

a) Peak clipping: Peak clipping is a DSM technique which helps to reduce peak of a load curve by reducing the load during peak hours.

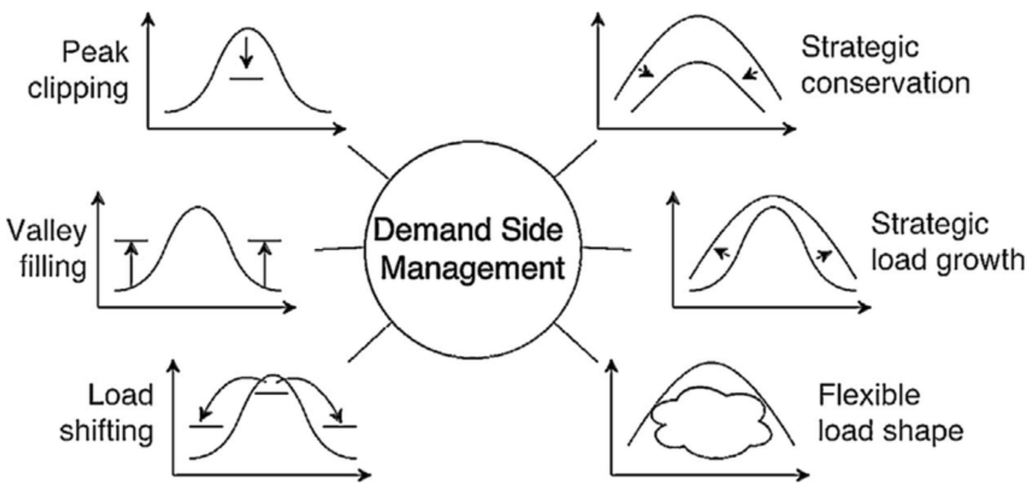

Fig 2.3: Visual representation of different DSM strategies

b) Valley filling: Mechanism to increase the load or demand in off peak hours is known as valley filling so that peak energy consumption can be reduced indirectly. Because area under the load curve needs to be maintain balance.

c) Load shifting: Load shifting mechanism is almost similar to the valley filling. The difference is that instead of increase consumption in off peak hours, now reduce consumption during peak hours and shift to off peak hours

d) Strategic conservation: This is the most adopted mechanism in developing countries where consumers are advised to use less electricity by using proper devices like LED instead of conventional bulb, such that peak can be reduced.

e) Strategic load growth: This mechanism suggests using more loads instead of reducing load.

f) Flexible load shape: In this strategy, load can vary in any direction. There should not be any restrictions on electricity consumption.

Essentially, utility is in charge of formulating and planning the DSM program's implementation strategy. Other implementers may include government agencies and regulators, for-profit and nonprofit organizations, or a partnership of various stakeholders in the formulation of DSM program design and implementation strategy.

2.2 DEMAND RESPONSE

Consumers can help the electric grid run more smoothly by lowering or adjusting their electricity usage during peak periods in response to time-based pricing or other financial incentives. Some electric system designers and operators use demand response systems as a resource for balancing supply and demand. These types of projects can reduce the cost of electricity in wholesale markets, resulting in reduced retail rates. Offering time-based rates such as time-of-use pricing, critical peak pricing, variable peak pricing, real-time pricing, and critical peak rebates are examples of ways to engage customers in demand response operations. It also includes direct load control programs, which let electricity companies to turn on and off air conditioners and water heaters during peak demand periods in exchange for a cash incentive and lower electric costs.

Demand response programs are becoming a more attractive resource alternative in the electric power market, as grid modernization activities expand their capabilities and potential consequences. Sensors, for example, can detect peak load problems and use automatic switching to reroute or reduce electricity in strategic locations, avoiding overload and the ensuing power outage. Consumers can now choose from a wider selection of time-based rate schemes thanks to advanced metering infrastructure. From information on their power use and prices, smart customer systems such as in-home displays or home-area networks can make it easier for consumers to adjust their behavior and reduce peak time consumption. These programs also have the potential to save money for electricity providers by reducing peak demand and deferring the development of new power plants and power distribution networks, particularly those used during peak periods.

One of the goals of the Smart Grid R&D Program is to develop grid modernization technologies, tools, and techniques to use demand response, as well as to assist the power industry in designing, testing, and demonstrating integrated national electric/communication/information infrastructures that can dynamically optimize grid operations and resources while incorporating demand response and consumer participation. OE is supporting smart grid technologies, distribution system modeling and analysis, transitive energy, consumer behavior modeling and analysis, and high-speed computational analysis capabilities for decision support tools in order to achieve this goal.

Electric utility companies employ demand response as a tactic to reduce or shift energy usage from peak hours of the day, when demand is highest, to leaner demand periods. It entails allowing customers to pick non-essential loads to be shed at peak times, either by the customers or by the utility. It is a pre-arranged agreement between the utility or intermediate agencies such as aggregators and the customer, with particular load, price, and time interval requirements. Because power plants and transmission networks are built to respond to the highest possible demand, lowering peak demand during high-demand times of the day helps utilities minimize total installation and operating costs while also reducing the risk of grid collapse.

Emergency demand response, economic demand response, and ancillary services demand response are the three basic types of demand response. Each one addresses a fundamental system requirement.

During times when demand threatens to surpass supply resources, Emergency Demand Response is utilized to prevent blackouts or brownouts. This usually happens on days when the weather is extremely hot or cold, and heating and cooling systems are putting more strain on the grid.

Utilities use Economic Demand Response to minimize the higher costs of producing electricity during peak demand periods of the day, which are linked with ramping up "peaking" power plants to meet greater-than-expected demand.

Ancillary Service Demand Response is used to assist the transmission of power to loads in a way that is consistent with the reliability criteria imposed by industry regulators on utility companies.

2.2.1 CLASSIFICATION OF DEMAND RESPONSE PROGRAMS

1. Price Based and 2. Incentive based

Different schemes for Price based DR:

a) Time of Day tariff (ToD): It provides a tariff structure with distinct pricing slabs for usage over different time periods. These values represent the average cost of generating energy over the course of a day. Customers can use this service to shift some of their loads to off-peak or typical hours, lowering their net energy costs

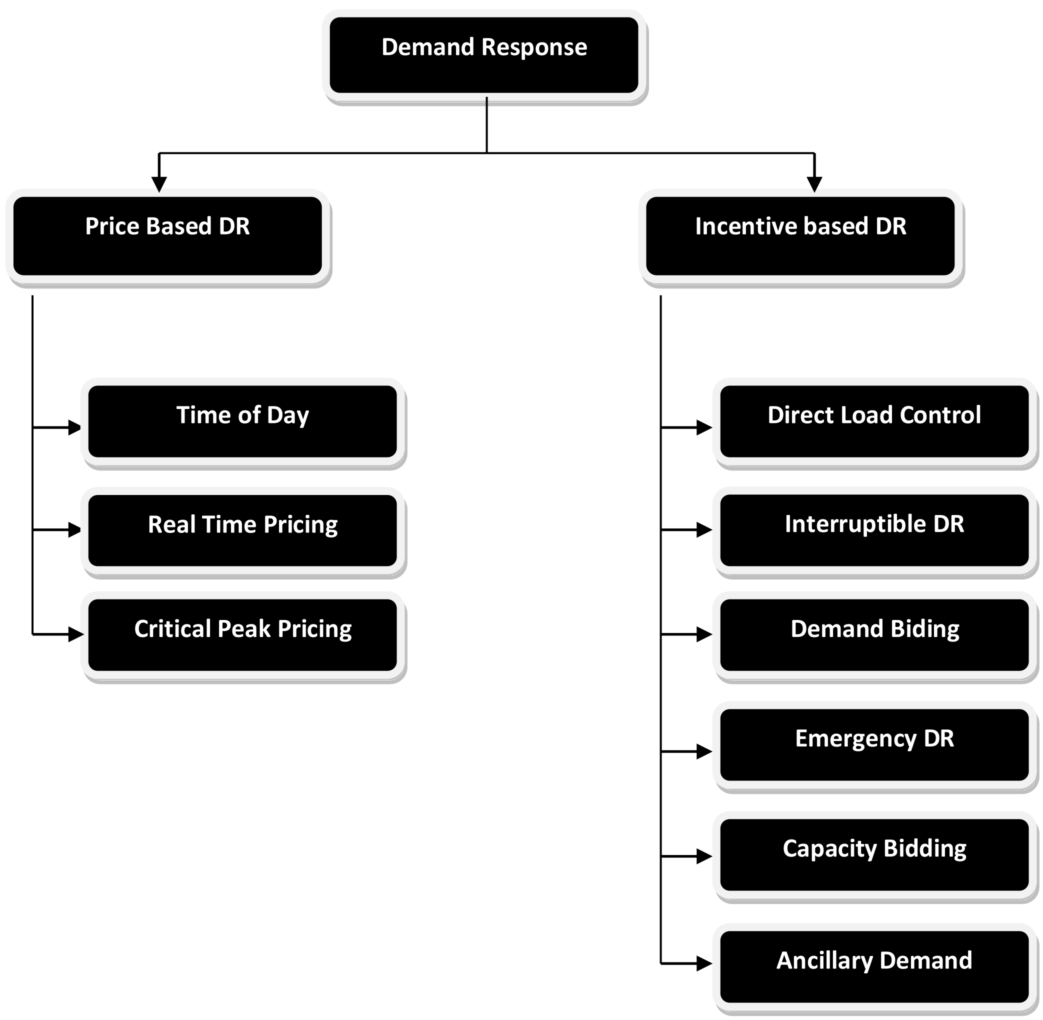

Fig 2.4: Classification of Demand Response

b) Real time pricing (RTP): Energy prices in the wholesale electricity market vary dynamically for each demand interval based on supply demand dynamics, and prices are broadcast to customers and aggregators on a day-ahead or hour-ahead basis. These prices serve as the foundation for customers' voluntary participation in DR.

c) Critical Peak pricing (CPP): This is a ToD and RTP mixed rate scheme with three slabs in the price. Utilities may declare critical events during a certain time period if they detect or expect high wholesale market pricing or power system emergency situations. Market dynamics influence the price over the chosen time periods. The ToD tariff is in effect on other days of the year.

Different schemes for Incentive based DR:

a) Direct Load control (DLC): Aggregators, for example, oversee the operation of client loads, including their curtailment and scheduling. This is appropriate for both residential and agricultural clients.

b) Interruptible or curtailable DR: Customers who participate in demand adjustment during scheduled or unscheduled system disruptions receive rate savings or bill credits. Customers who agreed to follow the contract but did not reduce their consumption during the outage hours will be punished according to the contract's terms. Large industrial loads are the target consumers for these projects.

c) Demand Biding (DB): Customers submit bids in the wholesale electricity market indicating their readiness to reduce their consumption. Bulk loads with consumption in the MW range are the target clients for this type of programs.

d) Emergency DR services: When the system runs out of reserves, customers are rewarded for reducing their consumption. Indirect load control system is used to carry out emergency DR.

e) Capacity Bidding: End-users, particularly during peak hours, offer load reduction in the form of system capacity as an alternative to expanding existing infrastructure.

f) Ancillary Demand services: Large rated customers place their potential to reduce usage as an operating reserve in the wholesale electricity markets in the form of a bid. It corrects short-term electrical market imbalances by deploying resources within seconds or minutes of an undesirable imbalance.

2.2.2 DEMAND & SUPPLY IN ENERGY MARKET

The demand side is referred to as the "load" in electricity markets. The load is the total of all electrical needs in a market at any one time. Elasticity is a measure of a variable's sensitivity to a change in another variable, most frequently the change in quantity requested in relation to changes in other factors, such as price. The price elasticity of demand is an economic measure of demand's sensitivity to price changes. Price elasticity of demand is a measurement of the change in quantity required as a result of a change in the price of a good or service. The degree to which demand responds to a change in another economic element, such as price, is referred to as inelasticity and elasticity of demand. Elasticity is a measure of how demand moves in response to changes in other economic conditions. Inelasticity occurs when fluctuating demand is not connected to any economic consideration. When determining elasticity or inelasticity, the most common economic component employed is price. Price elasticity of demand is a term used by economists to describe how sensitive demand is to price changes for a certain product. Consumer behavior and economic events can be forecasted using this indicator.

