Chapter 2

Background and Literature Survey

Preamble

Due to socio-economic reasons, the existing Vertically Integrated System is getting converted to Deregulated Systems. But the basic problems like catering extensively high demand, managing voltage stability and system efficiency remains same along with economical considerations. The present chapter deals with a thorough and meticulous survey of existing and projected technologies in the field of power engineering, to ensure safe and reliable operation of the system. The bright prospect of HVDC, FACTS and optimization techniques has been a part of the quest made in this chapter. Most recent development like Smart Grid has also been illuminated to extend this pursuit to future power networks.
2.1 INTRODUCTION

There are many factors involved in the successful operation of electric power system. The system is expected to have power instantaneously and continuously available to meet consumer demands. Hence, in order to meet the demands it is necessary to commit adequate generating units. The most economical operation of modern power market demands proper interaction of the major control functions such as economic dispatch, performance analysis etc. An overall solution to these sets of problems must result in a continuous and reliable supply of electricity while maintaining the optimal cost of production and desired operating conditions. Under the socio economic changes where the regulated or state-owned monopoly market have been deregulated, it has become a challenging task to improve the performance in terms of cost optimization and congestion management without breaching the stability limits and other operational constraints.

Henceforth the purpose of this chapter is to familiarize the reader with the implemented as well as proposed technologies available for the improvement of system performance. One of the primary requirements in this regard is to assess the present performance of the system with classical and neo-classical techniques, which have been presented in the beginning of this chapter. Implementations of FACTS controllers and HVDC links have been discussed to motivate the system operator to implement these devices for their long-term benefits. Present day optimization techniques have been discussed with an objective of approaching towards the most efficient algorithms. For the enrichment of this chapter the operating conditions, the performance, cost optimization methodologies and pricing technologies of regulated and deregulated power markets have been studied [1-4].

2.2 POWER NETWORK PERFORMANCE EVALUATION

The study of these markets has pointed toward a few common solutions for power network performance evaluation and improvement. Maintenance of considerable voltage stability margin, up-gradation of transfer capacity by compensation and optimizing the generation and load schedule are among important keys for the enrichment of network utilization. These techniques have been discussed in the following sub-sections.

2.2.1 Importance of Voltage Stability on Performance Evaluation

Power utilities are now forced to increase the utilization of existing transmission facilities to meet the growing demand and for the improvement of power network performance. Maintenance of voltage profile and stability are important to maximize the use of the network for catering the request of a particular region at high efficiency [5]. Voltage instability is
characterized by the inability of the system to retain its voltage near the nominal value, even with a change in connected susceptance at the load bus. To maintain a standard operational condition, the voltage stability should be vividly monitored by the system operator. Researches are going on for long to study voltage instability of an interconnected power system [6, 7]. The methods adopted for the determination of stability had turned up in different literatures and are furnished below.

A. Classical Methods of Ascertaining Stability

J. Deuse et al shows some examples of dynamic simulations of voltage phenomena using a new general purpose stability program (EUROSTAG) covering the classical fields of transient, mid-term and long-term stability, and also the quasi steady state conditions of a power system [8,9].

Morison et al discussed voltage stability analysis of power systems using static and dynamic technique. Using a small test system, results of time domain simulations were presented to clarify the phenomenon of voltage stability for better understanding and modeling requirements. The same system was then analyzed using static approach in which modal analysis was performed using system conditions (or snapshots, which approximate different stages along the time trajectory). The results obtained using the static and dynamic methods were compared and were shown to be consistent [10].

However, system voltage instability can well be treated as a dynamic phenomenon [11-14] and in weak power system, increase in dynamic load or line tripping may lead to voltage instability. The voltage collapse phenomenon is also to some extent dependent on load characteristics. Therefore load modeling plays a key role in voltage stability assessment [15,16]. Researchers have proposed a number of techniques to analyse voltage collapse phenomenon [17].

Conceptual and theoretical backgrounds of the voltage instability problems have also been established [18-23] covering both the static and dynamic aspect of the problem [24-26].

T. Lie et al developed two methods of determining weak transmission stability boundaries based on the strong controllability and observability properties of power systems. The groups of generators being identified, as the method described in [18] uses a coherency measure evaluated for the set of all inertial load flow contingencies to determine groups of coherent generators.

The problem of voltage control and voltage stability in Longitudinal Power Supply (LPS) system has attracted much attention since last decade [27-32] but its occurrence might not have been directly linked with 'angle instability' [19, 28]. Voltage stability being one of the
prime requirements for proper control and assessment of security of LPS systems, it hinges on the coordinated response of all voltage and reactive power status throughout the network and it is very sensitive to changes in real and reactive power demands [14, 31, 33]. Studies of voltage collapse [34] clearly indicate that voltage instability becomes almost certain following large contingencies.

R. Yokoyama et al presented a flexible approach to a coordinated control of voltage and reactive power in order to enhance voltage security of an electric power system [35].

T. Van Cutsen and C. D. Voumas [34] reviewed the general methodology of analyzing voltage stability in the mid-term and in the transient time scale. It points out how the stability of mid-term dynamics can be predicted using constant power loads in a transient time scale modeling.

