CHAPTER I

INTRODUCTION

1.1. PREAMBLE

The introduction of competition in power market aims to make it more efficient. In fact, the power market is referred to as the ability of market participants to profitably maintain prices above a competitive level for a significant period of time. Out of various objectives for an efficient competitive market, the social welfare maximization is an important objective. In general, to achieve the objective of maximum social welfare, it is necessary that the market structure should be fair and equitable giving all market participants incentives to maximize the total profits in a power market. Now a days, multi-transaction structures have been established in the power market. In multi-transaction power market, each transaction has certain number of generators and demands of consumers which are coordinated by bilateral/multilateral contracts. The sellers and buyers can pair up to reach at an agreement on the detailed bilateral/multilateral contracts. In this type of power market both are participating in double sided auction market and moreover they trade the power through bidding process. Thus, they are making contracts for future periods of few weeks or longer, up to several years. This can also be setup for few hours to next day. Now, some of the power markets are establishing the contracts for minute-ahead contracts among the participants. Recently, researchers have included the benefits of consumers in market operations in order to achieve improved social welfare. However, involvement of consumers makes the system complex and thus the operation of transmission network becomes even more important. This may cause congestion problem in the network. Thus the congestion management is one the important issues and it becomes more complex due to multi-transaction in the power market.

One of the congestion management techniques is by rescheduling the generators output at their minimum cost. In the present scenario, subsequent to considering their benefits, the consumers play a vital role in the market. Managing the congestion by only controlling the generators alone may not fulfill the above objective. Therefore, it is utmost important to incorporate the

producers and consumers to manage the congestion problem in the power system. In the deregulated power system, the operator creates a set of rules for congestion management. These rules ensure adequate control over producers and consumers to maintain an acceptable level of power system security and reliability. On the other side, this maximizes the market efficiency in both short term (real-time operations) and long term (transmission and generation expansion). Several congestion management methodologies have been adopted by different power system network operators. The optimal generation and demands rescheduling method is one of the efficient methods for congestion management. This method is frequently used by power system operators for the congestion management in power networks. In this method, all the operational and technical constraints such as voltages, generations, lines and transformers limits are added in the optimal power flow (OPF) based congestion management problem formulation.

Mostly, the operations of independent system operators (ISOs) are based on centralized decision supports. However, the centralized decision to mitigate congestion adversely affects the economic welfare of some of the participants who are not responsible for creating the congestion in multi-transaction markets which may cause dissatisfaction among such participants and giving rise to dispute in market operation. The decentralized decision support for the system operators can help in shorting out this problem. The present thesis proposes an approach towards congestion management with social welfare using centralized optimal power flow (COPF) and decentralized optimal power flow (DOPF) based decision supports in multi-transaction power market. The congestion management with social welfare in multi-transaction power market is considered as problem objective of this work. The solution of problem objective based on COPF and DOPF has been obtained using interior point (IP) based conventional optimization and particle swarm optimization (PSO) methods. The present work also proposes a new hybrid PSO technique for the present objective. This technique has been named as interior point initialized particle swarm optimization (IP-PSO) which is formed by combining the advantages of IP and PSO.

1.2. Literature Review

Now days, there is a world-wide trend towards restructuring and deregulation in the power industry. The competition in the wholesale generation market and retail market together promotes the open access of the transmission network. This provides many benefits to the end consumers. However, this competition also brings many new technical issues and challenges to the power system operators. In the recent past, many research papers have been published related to the operational issues of deregulation power system. This section presents the literature review of the following aspects of power market.

i. Deregulated power market and its operations
ii. Development of power market in India
iii. Centralized/decentralized decision supports and social welfare or benefit maximization in deregulated power market
iv. Various methodologies of security constraints optimal power flow in deregulated power system
v. Congestion management methodologies in deregulated power system
vi. Interior point optimization and its application to power system
vii. Particle swarm optimization and its application to power system

1.2.1. Deregulated Power Market and its Operations

The electricity industry forms a corporate environment in the power market and is going towards privatization and deregulation. In the present section some selective literature survey has been carried out which provides basic concepts of operational methodologies of deregulation in electricity market.