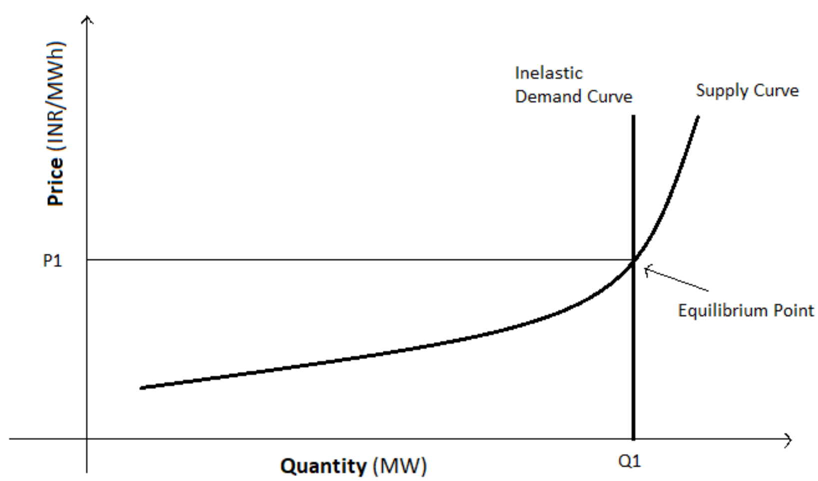

Fig 2.5: Electricity Demand-Supply (Inelastic) Curve

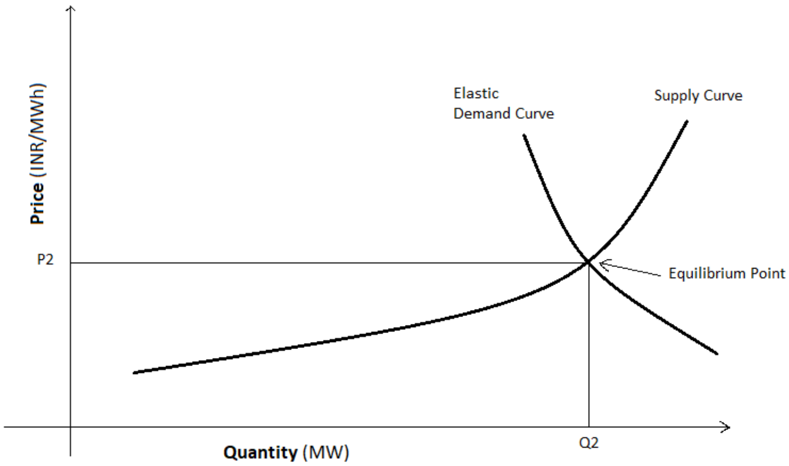

Fig 2.6: Supply-Demand (Elastic) Curve

2.2.3 Graphical Representation of DR

A supply and demand curve, like the one in Figure, can be used to demonstrate the idea od Demand Response. Since most customers are not directly affected by changes in spot prices, their short-term demand is idealized as a vertical line with no elasticity, representing the fact that most consumers are not responsive to spot pricing. A reduction in quantity demanded, from Q' to Q”, is how load curtailment is represented. Due to this, the spot price decreases from P' to P ".

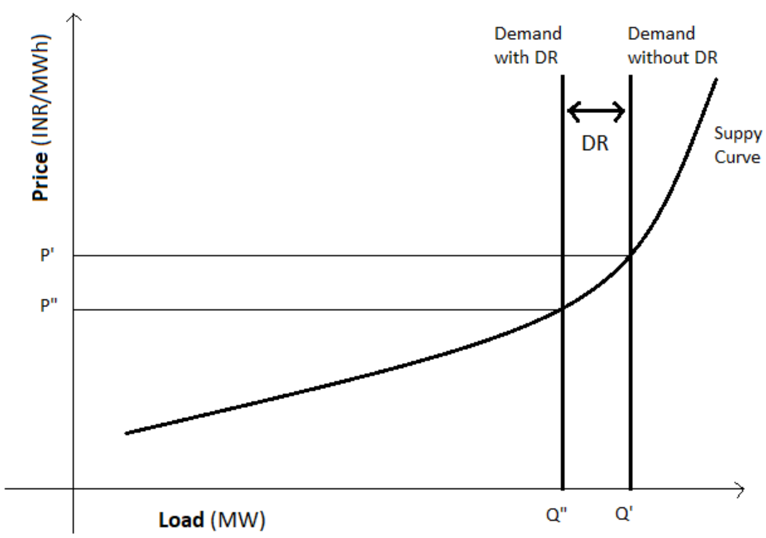

Fig 2.7: A conceptual representation of Demand response considering Inelastic Demand

2.3 LOCATIONAL MARGINAL PRICE

Locational Marginal Pricing, or LMP for short, refers to the price of purchasing and selling electricity at various locations within wholesale electricity markets, also known as Independent System Operators (ISOs). PJM, ISONE, MISO, CAISO, and NYISO are a few examples of ISOs. Losses, Congestion Cost, and Energy Price make up the three parts of LMPs. Day Ahead and Real Time LMPs are present in most ISOs. In order to reduce volatility, day-ahead markets allow market participants to purchase and sell wholesale electricity one day prior to the working day. Day-ahead LMPs represent prices in these markets. Real-time LMPs reflect pricing in real-time markets that enable buyers and sellers of power during trading hours.

LMP = System Energy Price + Transmission Congestion Cost + Cost of Marginal Losses

2.4 PJM WHOLESALE ELECTRICITY MARKET

Almost every RTO in the United States has some kind of market where customers or load aggregators can bid for demand reduction. Customers can participate directly in real-time and day-ahead energy markets through several DR initiatives. PJM offers two types of Demand Response programs: a) Economic Demand Response Program and b) Emergency Demand Response Program. Customers are paid the Locational Marginal Price (LMP) if the LMP in a specific zone is over a trigger point (established by PJM at $75/MWh) under the Economic Demand Response program. PJM pays the customer the difference between the LMP and the generation and transmission (G&T) components of the customer's bill when the LMP is less than or equal to $75/MWh. This economic DR program is available in both PJM's day-ahead and real-time markets (based on 2006 market). The real-time market has no penalties for non-compliance, whereas successful bidding in the day-ahead DR market entails a commitment to reduce load. The Emergency Demand Response Program is a voluntary reliability program that rewards customers that reduce load during a system outage with energy payments. The highest of $500/MWh or the zonal LMP for the hour determines the payment. There are no penalties for non-compliance, and PJM rarely uses this program (less than twice a year on average) [9]. During 2006, 1475MW of load was registered under the economic DR program, with a further 1081MW under the emergency DR program. During the peak load days in the summer of 2006, however, only 325MW of DR was cleared under the economic DR scheme. As a result, a distinction must be established between the amount of load that is registered to participate in the PJM DR markets and the actual amount of load that participates [9].

As previously mentioned, PJM's economic DR programme provides participation incentives in the form of payments connected to the LMP at the time demand curtailment occurs (which may differ from the time a customer commits to demand curtailment).The incentive is given under the economic DR programme after the LMP reaches a certain threshold, which we refer to as LMP*. The direct payment to the i^{th} market member for reducing demand by 1MW during hour t is made by

$$\pi_{i,t} = \begin{cases} LMP_t & LMP_t < LMP^* \\ (LMP_t - GT_i) & GT_i < \; LMP_t < LMP^* \\ 0 & GT_i \geq LMP_t \end{cases} \quad (2.1)$$

Here, LMP_t is the real time LMP at time t and LMP^* is the trigger point of price incentive DR model of PJM. GT is the total generation and transmission (G&T) components of monthly electricity bill for a customer. $(QR_{i,t} \times \pi_{i,t})$ is the direct payment for a i^{th} market player reducing $QR_{i,t}$ megawatts of demand during hour t [9]. Note that the direct payment $\pi_{i,t}$ indicates a payment from the rest of the system's participants (generators, other DR market participants, and energy market customers who do not offer DR) to the ith DR market participant. Even modest levels of DR, on the other hand, may have a significant impact on the system as a whole. Even though DR market participants receive subsidies, there are significant positive externalities from DR because prices are also reduced for individuals who do not reduce demand.

More broadly, the economic benefits of the PJM DR program can be broken down into four components, which are outlined graphically in Fig. 2.8. The transfer of producer surplus (short-run profit) to consumers who do not reduce their demand is referred to as Area A. Transfer from generators to price-responsive consumers is depicted in Area B. This transfer is essentially identical to the transfer in region A, but it provides the advantage of decreased energy prices to price-responsive customers. Area C denotes a gain in social welfare benefits for both consumers and producers. The incentive payout is represented by Area D. This represents a transfer of wealth from consumers who do not participate in the DR market to those who do.

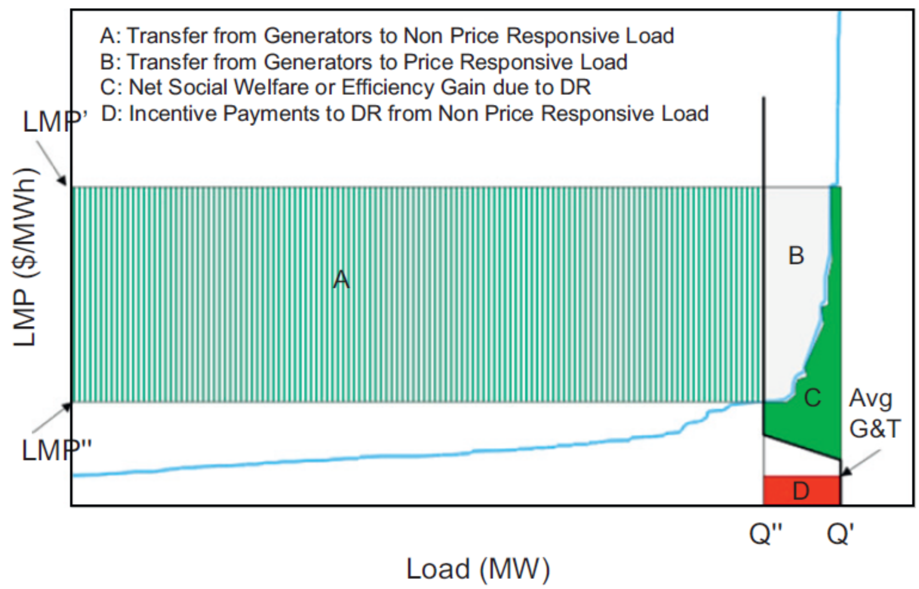

Fig 2.8: Conceptual framework for analysis of the PJM economic demand-response Program [9[

To determine the amount of DR for i[th] participant in the market for each hour *t*, DR supply-curve slope of α and each trigger point *LMP**, following equation 2.2

$$DR_{i,t} = \begin{cases} \min\left\{\frac{LMP"_t - LMP_j^*}{\alpha}, 7500\right\}, & when\ LMP_t > LMP_j^* \\ 0, & when\ LMP_t < LMP_j^* \end{cases} \tag{2.2}$$

Now, system load in absence of DR, possible system load is calculated using equation 2.3

$$Q'_t = Q"_t + DR_{j,t} \tag{2.3}$$

Using the values of load in absence of DR the probable LMPs in absence of DR can be calculated through a statistical model [9]. Four areas of Fig 2.8 can be determined using following equations 2.4-2.7

$$Area\ A = (LMP' - LMP") \times Q" \tag{2.4}$$

$$Area\ B = (Q' - Q") \times LMP' - \int_{Q"}^{Q'} LMP(Q_s)dQ_s \tag{2.5}$$

$$Area\ C = \int_{Q'}^{Q"} LMP(Q_s)dQ_s - \int_{Q'}^{Q"} LMP(Q_d)dQ_d \tag{2.6}$$

$$Area\ D = (Q' - Q") \times GT \tag{2.7}$$

Here, $LMP(Q_s)$ is Supply Curve and $LMP(Q_s)$ is Demand Curve and GT is Generation & Transmission cost.

2.5 WHOLESALE ENERGY MARKET IN INDIA

Wholesale markets function as a marketplace for electricity to be exchanged (bought and sold) before it is delivered to end users (households, businesses, industries, etc.). Trading like this is critical for the power system's stability since it allows demand and supply to be balanced.

Participants in the market include:

- Generators who trade and sell electricity generated by their power plants to either trading companies/power exchanges or distribution companies directly.
- Traders (power exchanges/trading businesses) who trade and source electricity to sell to distribution companies or end users.
- Load dispatch centers are responsible for maintaining balance by matching supply to demand and vice versa. They accomplish this by coordinating in real time with diverse stakeholders.
- Power is purchased directly from generators or from trading businesses by distribution corporations, who then sell it to clients.