Voltage stability has long been categorized as a phenomenon that could be investigated using load flow methods [36, 37]. Newton-Raphson (N-R) load flow technique and Fast Decoupled Load Flow (FDLF) technique are widely accepted in load flow algorithm and it can even be well utilized in order to check the system performance including system stability on off-line basis. The solutions may diverge once the power system is stressed [38]. Earlier researches have also indicated that when the voltage collapse region is approached, the load flow algorithm converges slowly or not at all and it becomes very difficult to find step-size to be used for next iteration [30].

P.W. Sauer [36] et al have established a relationship between a detailed power system dynamic model and a standard load flow model. The linearised dynamic model was examined to show how the load-flow Jacobian appears in the system dynamic state for evaluating steady-state stability. Two special cases were given for the situation when singularity of the load-flow Jacobian implies singularity of the system dynamic state.

The development of the physical concepts and mathematical backgrounds of voltage stability has been done with basis on load flow solution feasibility [39], optimal power flow [40], bifurcation technique [41, 42] and singularity of Jacobian [36] etc.

V. Ajjarapu and B. Lee [41] presented a tutorial introduction to bifurcation theory and the applicability of this theory to study nonlinear dynamical phenomena in a power network was explored.

C. A. Canizares [42] discussed the relation between bifurcations and power systems stability through a thorough analysis of several examples, to clarify some ideas regarding the usefulness and limitations of bifurcation theory in network studies and operation, particularly in voltage stability related issues. The Ecuadorian National Interconnected System (SNI in
Spanish) was used to depict and discuss the effect of load modeling in saddle-node bifurcation analysis of real power systems.

At the present time, it has been an accepted proposition that the singularity of the Jacobian in the load flow solution indicates critical state of voltage [36] and the voltage stability index can be obtained from feasibility of the solution to power flow equations for each of the buses [25] on off-line basis. The achievements lie in the domain of static model as well as on dynamic voltage collapse models [28]. These models predict the proximity of the system near critical state and determine the reactive reserves etc. However, it is not usually frequently explored about the margin or proximity to the stability limit that is of concern to any system operator. In the operation of Longitudinal Power System (LPS), it is very much pertinent to investigate about voltage stability and security margins [30, 43, 21, 17, 38, 44]. Many researchers have proved that sensitivity analysis is as an efficient tool to assess voltage stability [45, 39, 46]. Efforts have been made to determine suitable voltage stability indices to identify the weak/weakest bus in power system responsible for voltage collapse [18, 33].

T. Van Cutsen dealt with the diagnosis of voltage collapse situations, following large disturbances and/or load increases [46]. A method had been proposed to identify the set of buses where load restoration is responsible for the collapse and to determine the corresponding corrective actions. It was implemented in a fast voltage stability simulator, using sensitivity techniques. Tap changer blocking and load shedding were illustrated on a practical 410-bus system.

I. Musirin and T. K. Abdul Rahman [47] demonstrated the use of line stability index termed as Fast Voltage Stability Index (FVSI) in order to determine the maximum loadability in a power system. The bus that is ranked highest in this method was identified as the weakest bus since it can withstand a small amount of load before causing voltage collapse. The point at which FVSI close to unity was taken as indicator of the maximum possible connected load and has been termed as maximum loadability at the point of bifurcation. This technique was tested on the IEEE test system and results proved the applicability of the developed technique to estimate the maximum loadability in a system.

P-V and Q-V curves are commonly used to determine the steady state voltage stability limit of a power system. M. H. Haque presented a new method [48] of determining the voltage stability limit using the P-Q curve. For a given operating point, the voltage stability margin can easily be determined from the stability boundary in the P-Q plane. The developed method of determining the voltage stability limit was tested on a simple system and very interesting results were found. P-V or Q-V curves are also commonly used to determine the maximum permissible load (or static voltage stability limit) of a power system.
It has been observed from literature survey that most of the authors used the Jacobian of the load flow equations as the 'workhorse' for calculation of voltage stability; Kundur et al [49] probably had given more weightages in using reduced Jacobian matrix as well as modal form of analysis for assessing voltage stability. Young-Huei Hong et al presented a similar work where they had used the minimum singular value of the Jacobian matrix of the load flow equation as an indicator of voltage collapse [50]. A. K. Sinha also depicted similar Jacobian based proximity of voltage stability indicator.

Other than employing the Jacobian matrix, M. Moghavvemi presented a line stability index based voltage collapse indicator in [51]. Another collapse proximity indicator has been presented in [52]. [53-56] had depicted steady state stability based indicators.

Optimal Power Flow (OPF) techniques have also been used to assess voltage stability [57]. Some researchers have incorporated contingency constraint in optimal power flow for proper voltage control in a power system.

B. Neo-Classical Methods of Ascertaining Stability

Due to the time complexity of classical approaches of determining stability, some stochastic techniques were harnessed in the field of power engineering for faster on-line processing to ascertain stability. In the recent past a large number of research works have been developed for the solution of power engineering problems using ANN [58-62]. C. Dingguo and R. R. Mohler presented the possible consequences of not considering load dynamics, which at worst can be a complete voltage collapse. Based on this observation, modeling of load dynamics was considered in their paper, and Neural Networks (NN) including recurrent neural networks were applied for load modeling. Furthermore, they presented the strategies, for the first time, to incorporate the neural-network-based load model into static and dynamic voltage stability analysis. The computation of the relevant sensitivity was carried out for the neural-network-based load model, and the results were used in the popular modal analysis. The proposed methods were tested on both the IEEE 14-bus system and practical system [63].

A multi-layer feed forward Artificial Neural Network (ANN) with error back propagation learning has been proposed for the calculation of voltage stability margins by A. A. El-Keib in [64]. The method efficiently determined the variation of voltage stability margin in varying demand state of the network. D. Paul in [65] presented an ANN function approximation based training schedule of instability indicators, which utilizes the generator-load mismatch and active/reactive power margins for on-line assessment of proximity of voltage instability of power network. Another feed forward ANN based novel approach of finding voltage instability by training with L-index has been cited by S. Kamalasadan in [66].
A combination of AI technologies and three-dimensional PQV has been utilized by K. Yabe and J. Koda in [67] for locating the point of voltage collapse of a large power network. H. B. Wan in [68] presented a neural network based approach for contingency ranking of voltage collapse by the singular decomposition method. He used an RBF map to predict accurately, after training, the stability of a power network by its operating conditions. The effectiveness of ANN based technologies have been extended to even deregulated power networks by B. Suthar when he cited a novel stability assessment method by neural network training in a combined pool and bi-lateral transaction mode regime in [69].

An enhanced Radial Basis Function network based multi-contingency voltage stability monitoring system has been developed by S. Chakrabarti in [70]. The method effectively determines the power margin of different nodes in a large network for stability.

2.2.2 Significance of Compensation Techniques

The continuing interconnection of bulk power system brought about by economic and environmental pressure has let to an increasingly complex system that must operate even closer to the limits of instability. Increased use of transmission facilities due to higher industrial output and deregulation of power supply industry have provided the momentum for exploring new ways of maximizing power transfers in existing transmission facilities while at the same time maintaining acceptable levels of network reliability and stability. In this environment, performance control of power network is mandatory. An in-depth analysis of the options available for achieving such objectives has pointed in the direction of power electronics [71]. Series capacitors are widely used in ultra high voltage network in order to compensate for the series reactance of long lines [72-77]. In the recent past, they are more being used in the distribution networks in Japan. More over they are proposed to be used in arc furnaces feeding networks to increase production [75-77]. Like series capacitors, shunt capacitor can also be used to reduce artificially the transmission distance and to achieve maximum power transfer. In [78], shunt compensator modeling has been illuminated for the betterment of voltage profile of the system. Amalgamation of these compensation techniques with power electronics has produced a new series of ancillary services of power network known as FACTS.

There are two generations for realization of power electronics-based FACTS controllers: the first generation employs conventional thyristor-switched capacitors and reactors, and quadrature tap-changing transformers, the second generation employs gate turn-off (GTO) thyristor-switched converters as Voltage Source Converters (VSCs).

The first generation has resulted in the Static Var Compensator (SVC), the Thyristor-Controlled Series Capacitor (TCSC), and the Thyristor-Controlled Phase Shifter (TCPS). The second generation has produced the Static Synchronous Compensator (STATCOM), the
Static Synchronous Series Compensator (SSSC), the Unified Power Flow Controller (UPFC), and the Interline Power Flow Controller (IPFC). Though these two groups of FACTS controllers have distinctly different operating and performance characteristics but generally FACTS controllers are able to change the network parameters in a fast and effective way in order to achieve better system performance [79-82].

The thyristor-controlled group employs capacitor and reactor banks with fast solid-state switches in traditional shunt or series circuit arrangements. The thyristor switches control the on and off periods of the fixed capacitor and reactor banks and thereby realize a variable reactive impedance. Except for losses, they cannot exchange real power with the system. The VSC type FACTS controller group employs self-commutated DC to AC converters, using GTO thyristor, which can internally generate capacitive and inductive VAr for transmission line compensation, without the use of fixed capacitor or reactor banks. The converter with energy storage device can also exchange real power with the system, in addition to the independently controllable reactive power. The VSC can be used uniformly to control transmission line voltage, impedance, and angle by providing reactive shunt compensation, series compensation, and phase shifting, or to control directly the active and reactive power flow in the line [83].

Although, the FACTS controllers have copious advantages as compensating devices in power networks, but HVDC is one more approach to look up the system performances. During contingency or fault HVDC can insulate two interconnected systems from each other, thereby improving reliability. Though HVDC has numerous technical advantages over FACTS but its use is limited by the high investment cost associated with it [84,85].

The following part of chapter, concentrates on the developments made in compensation and HVDC technologies.