In India's wholesale market, there are three types of contracts:

- Long-term (>= 7 years) - A power generator may enter into a Memorandum of Understanding (MOU) with a distribution firm or a state government to sell power for a set period of time at a rate set by the regulator or discovered through competitive bidding.
- Medium term (1–5 years): Generators can sell power for a medium term through 'DEEP,' a marketplace platform for distribution firms and generators, based on competitive bidding.
- Short-term (0-1 year) – A short-term contract between a buyer and a seller can be bilateral in nature and can be completed through mutual talks or through power

exchanges such as Power Exchange India Limited (PXIL) and India Energy Exchange (IEX).

Distribution businesses establish long-term contracts with electricity providers to assure supply stability and lower prices. Short and medium-term contracts are used to meet surplus requirements. As India's energy deficit has been reduced over time, a trend of greater short-term power sales (particularly through power exchanges) has been observed. Increased activity in the power exchanges has been attributed to lower power consumption (due to economic slowdown and efficiency gains), excess long-term power contracts, and the integration of more variable renewable energy into the grid. Despite a supply surplus in the country, rising power prices have resulted in the last three years due to a lack of liquidity and products in the short term markets. The government intends to create new forwards and futures products to develop the markets through proposed amendments to the Electricity Act 2003 (September 2018) and the Five Year Vision Document for the Power Sector (June 2019). The separation of the distribution and supply of energy is a major recommendation in the proposed Electricity Act revisions. This might mean that even ordinary people can get power from the market at the lowest possible price.

2.5.1 INDIAN ENERGY EXCHANGE (IEX)

The leading energy market in India is called Indian Energy Exchange. It offers a national automated trading platform for the actual supply of power, renewable energy, and certifications. In an effort to develop an integrated South Asian Power Market, IEX has more recently led the way in cross-border electricity trade by extending its power market outside of India. Modern, user-friendly, and customer-focused technology powers IEX, enabling effective price discovery and enhancing the simplicity of power purchase. The IEX ecosystem is strong, with 6,800+ participants spread over 29 States and 5 Union Territories, including 500+ conventional generators and more than 55 distribution utilities. Additionally, it has a sizable base of 4400+ commercial and industrial clients, including those from the metal, food processing, textile, cement, ceramic, chemical, automotive, information technology, institutional, housing, and real estate sectors, as well as business organizations.

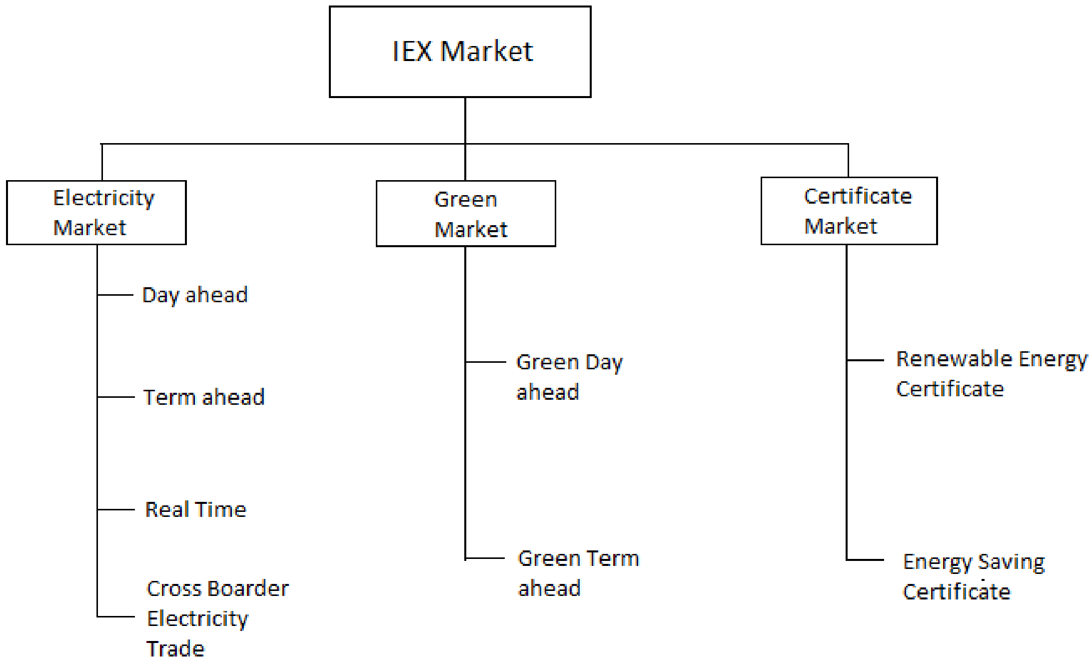

Fig 2.9: Different markets offered by Indian Energy Exchange

An aggregate demand supply curve of 16th May,2022 day ahead market for the time period of 10:15-10:30 has been show in Fig 2.10. Here the x axis and the y axis indicate the power quantity (MW) and energy price (INR/MWh) respectively. The red and the blue curves indicate the buy and sell BIDs registered in day ahead market respectively for the time period 10:15 to 10:30. Using this plot, a price-quantity relation of market demand and supply can be found for each 15 min time block. The intersection of supply and demand curves results in Market Clearing Price (MCP) and Market Clearing Volume (MCV), which are the intersection point's price and volume, respectively. Buy and sell bids for another 15 min for the same summer day is shown in Fig 2.11.

Fig 2.10 Aggregated Demand Supply plot of a 15 min (10:15 – 10:30) time block of 16th May, 2022 (Day ahead market)

Fig 2.11 Aggregated Demand Supply plot of a 15 min (19:00 – 19:30) time block of 16th May, 2022(Day ahead market)

CHAPTER 3

SIMULATION & RESULTS

3.1 DEMAND RESPONSE SUPPLY CURVE SLOPE:

3.1.1 DATA COLLECTION

Data is most important source of tool for analyzing and understanding any system, process and result. PJM Load curtailment market data of total 6 days in 2006 is collected from the plot of shown in Fig 3.1

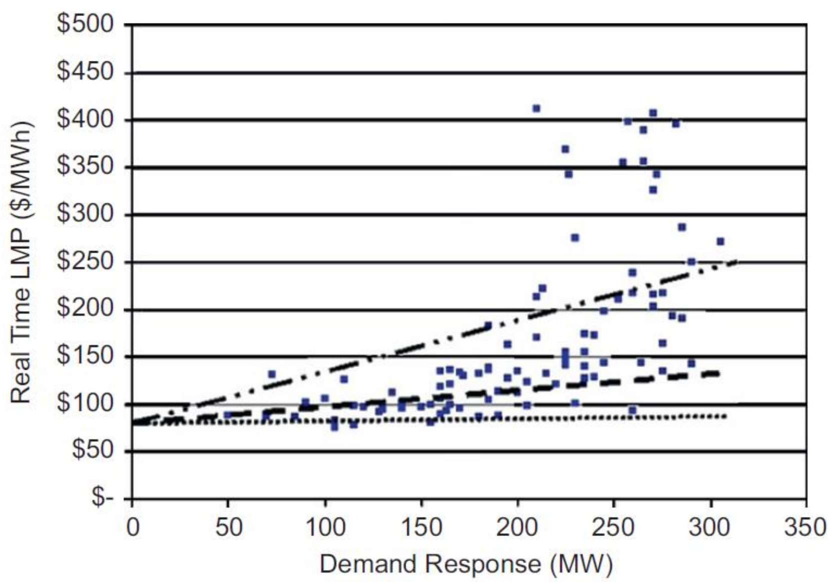

Fig 3.1: Load curtailment market results from the PJM economic demand-response market during 6 days in 2006 and three possible DR supply curves [9].

This graph depicts a price–quantity representation of actual market clearance bid data into the PJM economic DR day-ahead and real-time markets. These are the only price–quantity data for PJM's economic DR programme that have been disclosed. Here, three demand supply curve have been assumed for comparative social welfare analysis with slope 0.01, 0.15 and 0.54. This plot does not indicate actual load curtailment bids by the consumer rather it shows the actual LMP (Real time LMP) at which the loads had been curtailed and the amount of curtailed load (Demand Response).

Real Time Price and Demand Response follow a general linear equation as

$$LMP'' = \alpha \times (Q' - Q'') + LMP^{*} \quad (3.1)$$

Where, Demand Response is $(Q' - Q)$

Slope of DR supply curve is α and

LMP* is the trigger point of price incentive scheme. (In case of PJM model, LMP*=75$/MWh)

3.1.2 MATLAB SIMULATION

The above collected data has been plotted in MATLAB and using curve fitting tool, an approximate linear relation between Real Time LMP and curtailed load has been found as shown in Fig 3.2. The unit of Real Time Price and Load curtailment amount are $/MWh and MW respectively.

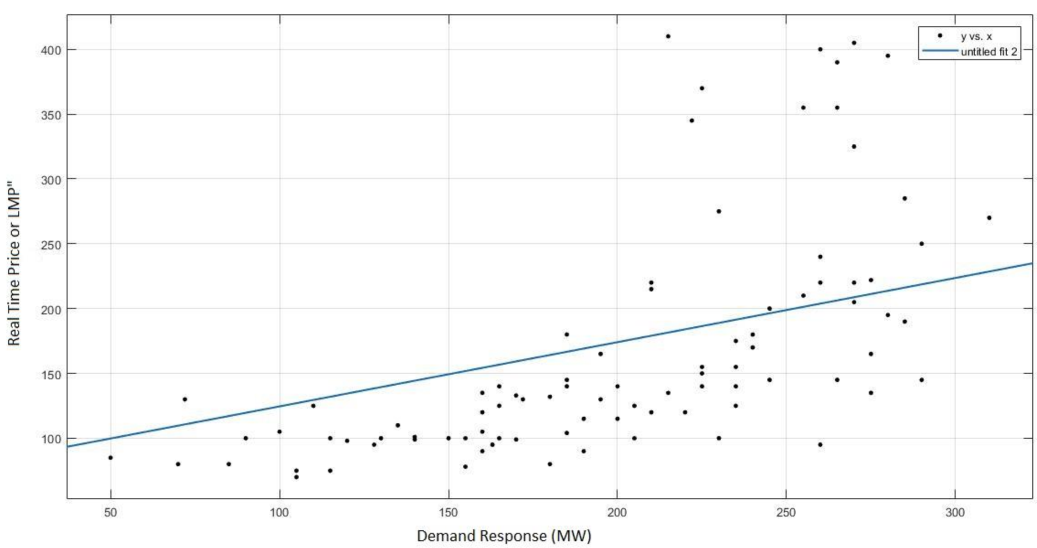

Fig 3.2: Graphical representation of PJM actual Load Curtailment data during 6 days in 2006 with a Demand Supply Curve, simulated in MATLAB

Quantitative General model: $f(x) = a * x + 75$ (3.2)

Coefficients (with 95% confidence bounds): a= 0.4955 (0.4201, 0.5708)

Here, $f(x)$ is Real time LMP with unit $/MWh and x is the Demand Response with unit MW. The value of a must be within 0.4201 and 0.5708 according to the fit.

Note that Demand Response Supply curve slope = α = a

Table 3.1: Goodness of fit for equation 3.2

SSE	R-square	Adjusted R-square	RMSE
4.915e+05	0.3014	0.3014	74.73

3.1.3 DISCUSSION

Instead of assuming demand response supply curve with multiple slopes as in Fig 3.1 [9], a particular slope value has been calculated [Fig 3.2] by fitting a linear equation with the help of same data set. The above mathematical model generates a slope value 0.4955 which will be used in next steps for further analysis. DR supply curve slope depends upon the trigger point LMP*. In case of PJM electricity market, LMP* was fixed already at 75$/MWh in 2006. That is the reason behind considering a fixed LMP* value in this model.

3.2 PROBABLE DEMAND RESPONSE:

3.2.1 DATA COLLECTION:

PJM Market report 2006 helps to collect the data of hourly load in PJM wholesale market. As this price incentive strategy was applicable in PJM market in the year 2006, the collected data is considered as load data with the effect of DR in each hour t. Considering DR, Real Time Load or Demand is denoted as Q'' and Real time LMP is denoted as LMP''. In absence of DR, Possible Real time load is denoted as Q' and Possible LMP is denoted as LMP'. Fig 3.3 is showing System load (Q'') and Real Time LMP (LMP'') for each hour of a summer day (2nd Aug, 2006).