A. Series and Shunt Compensation Employing FACTS Devices

For the purpose of this review, a literature survey has been carried out including two of the most important and common databases, namely, the IEEE/IEE electronic library and Science Direct electronic databases. The survey spans over the last 15 years from 1990 to 2004. For convenience, this period has been divided to three sub-periods: 1990–1994, 1995–1999, and 2000–2004. The number of publications discussing FACTS applications to different power system studies has been recorded. The results of the survey are shown in Figure 2.1. It is clear that the applications of FACTS to different power system studies have been drastically increased in last five years. This observation is more pronounced with the second-generation devices as the interest is almost tripled. This shows more interest for the VSC-based FACTS applications. The results also show a decreasing interest in TCPS while the interest in SVC and TCSC slightly increase.
Generally, both generations of FACTS have been applied to different areas in power system studies including optimal power flow [86-90], economic power dispatch [91], voltage stability [92, 93], power system security [94], and power quality [95-96]. Applications of FACTS to power system stability in particular have been carried out using same databases. The results of this survey are shown in Figure 2.2. It was found that the ratio of FACTS applications to the stability study with respect to other power system studies is more than 60% in general. This reflects clearly the increasing interest to the different FACTS controllers as potential solutions for power system stability enhancement problem. It is also clear that the interest in the 2nd generation of FACTS has been drastically increased while the interest in the 1st generation was decreased. The potential of FACTS controllers to enhance power system stability has been discussed by Noorozian and Anderson [97], where a comprehensive analysis of damping of power system electromechanical oscillations using FACTS was presented. Wang and Swift [98] have discussed the damping torque contributed by FACTS devices, where several important points have been analyzed and confirmed through simulations.
For the enhancement of power system performance, as discussed earlier, deployment of compensating devices has become quite imperative in modern power system networks. In [99], M. Z. El-Sadek et al presented a steady state voltage stability enhancement technique with a combined effort of series capacitor and SVC. M. H. Haque in [100] depicted the fact that the voltage stability margin can be widened by employing SVC. For the improvement of dynamic performance, C. W. Taylor proposed a SVC model in [101]. The model proposed proved to be better than the model offered by CIGRE in [102]. One year later, however, IEEE working group produced another model described in [103]. One of the crucial issues of deploying SVC is its placement. [104] enlightens the critical understanding of optimal placement of SVC. Newton Raphson based algorithm for reliable solution of large power networks with FACTS devices has been proposed by C. R. Fuerte-Esquivel in [105]. The work efficiently models the FACTS devices with tap changer, phase shifter and series compensators. The same author extended his work in [106,107] to optimize the model of TCSC and SVC respectively to meet the requirements of practical power networks. Several other examples of FACTS device modeling have been found in literatures [78], [108,109]. In [110], for faster prediction of voltage instability and restoration of the system by SVC has been proposed by S. Dey. The work developed a unique global voltage security indicator for
the assessment of voltage stability. Being associated with static switching devices the response of these FACTS devices may be oscillatory and to damp out this switching oscillation a robust control strategy has been proposed by M. Noroozian in [111]. C. R. Fuerte-Esquivel implemented their model successfully to develop object oriented power system software for the analysis of large-scale networks in [112].

**B. Employment of HVDC Link**

The profound utilisation of the power electronic technology has reached on the threshold of optimizing system performance by the incorporation of HVDC in power networks. The numerous aspects of improvement of system operating condition, it has even left behind the high investment cost associated with it. In the present power market scenario, where different multinational concerns are investing heavily for reliability and quality of power, HVDC can be a great choice. To increase distributed generation specially off-shore wind power plants, HVDC can be taken as a better alternative of conventional transmission systems. Though on paper, HVDC is profitable only for long distance lines, different power systems round the globe are adopting this technology even for back to back connection of grids. Power systems under development are strongly recommended for the procurement of an HVDC links to encourage disperse generation and to improve reliability and quality of power to be transferred. It is a prudent fact that the future power system is going to work at its optimum stress, to increase the sustainability of power, to encourage clean energy and to increase system efficiency HVDC link is the only solution. This has caused power system researchers to continuously project different ways of improving the system efficiency and reliability by the bulk use of HVDC.

In [113], the researchers have focused on the reliability statistics of HVDC technology. D. A. Waterworth in [114] went one step further to produce a technique to determine the reliability of these links. In [115], D. Jovicic presented a new controlled strategy of inverter side of HVDC to strengthen a weak HVAC system. The method cited, comprehensively reduced the switching transient of the inverter side to upgrade the transient stability margin of the system. [116] developed non-linear control strategy for the further improvement in stability margin. In the work, G. J. Li proposed and proved a pulse triggering technique which effectively reduces the transient time to aid stability.

Though this technique enhances the stability margin quite effectively, one of the primary hindrance of implementing HVDC in practical system is its high investment cost. ABB Corporation took a great initiative and cited a few cost comparisons in [117] of HVDC systems for better marketing of the product to maximize transmission network facilities (Table 2.1). The work also depicted the recent development made to project the advantages offered by different HVDC topologies.
TABLE 2.1

COST COMPARISON OF AC TRANSMISSION AND DIFFERENT HVDC TOPOLOGIES

<table>
<thead>
<tr>
<th>Alternative</th>
<th>500kV Single</th>
<th>500 kV Double</th>
<th>765 kV 2 Single</th>
<th>500kV Bipole</th>
<th>500 kV Single</th>
<th>Total AC+DC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power (MW)</td>
<td>3000</td>
<td>3000</td>
<td>3000</td>
<td>3000</td>
<td>1500</td>
<td>4500</td>
</tr>
<tr>
<td>Station Costs including</td>
<td>542</td>
<td>542</td>
<td>630</td>
<td>420</td>
<td>302</td>
<td>722</td>
</tr>
<tr>
<td>Reactive Compensation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transmission Line Costs</td>
<td>2.00</td>
<td>3.20</td>
<td>2.80</td>
<td>1.60</td>
<td>2.00</td>
<td>-</td>
</tr>
<tr>
<td>(M$/mile)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distance in mile</td>
<td>1500</td>
<td>750</td>
<td>1500</td>
<td>750</td>
<td>750</td>
<td>1500</td>
</tr>
<tr>
<td>Transmission Line Costs</td>
<td>3000</td>
<td>2400</td>
<td>4200</td>
<td>1200</td>
<td>1500</td>
<td>2700</td>
</tr>
<tr>
<td>(M$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Cost (MS)</td>
<td>3542</td>
<td>2942</td>
<td>4830</td>
<td>1620</td>
<td>1820</td>
<td>3422</td>
</tr>
<tr>
<td>Annual Payment, 30 years</td>
<td>376</td>
<td>312</td>
<td>512</td>
<td>172</td>
<td>191</td>
<td>363</td>
</tr>
<tr>
<td>@ 10%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost per KW-Yr</td>
<td>125.24</td>
<td>104.03</td>
<td>170.77</td>
<td>57.28</td>
<td>127.40</td>
<td>80.66</td>
</tr>
<tr>
<td>Cost per MWh @85% utilization Factor</td>
<td>16.82</td>
<td>13.97</td>
<td>22.93</td>
<td>7.69</td>
<td>17.11</td>
<td>10.83</td>
</tr>
<tr>
<td>Losses at full load in %</td>
<td>6.93%</td>
<td>6.93%</td>
<td>4.62%</td>
<td>5.29%</td>
<td>4.79%</td>
<td>5.12%</td>
</tr>
<tr>
<td>Capitalized Cost of losses</td>
<td>265</td>
<td>265</td>
<td>177</td>
<td>135</td>
<td>61</td>
<td>196</td>
</tr>
<tr>
<td>@ 1500KW(M$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Siemens in [118] marketed their HVDC product and depicted the growing population of integration of HVDC links in the system world-wide (Figure 2.3).

Figure 2.3 Worldwide installed capacity of HVDC link

Worldwide installed HVDC
"Capacity": 55 GW in 2005
This is 1.4 % of the Worldwide installed Generation Capacity

An additional 48 GW are expected from China alone until 2020!
H. F. Latorre in [119], turned up with a design of VSC controlled HVDC link for the improvement of system stability. In his work, he has developed a technique to determine the most suitable location for the incorporation of HVDC link.

An investigation of the improvement of voltage stability employing HVDC link has been presented in [120]. The authors in this papers have discussed the perturbation of PV and QV curves under the influence of hybrid HVDC-AC link. Practical implementation of HVDC-AC link in Australian and European grids were presented in [121, 122]. They simulated a practical system with HVDC link to find numerous power flow solution and wider stability margin.

In recent works, the firing angles of HVDC converters have been determined by employing stochastic algorithm like Particle Swarm Optimization (PSO) for faster implementation and better transient response of the system [123].

### 2.2.3 Optimization Methods with System Performance Emphasis

In power systems, to maximize system performance under operational constraints proper objective function has to be formulated and efficient analytical tools are to be designed to obtain global optima of these objectives. Hence, formulation of objective function and choice of optimisation technique is of equal importance. The endeavor of the researchers over the years, have been to formulate most desirable objective function and to search the solution with the most efficient optimization method. The incapability of classical methods (Lagranges and Bellmon's) to obtain the optimal solution in a rough working plane have given birth to neo-classical techniques like Swarm Intelligence, Fuzzy Logic, Genetic Algorithm and Evolutionary Programming. The following sections enlighten the evolution of optimization algorithms to the improvement of power system network performance.

**A. Classical and Neo-Classical Optimization methods**

The optimal system operations in general involves the consideration of economy of operation, system security, emission at certain fossil fuel plants, optimal releases of water at hydro generation plants etc. All these consideration may make for conflicting requirements and usually a compromise has to be made for optimal system operation. In early seventies Dynamic Program (DP) was quite popular to obtain the solution of power system optimization problems. The expansion of electric power transmission system was proposed by J. C. Kaltenbach, which employed DP to maximize the transmission extension in [124]. State-Space modeling of power network constraints and solution of power network problem using optimal control strategy has been successfully implemented by Y. N. Yu in [125]. In [126], A. M. Sasson utilized Lagrange's multiplier technique to optimize the solution of power system network problems. In [127], J. Nanda used Fletcher's QP method to the solution
of optimal power dispatch problem. More derivatives based optimization techniques have been reported in [128-133]. These classical techniques of obtaining numerical solution of power network problem have been summarized in [134]. All these techniques suffer from pre-matured adoption of solution i.e. the obtained solution cannot get near to the global possible best solution in the working plane. This is basically due to their heavy reliance on the first derivatives of the constraints. To assess the accuracy of these optimization methods in [135,136] R. Billinton proposed some methodologies for the evaluation of reliability of the solution obtained by classical optimization method.

In [137], J. Kenedy and R. Eberhart came up with a neo-classical technique of obtaining solution to optimization problems inspired by social behavior of birds and fishes. The technique referred as Particle Swarm Optimization soon got popular to the power system researchers for its ability to reach a global solution with a minimum number of iterations and found its applications as a stochastic technique of optimization in [139-144]. The confinement of the solution within the generated population is the social metaphor of PSO, which does not let the algorithm to produce best optimal solution in the working plane.