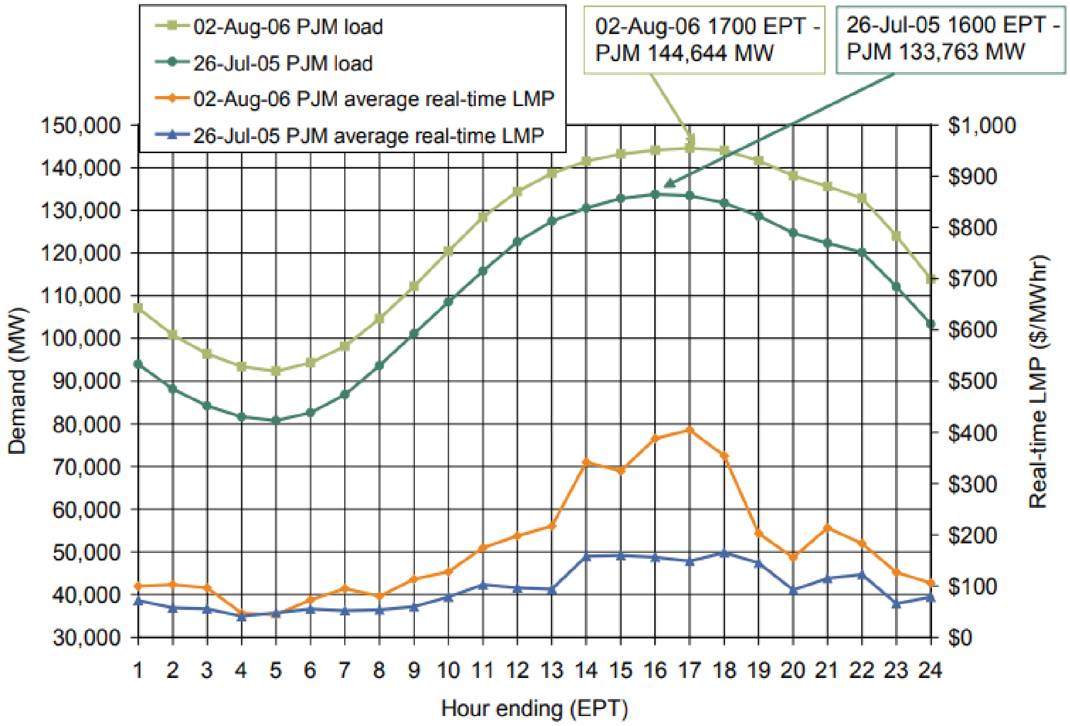

Fig 3.3: Graphical representation of Hourly Demand and Real time LMP of PJM on 2nd Aug, 2006 with peak load [22]

3.2.2 MATLAB SIMULATION:

With the help of collected hourly system load and real time LMP data, hourly probable DR, and probable system demand with DR has been calculated following equations 2.2-2.3 and represented for different values of incentive trigger point (LMP*), 60 $/MWh and 75 $/MWh. A wide range of LMP* values have been used to analyze and understand system behaviour. It shoul be noted that in Demand vs Hour plots shown in Figs 3.6-3.7, blue and orange curve denote PJM load with and without DR respectively. Here the unit of x axis is hour. Unit of y axis is GW for Demand plot and MW for Demand Response plot.

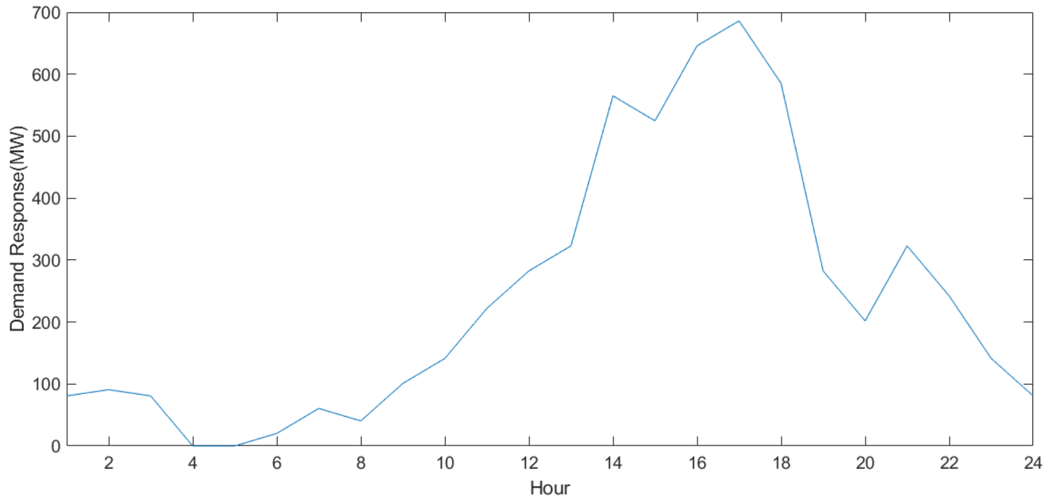

Fig 3.4 Hourly DR for LMP*=60 $/MWh

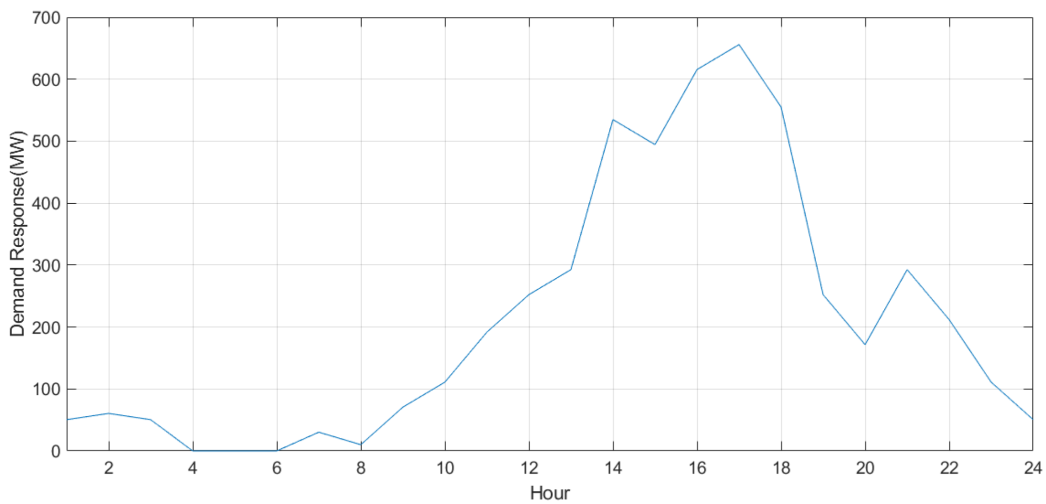

Fig 3.5: Hourly DR for LMP*=75 $/MWh

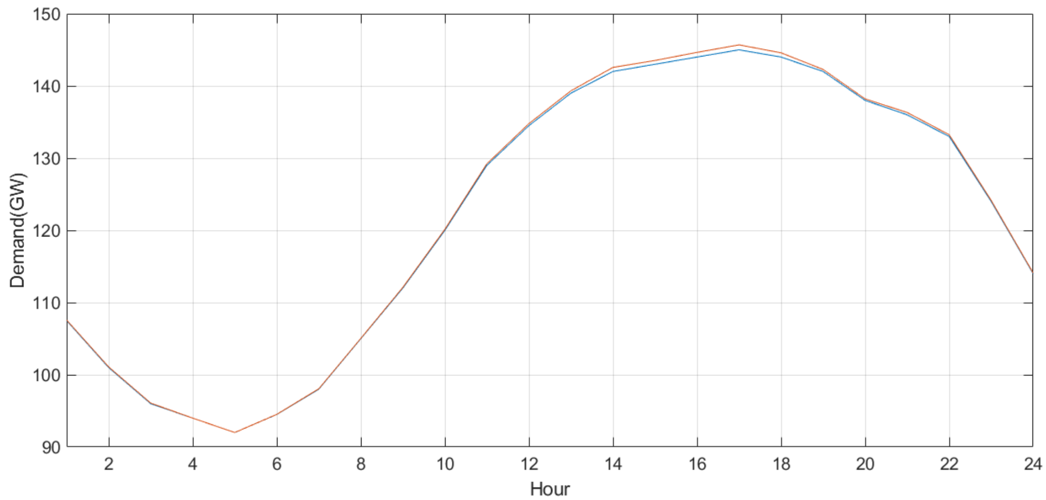

Fig 3.6: Hourly load with and without DR for LMP*=60 $/MWh

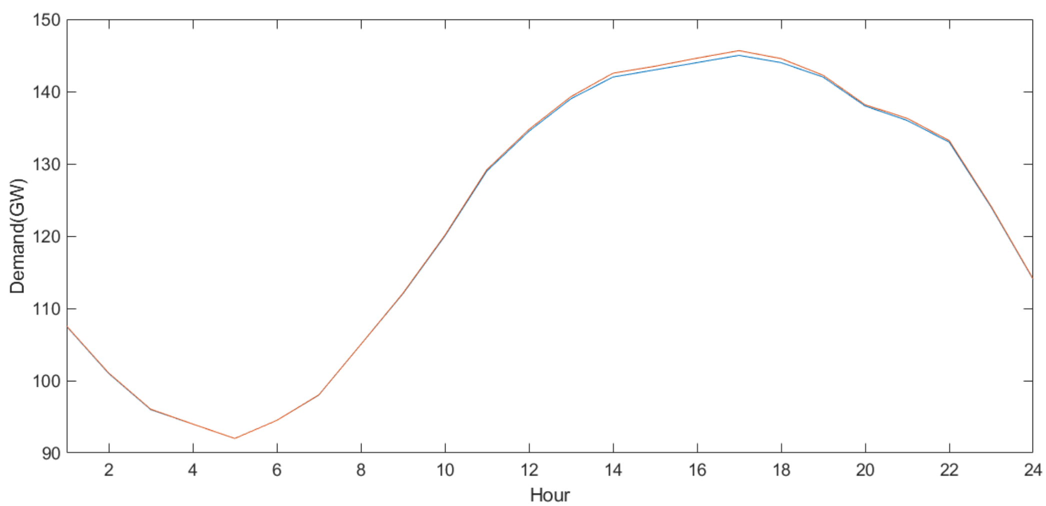

Fig 3.7 Hourly load with and without DR for LMP*=75 $/MWh

3.2.3 DISCUSSION

From the above plots, it is clearly visible that peak load occurred in evening hours on 2nd Aug in PJM which created a high surge in price. Demand response plots are the evident of successful participation of demand side participants during the peak hours as DR should be following the demand.

3.3 PJM SUPPLY CURVE

3.3.1 DATA COLLECTION

PJM market report 2006 PJM helps to collect average supply curve data during June to September for the year 2006. Peak load is also mentioned in the plot shown in Fig 3.8

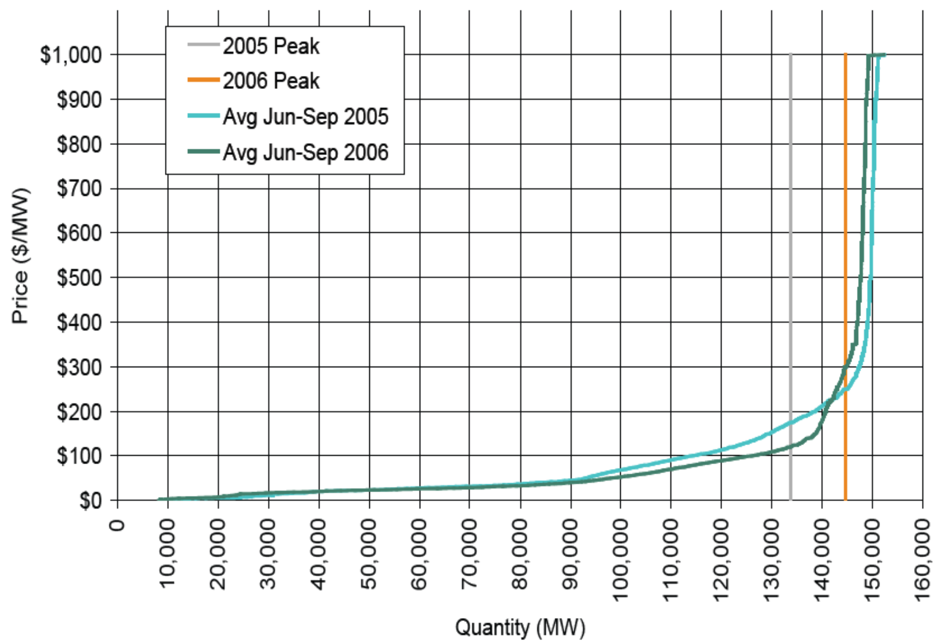

Fig 3.8: Average Supply Curve of PJM during Jun-Sep, 2006

3.3.1 MATLAB SIMULATION

Collected data has been plotted using MATLAB and using Spline Interpolant technique, an approximate price for each possible system load has been recorded. MATLAB generated average supply curve is shown in Fig 3.9.