Genetic Algorithm (GA) endowed with mutation and crossover phenomena inspired from biological cell division, can produce relatively new solutions to survive and to be the fittest one to remain optimal. This up-gradation of solution in every iteration attracted the power system researchers to implement it for the best possible solution of network problem. L. L. Lai in [145] proposed an improved Genetic Algorithm based optimal power flow solution for optimizing network problem in both normal and contingent states. [146-148] followed the same foot-steps to obtain the most logical solution of network problems. The up-gradation work of GA for power network problems was got ahead by one step when W. Yan introduced hybrid GA interior point method to optimize reactive power flow. Though the reliability level of classical technique has made them extinct, some numerical methods with classical operators are producing better results than even GA. [149,150] used predictor corrector and conic quadratic formulation to establish the applicability of modified classical operator to produce better results. Never-the-less GA can be more effective with non-linear problems and can handle large number of constraints. Hence its application is quite evident in [151-154].

To up-grade GA, Storn and Price introduce a differential operator to initialize population (probable solution) with a logic (which was random in case of GA) in [155]. The later works in this field followed DE to search for the best possible solution in [156-160]. S. Rannamayan in [161] introduced opposition based Differential Evolution for the up-gradation of the same. In [162], M. Metwally modified the differential operator to produce
better results. John G. V in the same year in [163] had introduced Quantum Inspired Evolutionary Algorithm.

One of the remarkable adaptation in power system optimization problem is the inclusion of century old Fuzzy Logic. Elementary example of it can be found in the recent works of S. K. Bath, V. C. Romesh and D. Hur in [164-169].

**B. Application of Optimization Methods in Regulated and Deregulated Power Networks**

In recent years, the electricity industry has been undergoing unparalleled restructuring all over the world. The regulated or state owned monopoly markets have been deregulated [170]. This process is intended to open the power sector to market forces with the ultimate target of reducing consumer prices. Therefore, central ideology of electric power industry deregulation is that the delivery of power must be decoupled from purchase of the power itself and be priced and contracted separately [171]. In these markets, the reliability and quality of power are priced and market participants rely heavily on the System Operator to decide these prices.

To ensure high reliability, the same transmission network is being and to be used by different market participants simultaneously and is predicted to operate at its optimum design limit. Hence line congestion [172] has become almost inevitable where lines of insufficient power flow capacity have to accommodate all the requests of the market participant. This line congestion and utilization of an already congested line for a new request will charge the participant with congestion management cost to avoid congestion by rescheduling. The conversion of Vertically Integrated System to Deregulated system shown in Figure 2.4, thus will increase the reliability but at the cost of price volatility, line congestion and excess power loss.

![Figure 2.4 Conversion from VIS to deregulated power network](image-url)
The next section highlights the developments in the field of cost optimization; congestion management and power loss minimization strategies intended to improve the overall performance of the network in deregulated scenario of power system. After the inclusion of deregulation, the objective functions become more complex and non-linear, hence the optimal power flow solution relied more on optimization techniques like PSO, GA and DE.

(i) Cost optimization strategies

The main aim of Economic Load Dispatch (ELD) problem is to minimize the total cost of generating active power at various stations while satisfying the loads and the losses in transmission links. If the specified variables are allowed to vary in a region constrained by practical considerations, there results an infinite number of load flow solution each pertaining to one set of specified values the best choice in some sense of the values of specified variables leads to the best load flow solution. Economy of operation is naturally predominant in determining the best choice though there are other factors that should be given consideration.

These issues have been highlighted by IEEE Committee in [173]. In [174, 175], T. W. Berrie highlighted power system economics and planning considerations. Optimal power flow solution to load dispatch problem have been illuminated in [176-178]. [179] cited optimal maintenance scheduling of generating units. In a multi-objective optimal thermal power dispatch schedule, J. S. Dhillon [180] included transmission line flow constraints into economic load dispatch problem.

The challenges to on-line OPF implementation have been presented by J. A. Momoh in [181]. In the work, several control strategies for real time implementation of Optimal Power Flow solutions have been cited. This work has been developed from [182] where R. Bacher being the pioneer of this field depicted automatic generation control for real time optimum power flow. Implementation of stochastic methods for optimal power flow has been found in [183-185]. Some more instances of power flow solution can be found in [186-190].

One of the constraints of real time pricing of electricity is that it requires efficient monitoring and control system, which is of course costly and requires faster determination of price. In [191], Goldberg presented a Genetic Algorithm based search optimization. Optimal spot pricing of electricity has been proposed by F. C. Scheppe [192]. The method implemented effectively reduced the constraints of the deregulated systems to simplify the cost optimization process. In [193], the same author illustrated different spot pricing practices round the globe to compare their effectiveness in social welfare. Another approach of generating price signals is the determination of Locational Marginal Price or LMP. Different LMP calculations have been presented in [194]. A short run marginal price based active and
reactive power production has been proposed in [195]. The method proposed a comparatively faster calculating program to determine the price signals. Similar approaches of determining optimal spot price can be found in [196-200]. Power Transfer Distribution Factor (PTDF) based optimization model has been illustrated in [201] where, PTDF employed for allocating power transaction in deregulated market. A hybrid model of electric power spot price presented by Matt Davison illuminated the basic difficulties of controlling price spike in deregulated market. Related works were carried out earlier in this field can be found in [202-209]. All these optimal power flow model aim for maximization of utilization of available resources pointed towards a common solution that is compensation. A compensation technique for optimal choice and allocation of FACTS devices has been presented in [210]. Different FACTS based optimal power flow models have been proposed in [211-214]. The research work in the field of cost optimization is still going on with the aim of maximizing the capability of power networks. But day-by-day the constraints are increasing (pollution, emission, congestion) and the objective function is getting more and more complex. Hence, an absolute formulation of objective function for OPF is imperative and still to be designed near future.