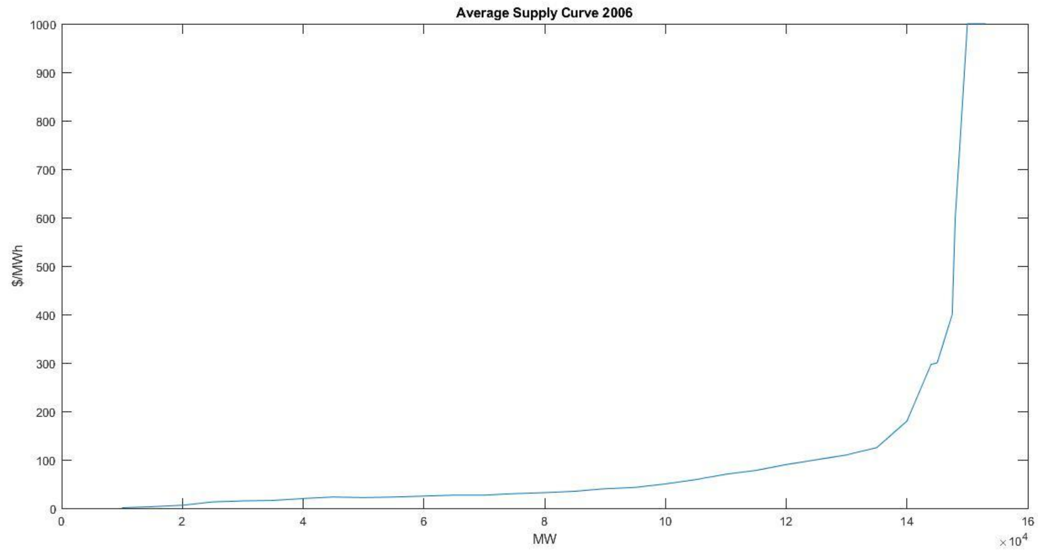

Fig 3.9: Average Supply Curve of PJM in 2006, generated in MATLAB

3.4 EFFECT OF TRIGGER POINT (LMP*) ON SOCIAL WELFARE

3.4.1 MATLAB SIMULATION

There are total four areas A, B, C and D indicating four different portion of wealth transfer in the energy market [Fig 2.8]. Area C represents the net social gain and area D represents the incentive payments due to DR. Following the 'Conceptual framework for analysis of the PJM economic demand-response program', four areas can be calculated. Using parameters *Q'*, *Q''*, *LMP'* and *LMP''*, areas C and D have been calculated using equations 2.6-2.7 and plotted with the variation of Trigger Points (LMP*) in MATLAB, considering a fixed value of DR supply curve slope and G&T cost. 12 different LMP* values has taken into consideration for doing the simulation. LMP*={30,40,50,60,65,70,75,80,90,100,110,120}

Here, the red curve denotes area D (incentive payments due to DR) and blue curve denotes area C (net social gain).

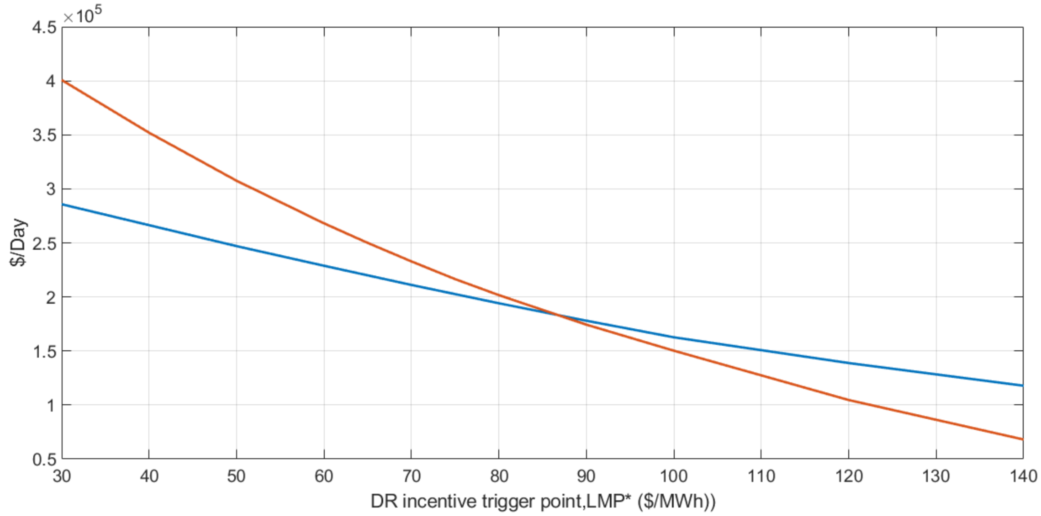

Fig 3.10: Impact of LMP* on incentive payments and net social welfare (without considering scarcity pricing rules) considering slope =0.4955 and G&T=40 $/MWh

3.4.2 VARIATION OF DR SLOPE

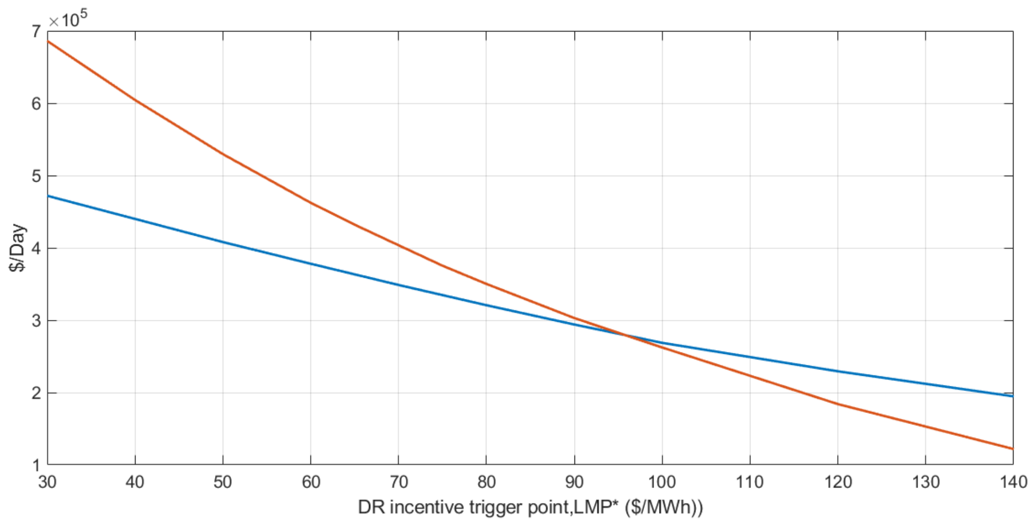

Fig 3.11: Impact of LMP* on incentive payments and net social welfare (without considering scarcity pricing rules) considering slope =0.3 and G&T=40 $/MWh

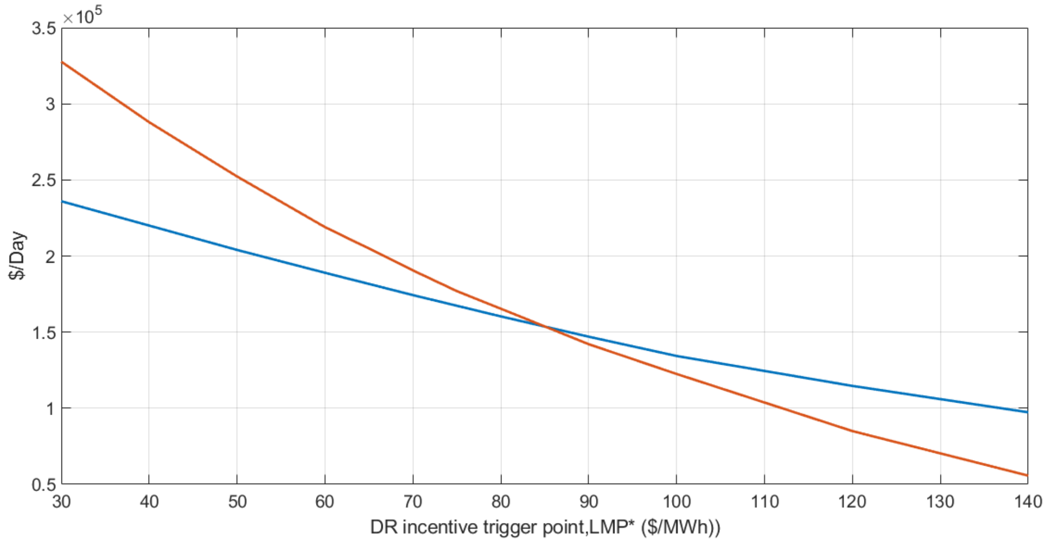

Fig 3.12: Impact of LMP* on incentive payments and net social welfare (without considering scarcity pricing rules) considering slope =0.6 and G&T=40 $/MWh

It is clear from Fig.3.10-3.12, that there is a particular value of LMP* (say LMP**) for which incentive payments and net social welfare become same. Otherwise it is required sacrifice one of them for the other. In Fig.3.12, approximately, 86 $/MWh is that the value of LMP*. Network social gain or efficiency gain is possible above LMP*=85$/MWh at the cost of incentive payments.

Table 3.2: Compromised value of incentive payment and net social gain for variation in DR slope with fixed G&T cost 40 $/MWh

DR slope	incentive payment due to DR	net social gain	LMP**
0.4955	1.833e+05	10833e+05	86.75
0.3	2.8e+05	2.8e+05	95.75
0.6	1.535e+05	1.535e+05	85.1

3.4.3 VARIATION OF G&T COST:

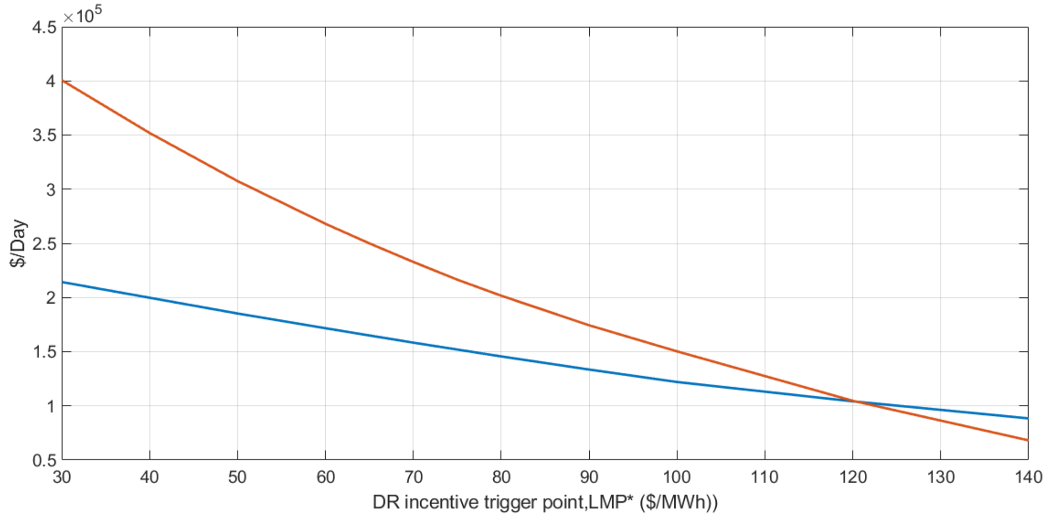

Fig 3.13: Impact of LMP* on incentive payments and net social welfare (without considering scarcity pricing rules) considering α =0.4955 and GT=30 $/MWh

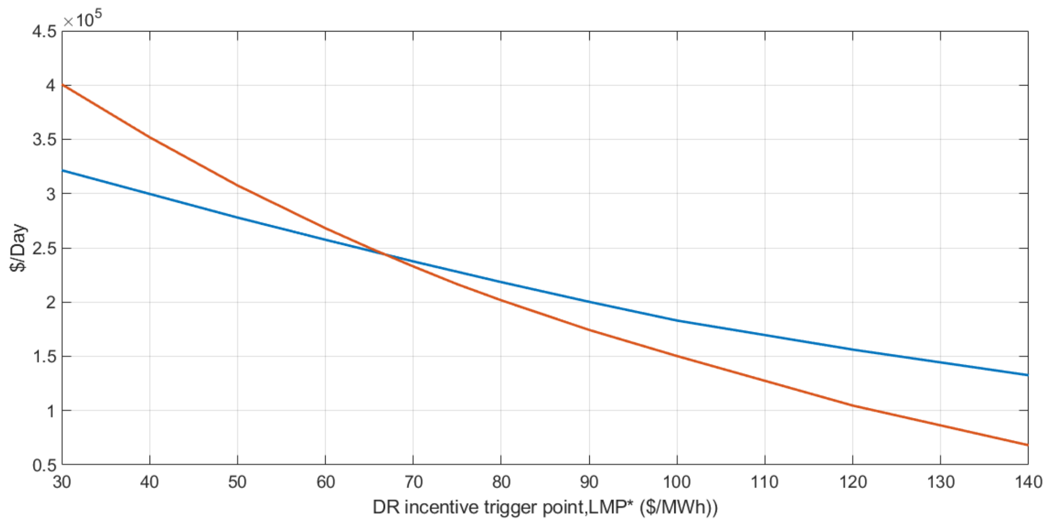

Fig 3.14: Impact of LMP* on incentive payments and net social welfare (without considering scarcity pricing rules) considering slope=0.4955 and G&T=45 $/MWh

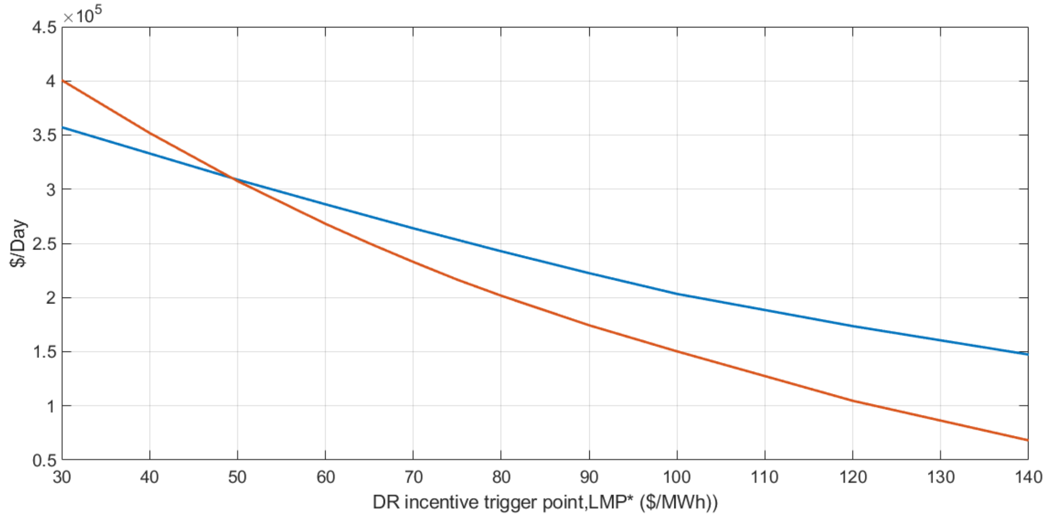

Fig3.15: Impact of LMP* on incentive payments and net social welfare (without considering scarcity pricing rules) considering slope =0.4955 and G&T=50 $/MWh

It is also clear from Fig.3.13-3.15, that there is a particular value of LMP* (say LMP**) for which incentive payments and net social welfare become same. Otherwise it is required sacrifice one of them for the other.

Table 3.3: Compromised value of incentive payment and net social gain for variation in G&T cost with fixed DR supply curve slope =0.4955

G&T cost($/MWh)	Incentive payment due to DR($/Day)	Net social gain ($/Day)	LMP** ($/MWh)
30	1.04e+05	1.04e+05	120.5
45	2.44e+05	2.44e+05	66.75
50	Not applicable**	Not applicable	49.4

** DR does not make any profit when trigger point (LMP*) becomes less than G&T cost

3.4.4 DISCUSSION

Net social gain must be more than the incentive payments and then only DR strategy said to be successful and that can be accessed from tables 3.2-3.3. So for a successful incentive based DR strategy, LMP* should be greater than LMP**.Through the simulation results, area C and area D have been plotted against the trigger point (LMP*) as described above. The crossover point of area C and area D depends on other parameters like DR supply curve slope and G&T cost. Variation of crossover points with variation of DR slope and G&T cost have also been represented graphically in Fig 3.10 to Fig 3.15. For G&T cost 50 $/MWh and DR supply curve slope 0.499 the strategy will not be applicable because incentive trigger point is less than G&T or fixed cost of the utility[Equation 2.1]. Therefore, proper planning and application of incentive based Demand Side Management requires a correct set or range of parameters like LMP*,DR supply curve slope, G&T cost. Due to fluctuations in fuel prices, the G&T component might shift dramatically from year to year. G&T fees could be determined by customer class and previous retail rates. While for some clients the G&T component may be linked to day ahead or real-time LMP. After a functional analysis of PJM electricity market, an application of similar kind of incentive based strategy is attempted for Indian electricity wholesale market in this research work

3.5 APPLICATION IN INDIAN ELECTRICITY MARET

3.5.1 AGGREGATED DEMAND SUPPLY CURVE

Aggregated Demand-Supply data has been collected form ‘Indian Energy Exchange’ (IEX) official portal. Day ahead market, term ahead market, real-time market, and cross-border power trade are among the four types of electrical markets offered by IEX. The Day-Ahead-Market (DAM) is a physical electricity trading market for delivery for all or some of the 24 hours of the next day, beginning at midnight. A double-sided closed auction bidding method is used to establish the pricing and quantity of power to be traded. Let us consider a summer day in India. Market data of aggregate demand supply curve for all the 15 minute time blocks of 16th May, 2022 has been recorded.

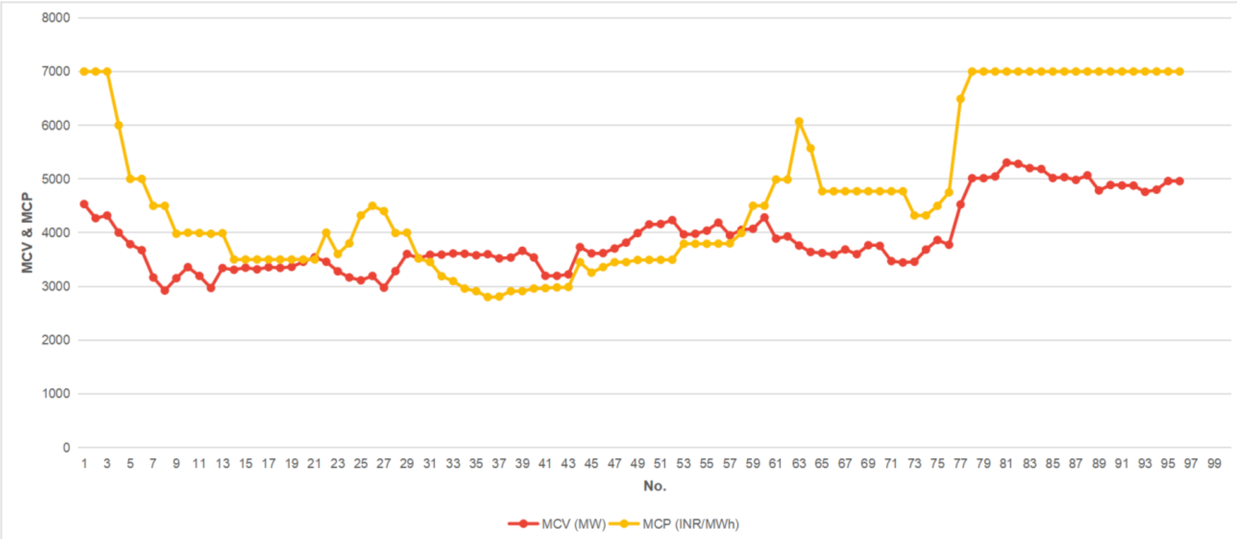

Fig 3.16: MCV and MCP values for each 15 min time block for a summer day in India (16th May, 2022)

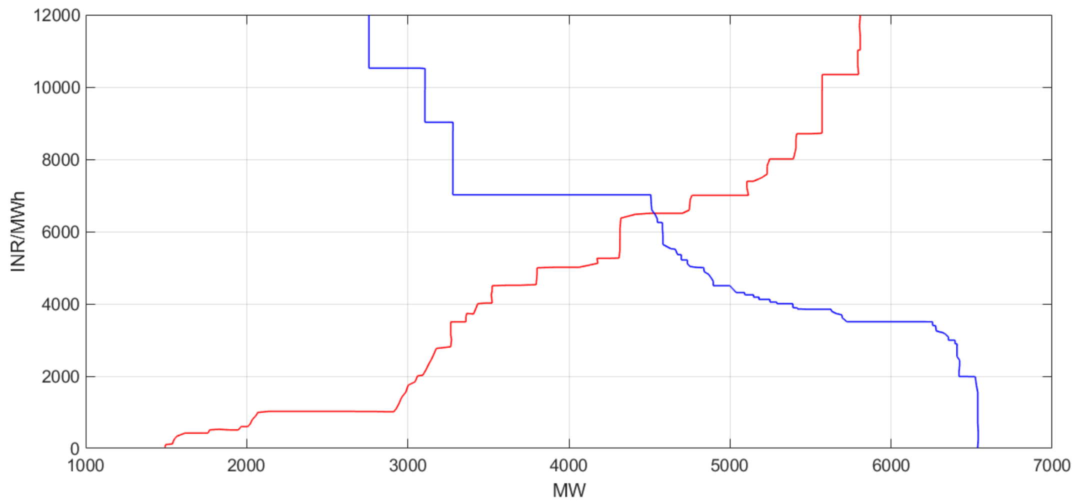

Fig 3.17: Aggregated Demand Supply plot of a 15 min (19:00 – 19:30) time block of 16th May, 2022 (Simulated in MATLAB)

There are a total of 96 time blocks (15 min each) present per day. Based on the market clearing volume (MCV) and market clearing price (MCP), a load and price data for a whole day have been plotted in Fig 3.16. MCV and MCP are indicated through red and yellow lines respectively. Unit of MCV is MW and the unit of MCP is INR/MWh.

Market clearing volume and market clearing price are defined based on buy and sell bids registered on IEX day ahead market. A typical demand and supply curve is shown in Fig 3.17 which is a simulated plot in MATLAB using data collected from Fig 2.9

3.5.2 QUANTIFICATION OF DR

Let us apply the concept taken from PJM market in Indian Power market. Consider at a point of time the connected system load is *Q'*. For the demand *Q'*, locational marginal price is *LMP'*. After load curtailment total demand is *Q''* and locational marginal price comes down to *LMP''*. So, Demand Response is the amount by which load is curtailed by the consumer in accordance with the price signal given by utility or Indian exchanges.

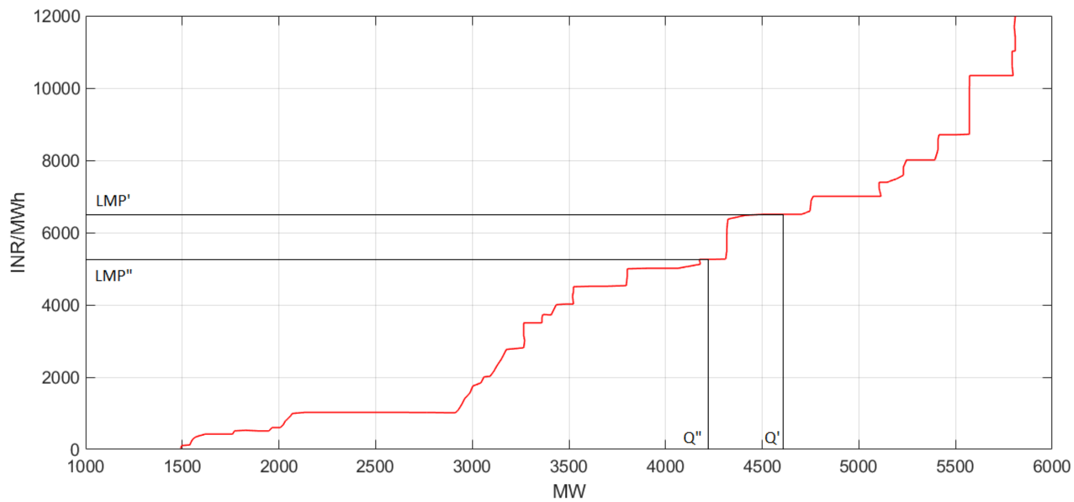

Fig 3.18: Conceptual model of DR representation in IEX day ahead aggregated supply curve with the help of Inelastic Demand

Table 3.4: Data used for above model in Fig 3.18

Demand (MW)		LMP (INR/MWh)		DR (MW)
Q'	Q"	LMP'	LMP"	Q'-Q"
5382	5002	8045	7040	380

3.5.2.1 ASSESSMENT OF DR SUPLLY CURVE DATA

A demo Demand Response supply curve is modeled based on theoretical data of a typical aggregated supply curve of IEX day ahead market in Fig 3.17. As there is no field or market data available for Indian power market, 10 different cases of load curtailment and respective real time LMP has been considered for create a linear relationship between DR amount and LMP. All the data used for this model has been shown in table 3.5. A variety of DR value at different price point are tried to incorporate in this model.