(ii) Congestion management strategies

Transmission network congestion is the main constraint to optimum exploitation of energy sources. Congestion can be caused by transmission line and generator outages, changes in energy demand and uncoordinated transactions, which can lead to network congestion when the transmission system is not able to respect security requirements due to line overload, transient and stability constraints [215-216]. Looking for increased competition on electric power markets, the industry restructuring process tends to deepen the congestion problem [217]. Therefore some schemes of congestion management are to be implemented which will internalize the dispatch process with externalities without increasing the electricity prices unreasonably and will keep the motivation for the market players to make investments on system expansion. A modal participation factor based congestion management algorithm has been developed in [218] for effective reduction in line congestion by monitoring the Jacobian matrix and Eigen values of the system. [219] came up with an hybrid model with the curtailment strategy to optimize generation cost in a deregulated fuzzy environment with congestion management.

Line congestion apart from causing limit violation can cause a serious rise in spot price. Ye Peng, in [220] has depicted different control mechanisms to limit spot price by congestion management. He presented some of congestion management methods namely generation control, demand control and FACTS control. Mitigation of congestion by employing FACTS devices can be found in some recent works as studies in [223-227]. Reliability evaluation of
hybrid power markets during congestion has been depicted in [228]. It discussed about an optimal load curtailment strategy managing congestion. An optimum load shedding based congestion management has also been found [229] but due to the loss of reliability associated with it and the installation cost involved with FACTS devices have made the researchers to emerge with alternative strategies like bidding control, generator and load contribution factor based management, generation rescheduling and dynamic congestion management. Extensive endeavor in the deployment of this technique can be found in [230-238]. As the modern electricity market is getting deregulated congestion management should cost the market players, so that they can be more conscious about avoiding transaction causing line limit violation. Aumann-Shapley presented a bilateral model for congestion cost evaluation in [239].

As different transmission companies have embarked upon providing a for-profit transmission service to market players for the changing power industry, estimation and projection of the transmission congestion range has become crucial. The task is complicated due to the difference in the congestion management and pricing protocol adopted by different electricity market as well as the lack of relevant data posted by ISO. The congestion rent calculation for the California and New York electricity markets are summarized in [240]. The lack of public information concerning line power flows in the grid has made it difficult to estimate the total transmission congestion cost to be collected by ISO. Accordingly sophisticated tools such a Probabilistic Optimal Power Flow (POPF) are needed to accomplish the task. Unfortunately, due to numerous uncertainties associated with the behavior of the market players and the evolution of the power system topology coupled with the computational efforts severely limit the successful application of POPF for this purpose. Hence, development of POPF algorithm for congestion management has become a great challenge for the power engineers of 21st Century.

(iii) Improvement of transmission efficiency

Transmission loss incurs roughly 3-5% of the total generation to be considered as one of the major factors in locational spot pricing. This means that loss allocation may considerably affect the competitive position of the GENCOs. Never the less, it seems that most of the electric markets hardly ever reflect the transmission loss in their spot pricing due to its complicated aspects of loss allocation such as non linearity, path dependency and non-uniqueness of the solution. The important issues are to reduce allocation error that is the discrepancy between the sum of theoretically allocated losses and the actual system loss. Efficient loss allocation and loss optimization methods can upgrade the transmission efficiency not only to improve performance but also for consumer welfare by lowering the price volatility of electricity market. Several models of loss optimization have proposed and
still being proposed by the power engineers to improve the loss profile of a system. An OPF tool with an objective of minimizing transmission loss can found in [241]. The approach has been followed by numerous developments [242-244]. But the idea of loss optimization can prematurely converge to a sub-optimal solution for the constraints involve in modern power networks. Transmission loss allocation approach has upgraded power loss optimization model. S. Abdelkader has proposed a loss allocation model in deregulated electricity market to minimize the physical flow in transmission line by reducing the contribution of individual loads to the losses [245]. The work is inspired from the developments of T. K. Han for calculating transmission loss factor to be found in [246]. The loss allocation approach is still under the stage of development and hence different strategies can be found in [247-250]. The contributing factors of transmission loss are not only the active power requirement of the market players but also the reactive power requirement. Optimal reactive power flow and consistence management of the same is highly desirable with systems conceding more cost to produced power to be lost. A reactive power management proposal can be found in [251]. [252] utilized stochastic approach with GA to optimize reactive power under deregulation. Reactive power allocation as found by these researchers is a very task and the direct solution cannot be obtained with conventional algorithms and methodologies.

The last decade has witnessed drastic changes in the electric power industry in the many parts of the world. The Vertically Integrated System (VIS) have been restructured and unbundled to one or more generation companies, transmission companies and number of distribution companies. The implementation of deregulation in power system based on two main different concepts: power pool and bilateral contacts. In both the cases, a transparent method for allocating transmission losses between all of the interested parties in an equitable and fair manner is required. Hence, some methodologies and algorithms are required for loss optimization, if not possible then proper allocation of the same.

2.2.4 Enrichment of System Performance in Smart Grid Arena

The huge interconnected machines spanning to large area of the globe is the century old power grid, which are massively complex and are inextricably linked to social and economic activities [253]. These grids are designed to connect large power station to high voltage transmission system, which in turn supply power to medium and low voltage local distribution systems [254]. Due to socio-economic reason the growth of electricity demands require reliability and quality of power supply and for the maintenance of the same the power industry is now facing unprecedented challenges and opportunities.

The Smart Grids technologies are currently undergoing a development in an effort to modernize legacy power grids to cope with increasing energy demands without violating the
above constraints [255-257]. It has been shown by the researchers that the transmission, distribution and end users can be interconnected by high-speed bi-directional communication network to optimize the grid operation. Integration of automation, SCADA and smart metering in power networks can enable the grid to rapidly self regulate and heal to improve system reliability and security [258].

The vision and different logical domain of a Smart Grid is illustrated in Figure 2.5. As a roadmap for research and development, the smart features of the transmission grid are envisaged and summarized in following figure as digitalization, flexibility, intelligence, resilience, sustainability, and customization. With these smart features, the future transmission grid is expected to deal with the challenges in all identified areas.

For the efficient operation of Smart Grids, the researchers have felt for more participation of the consumers in scheduling of power of different sources. So far there has been a significant research integrating consumer demand side management into Smart Grid to improve the system load profile and reduce peak demand [259]. Demand Response (DR) allows the consumer load reduction in response to emergency and high price condition on the electricity grids. Such conditions are more prevalent during peak loads or congested operation. Non-emergency Demand Response (DR) can provide substantial benefits in reducing the need for additional resources and lowering the real time electricity price or spot price. Presently, the Independent System Operator (ISO) has visibility into transmission
substation but generally does not have visibility into distribution network where most of the small commercial and the main residential DR take place. Other entities like UDCs, LSEs, ESPs and CSPs interact directly with the consumers to bundle the DR and presents it to the ISO/RTO.

Several methods of load management by DR have been reported. In [260], a model reference adaptive control strategy for interruptible load management that handles load variation is presented. But, the model could not maintain a flat demand response as required. A fully decentralized grid-scheduling framework has been reported in [261] but the model unable to utilize the DR data for optimization of grid operation. A cellular technology based demand side energy management has been proposed in [262] but the framework is only capable of operating in distribution networks rather than the optimizing the whole grid operation. In [263], a optimization algorithm to schedule direct load control DR as a part of virtual power plant is presented but the participation of the loads in scheduling the plants are nominal in the cases cited. A harmonic distortion and transformer derating based load management in Smart Grid has been proposed in [264], but the algorithm proposed in this work does not incorporate the cost factors of the DR. A Pulse Width Modulation (PWM) based direct load scheduling is proposed in [265], but the involvement of distribution networks has not been shown in this work. A DR based market resource planning strategy has been shown in [266] but the model proposed only shows the DR connectivity in the network rather than enlightening the optimization scheme to be harnessed in utilizing DR for optimal operation of smart grids. A DR based distribution grid operation model is shown in [267], but its inclusion in the transmission part of the grid has not been shown. An optimal real time pricing algorithm depicted in [268] for utility maximization in Smart Grid. In this case also the authors could not utilize the DR effectively for load management. In [269-270], researchers have tried to develop different smart grid business models. All these methods are basically based on some proposed architectures, which considers DR but could not maximize the utilization profit in Smart Grid environment governed by deregulation and distributed generation.

2.3 CONCLUDING REMARKS ON EXISTING EFFORTS

Literature survey reveals that a lot of research works have already been done and going on to evaluate and improve the performance of power system in regulated as well as deregulated environment. Every technique has its' own advantages and disadvantages in terms of accuracy, sensitivity, reliability, response time and computational complexities. Hence, the choice of the method or the algorithm is solely application specific. In this thesis, some novel techniques or algorithms for the assessment and amelioration of power system performance
in terms of economy, stability and security have been presented. In an endeavor of reconciling the modern power network problems, some remedial methodologies have been developed in this thesis, which apart from mitigating constraint violation produce cost effective solution to improve both security and reliability of a network.

Annotating Outlines

- The field of improving stability by compensation and operating conditions by optimization is enormously popular for the power system engineers as they can feel hidden opportunities in this regard.

- The scope of improving system performance in terms of stability and efficiency lies on effective utilization of modern technologies like HVDC and FACTS.

- The existing network getting transformed from VIS to deregulated system will work under an optimum stress; hence, new solutions are to be harnessed in the form of compensation, optimization and supervision.

- Issues like cost volatility optimization, congestion management are still to be taken under proper care by efficient formulation of optimization algorithms and their effective implementation in both off-line and on-line monitoring.

- Smart Grid technologies are currently undergoing a development to modernize power grids to cope with system demand without violating network constraints.