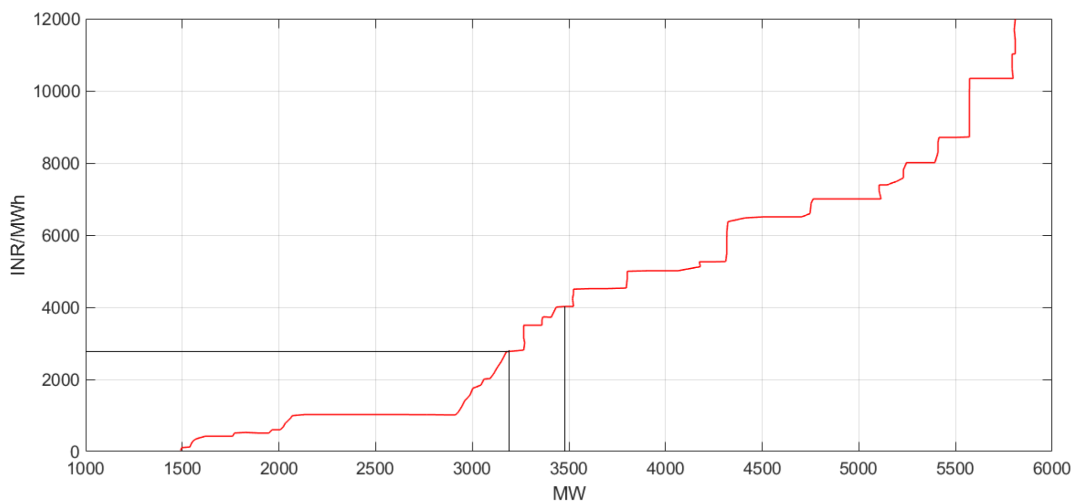

Fig 3.19 An assumption of DR at a low price region

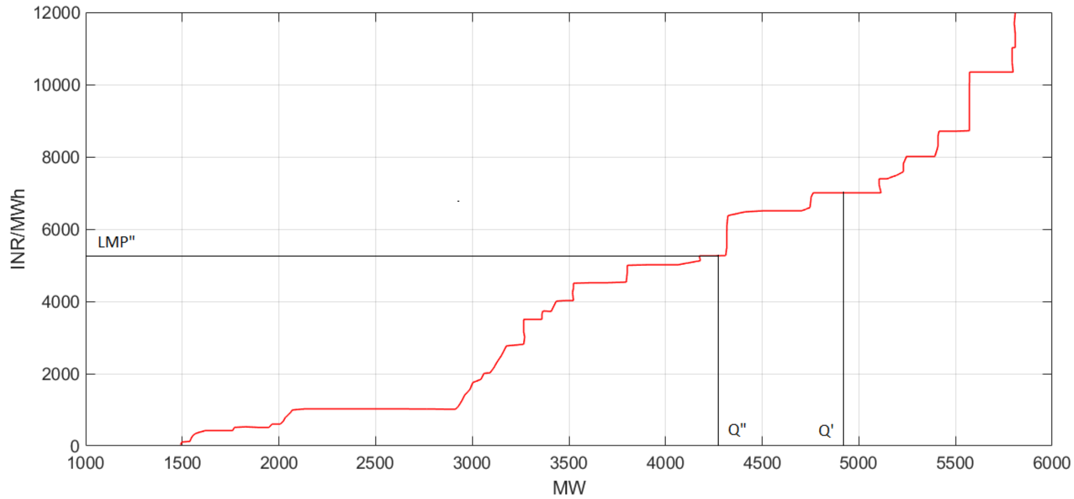

Fig 3.20 An assumption of DR at a medium price region

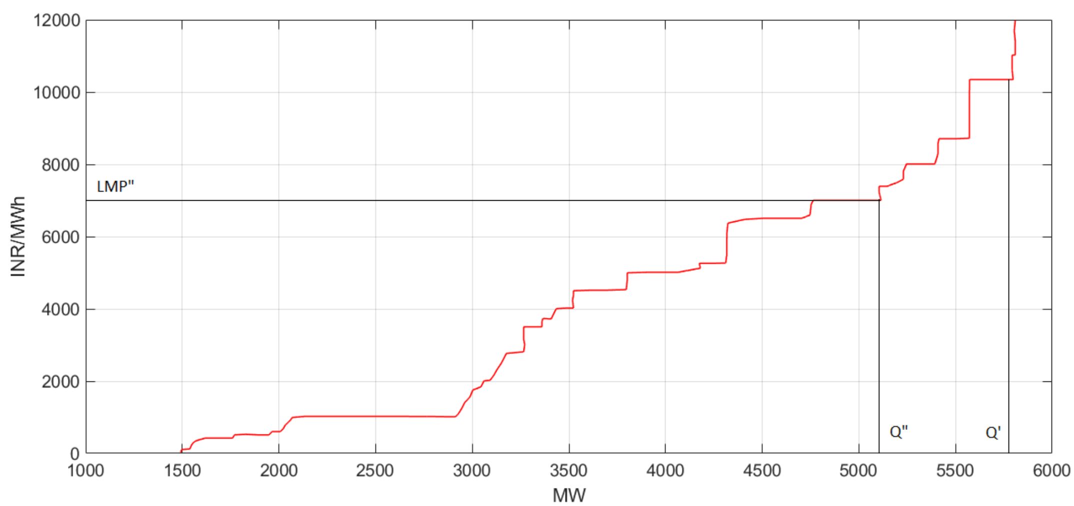

Fig 3.21 An assumption of DR at a high price region

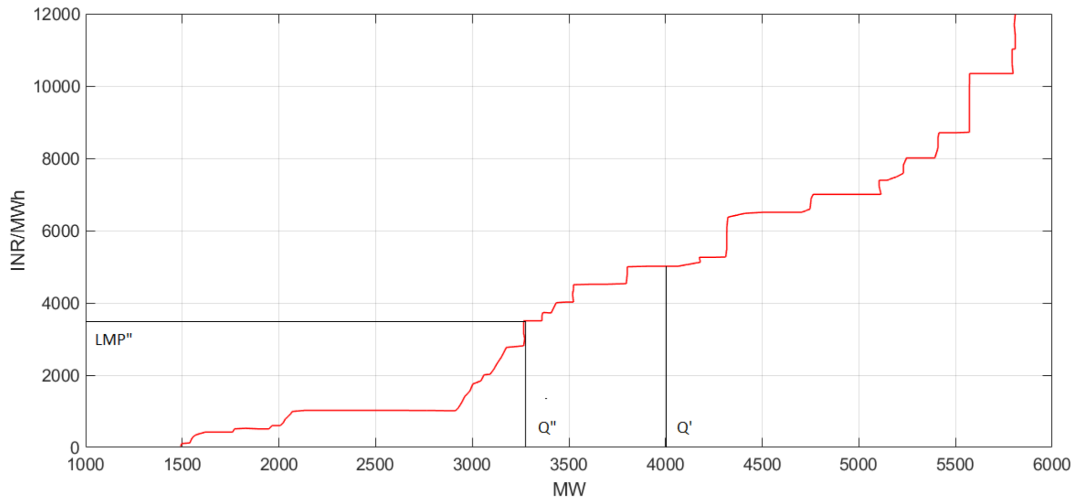

Fig 3.22 A considered case of DR with a 727MW load curtailment in total

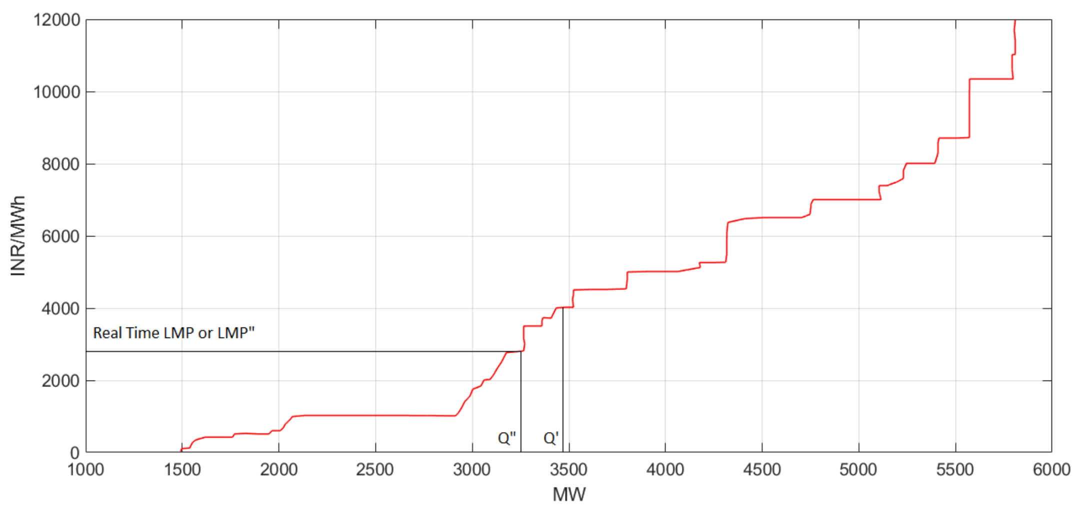

Fig: Fig 3.23 A considered case of DR with a 218MW load curtailment in total

Table 3.5: Data used for modeling Demand Response Supply Curve for India

No.	Q'	LMP'	Q"	LMP"	DR
	(MW)	(INR/MWh)	(MW)	(INR/MWh)	(MW)
1	3465	3992	3247	2771	218
2	4226	5263	3592	4475	634
3	4918	7002	4270	5252	648
4	4908	7002	4436	6469	472
5	3521	3992	3077	1958	444
6	4497	6469	3996	4973	501
7	5773	103501	5102	7027	671
8	3998	5023	3271	3450	727
9	4307	5237	3990	4983	317
10	3476	3992	3187	2746	289

Table 3.6: Values denoting percentage reduction of system load due to DR

Sl. No.	DR	Load before DR	Operating/ acting LMP after DR	% reduction load after DR
	(MW)	(MW)	(INR/MWh)	(MW)
1	218	3465	2771	6.291
2	634	4226	4475	15.002
3	648	4918	5252	13.176
4	472	4908	6469	9.617
5	444	3521	1958	12.610
6	501	4497	4973	11.140
7	671	5773	7027	11.623
8	727	3998	3450	18.184
9	317	4307	4983	7.360
10	289	3476	2746	8.314

3.5.2.2 MATHEMATICAL MODEL FOR DR SUPPLY CURVE

Based on the data in table 3.5-3.6, the fitted curve in MATLAB curve fitting tool is as below:

General model:

$$f(x) = a * x + b \tag{3.3}$$

Coefficients (with 95% confidence bounds):

a = 4.092 (-2.802, 10.99)

b = 2397 (-1187, 5981)

Table 3.7: Goodness of fit of the equation 3.3

SSE	R-square	Adjusted R-square	RMSE
2.012e+07	0.1897	0.08844	1586

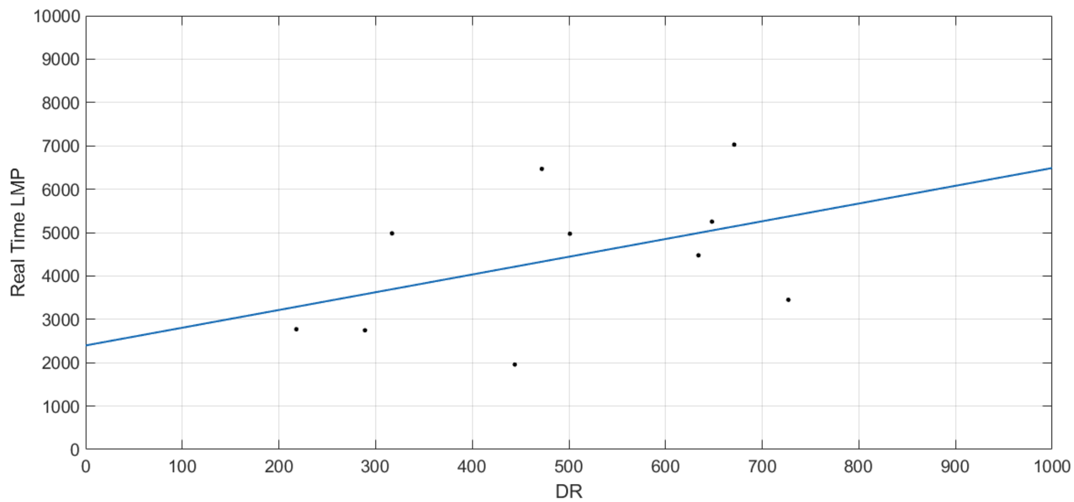

Fig 3.24: DR slope model with slope (a) 4.092 and Trigger point (LMP*) 2397 INR/MWh

By varying the trigger point or *b* value in the general model, variation of DR slope *a* is described with the help of different cases below.

Case 1:

General model:

$$f(x) = a * x + 1000 \tag{3.4}$$

Coefficients (with 95% confidence bounds):

a = 6.635 (4.476, 8.794)

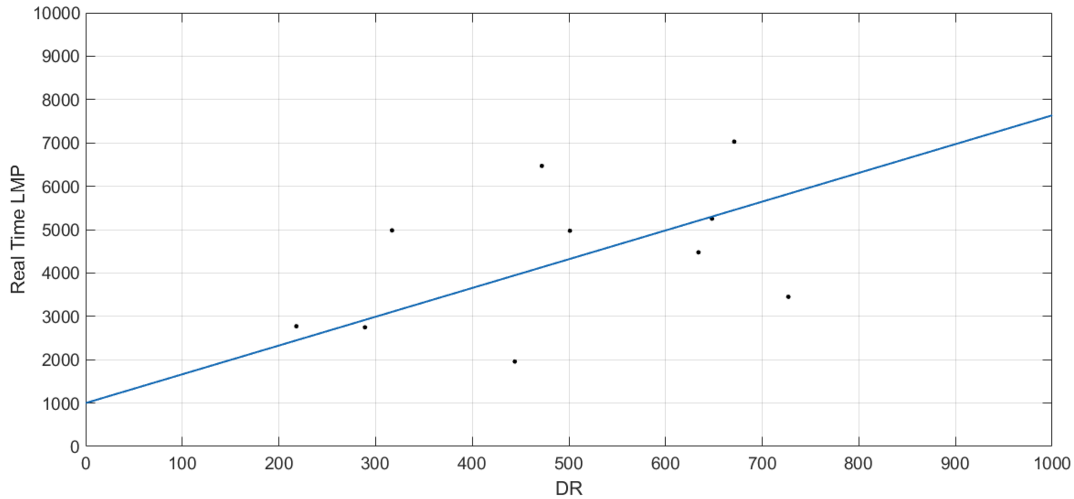

Fig 3.25 DR slope model with slope (*a*) 6.635 and Trigger point (*LMP**) 1000 INR/MWh

Table 3.8: Goodness of fit of the equation 3.4

SSE	R-square	Adjusted R-square	RMSE
2.216e+07	0.1079	0.1079	1569

Case 2:

General model:

$$f(x) = a * x + 2000 \tag{3.5}$$

Coefficients (with 95% confidence bounds):

a = 4.814 (2.748, 6.88)

Table 3.9: Goodness of fit of the equation 3.5

SSE	R-square	Adjusted R-square	RMSE
2.029e+07	0.1831	0.1831	1501

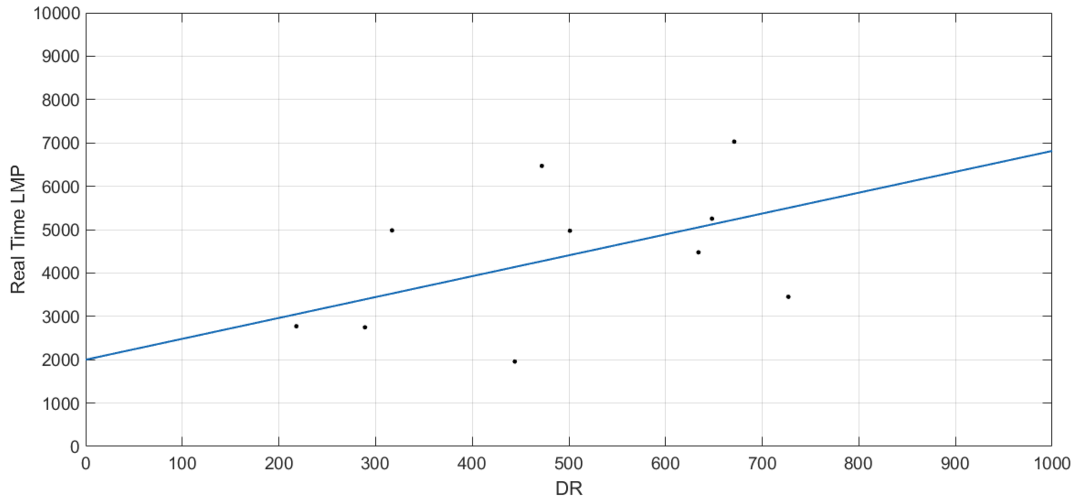

Fig 3.26: DR slope model with slope (*a*) 4.814 and Trigger point (*LMP**) 2000 INR/MWh

Case 3:

General model:

$$f(x) = a * x + 2500 \quad (3.6)$$

Coefficients (with 95% confidence bounds):

a = 3.904 (1.846, 5.962)

Table 3.10: Goodness of fit of the equation 3.6

SSE	R-square	Adjusted R-square	RMSE
2.013e+07	0.1893	0.1893	1496

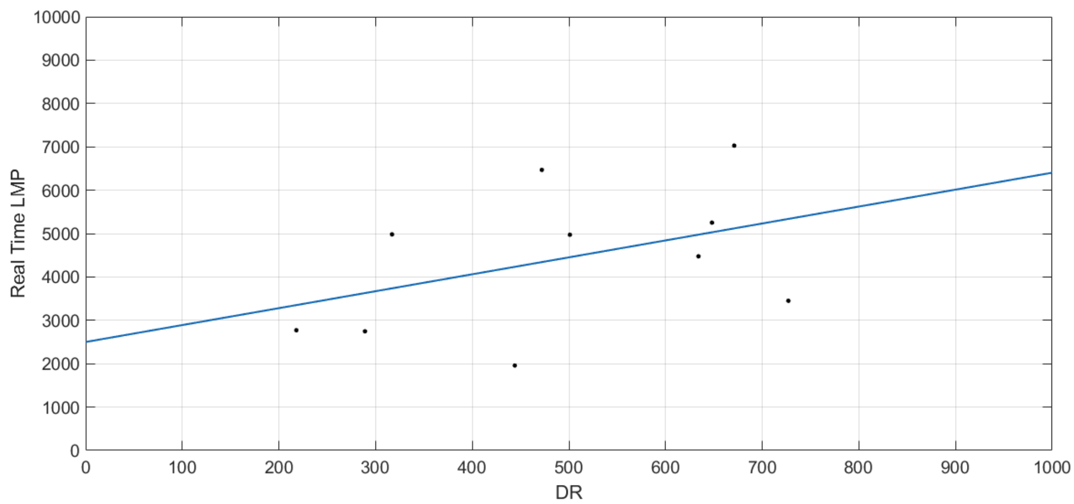

Fig 3.27: DR slope model with slope (*a*) 3.904 and Trigger point (*LMP**) 2500 INR/MWh

Case 4:

General model:

$$f(x) = a * x + 3000 \tag{3.7}$$

Coefficients (with 95% confidence bounds):

a = 2.994 (0.917, 5.07)

Table 3.11: Goodness of fit of the equation 3.7

SSE	R-square	Adjusted R-square	RMSE
2.05e+07	0.1745	0.1745	1509

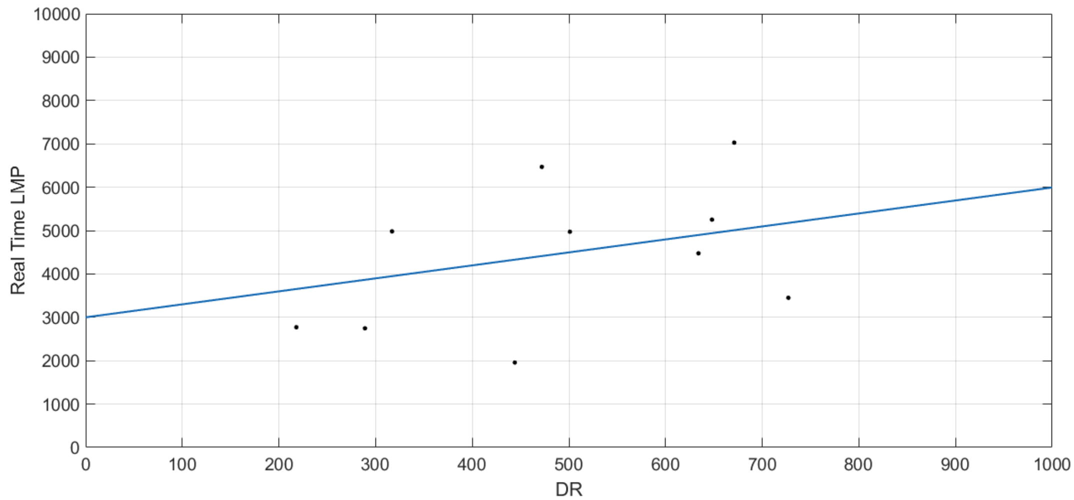

Fig 3.28: DR slope model with slope (*a*) 2.994 and Trigger point (*LMP**) 3000 INR/MWh

3.5.3 DISCUSSION

As there is no market data available of incentive based strategy in India, aggregated demand supply data of IEX day ahead market helps us to simulate an artificial model for better understanding of DR strategy. A typical supply curve of a summer day in India is used for this application [Fig 2.11]. 10 different load curtailments at high, medium and low LMP region has been considered and shown in Table. Based on these DR data, a general mathematical model has been established. In this model, there are two parameters. One is LMP* for incentive based DR and DR supply curve slope. Variation of the fit curve with the variation of any of these two parameters at a time is also presentenced. In Indian scenario, it is not possible to analysis actual social gain and incentive payments at present due to absence of field data and feasible value of DR parameters like incentive trigger price (LMP*). Whereas, In case of PJM, actual LMP* (75$/MWh) value for incentive based DR model is present and based on that comparative analysis was done.

CHAPTER 4

CONCLUSION & FUTURE SCOPE

4.1 CONCLUSION

Demand side participation of PJM price incentive DR model is reanalyzed and the effect of similar price incentive based DR on Indian electricity market has been attempted to quantify through data collection and MATLAB simulation, in this thesis. An effort has been given to collect precise data as much as possible. Due to the variation of input data of different parameters for PJM wholesale electricity market used in simulation procedure, the outcome may vary with other research works on the same system. Following conclusions can be drawn from results and observations:

1. The concept of Locational Marginal Pricing (LMP) in day ahead and real time market has a huge impact on price incentive based Demand Response strategy. Successful demand side participation depends on a proper selection of trigger point (LMP*) and amount of price incentives for a wholesale market.

2. Demand Response supply curve indicates a price quantity relationship of demand side participation. Only theoretical concept of strategies is not sufficient to understand the demand side participation, a theoretical concept followed by strong analytical model is necessary for proper understanding. Mathematical model of DR supply curve is very important analytical tool to analyze and understand the characteristics of any electricity market. Also a comparative analysis of DR model with the variation of market variables like LMP, DR slope, fixed cost is required which has been shown in this research work thoroughly.

3. As there is no field data available for Indian electricity market supporting demand response, bidding data or trading data of one of the biggest electricity exchange of Indian wholesale electricity markets, Indian energy exchange (IEX) can be a great tool for understanding the behaviour of demand side.

4.2 FUTURE SCOPE

There are lots of research work can be done based on this work such as:

1. A study of the same assessment model using more generalized supply curve of Indian electricity system can be a supporting work.

2. Finding a trigger price (LMP*) for incentive based DR for Indian energy market.

3. Incentive model will vary market to market because demand side participation depends on many external factors like time of use, geographical location, weather etc. An extensive study is required on Incentive payment model for Indian Electricity market.

4. A market survey on DR participation based on a consumer friendly incentive model is required and data collected through that survey will be a great tool for analysis Demand Response in India.

5. Smart metering techniques, efficient load forecasting tools may be linked with available DR program to get more realistic view.

6. Assessment of participation of DR from the present study can be used in dynamic stability analysis of power system also, as DR reduced sudden change in load from itself.

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