The present literature survey starts with work of Christie and Wangensteen [1] which have been described the philosophy and operational fcaturcs of spot and futurc markct in dcrcgulatcd cnvironmcnt of thc clcctricity industry of Norway and Sweden. The concept and the operational mechanism of spot and future markets have been defined in this work. This work gives the basic concepts of electricity market. A detailed discussion on restructuring of power system and deregulated operation has been presented by Lai [2], where the deregulation and trading of power in electricity market has been discussed

in detail. The various terminologies used by deregulated power system such as open access and transmission system expansion have also been explained in this book. Another detailed analysis on restructured electrical power systems operation and trading in electricity market has been reported by Shahidehpour and Alomosh [3]. In this book, the main focus is given on the need of restructuring, ISO operations and models of different existing markets of United States. Later on, a survey has been reported by Sood *et al.* [4] which gives the basic ideas and definitions of various terminology of power market such as wheeling, marginal cost and available transfer capacity (ATC). In the same way, Song and Wang [5] presented a book which covers all the major operational issues, such as scheduling and dispatch, congestion management, available transfer capability calculation, optimal bidding strategies. This presents a brief introduction on operational strategies of various power markets world-wide.

It is a known fact that the deregulation establishes a market in the power systems. Hogan [6] has reported a detail review on electricity market infrastructure and operation methodology in regulated setup of the power system. This work discusses the requirements of investment and future policies for the improvement of power market. The opportunity of privatization in wholesale electricity market has also been discussed in this paper. Two major analyses; the analysis for market designs implementations and solution for the market failures, and creation of regulatory and central planning bodies and their involvements which are compatible with the market design have been carried out in this work. This work is considered as a major milestone in the area of electricity market infrastructure development. The transmission networks operations play an important role in the market operations. The transmission operators operate the system as per the transaction contracts which are classified as feasible and unfeasible. The transmission system constraints are violated by the unfeasible transactions. Therefore, the feasibility assessment is an important issue in deregulated power system. Hamond [7] has covered the feasibility based issues in bilateral contract based deregulated power market. Later on, David and Wen [8] presented a compressive review related to emerging issues of power market dealing with the different available methodologies to mitigate the problems of power market. The different terminologies such as transmission network expansions, contract based

marketing, demand side bidding price cap are defined in this paper. Thereafter, Bompard *et al.* [9] have reported a direct analytical approach to find the market equilibrium based on supply function game model. This work represents a DC power flow model of power network and analyzes the sensitivities of the producers' surplus with reference to the line flow limits. This helps the market regulators to focus on the network weaknesses in terms of possible market outcome from the supply end.

Recently, the market operators have tried to integrate the different markets to form a mixed market design based operational approach in the electricity market. The electricity markets are establishing the power exchanges in the power system and these exchanges operate the system as a mixed market based system. Bikas *et al.* [10] and [11] have reported an exhaustive work for European electricity market and its advancements. This work has proposed the solutions of different operational constraints associated with power exchanges offers/bids of day-ahead market. The result shows future scope for constraint handling in European power exchanges. Fundamentally, the two types of market models; pool and bilateral markets are used in deregulated power system worldwide. The working methodology of power dispatch in a mixed pool and bilateral markets has been reported by Kockar and Galiana [12]. The paper presents the behaviour and performance of market operations in terms of pricing, revenues, cost and power level. The authors have also incorporated the curtailment method of power in mixed market. The results of this work provide various types of information about operational methodology of contract making in pool and bilateral market. The main goal of this work has been to set the generation level to improve the performance of the market.

In deregulated electricity market most of the independent system operators (ISOs) adopt the cost minimization based generator scheduling and market clearing prices mechanism to settle the payment amount. Hosseinian *et al.* [13] reported an auction mechanism in deregulated market using payment cost minimization methodology. The optimal solution has been obtained by mixed integer linear programming based approach. The paper reported the superiority of payment cost minimization (PCM) over offered cost minimization (OCM). The work shows the effectiveness of demand profit shape on both PCM and OCM. Further, the results obtained by mixed-integer linear programming

provide a novel solution for PCM problem. It has also been recommended that the application of PCM auction is useful for joint dispatch of energy and ancillary services. Later on, Wang *et al.* [14] presented a model for reserve and regulation prices in the electricity market. The work has also incorporated the feature of smart grid technologies, large scale integration of variable resources and ancillary services into the grid to show the importance of their prices. The power market, in general, considers the active power as a commodity and its pricing based marketing is used in the system operation.

The reactive power pricing also plays an important role in the power market game. Dai *et al.* [15] have reported a work related to reactive power pricing in electricity market, wherein the sequential quadratic programming method has been used to solve the optimization problem for obtaining the reactive power marginal prices of generators. Similarly, the reactive power planning in deregulated power market has been reported by Zhang *et al.* [16]. In this paper, the authors have reported a bibliographical review on reactive power planning methodologies with various constraints and solution algorithms. This work has also reported the security constraints optimal power flow (SCOPF) using different optimization techniques. The transmission loss allocation is a changing issue in power markets. Conejo *et al.* [17] have reported work on comparison of various practical algorithms of transmission loss allocation in power market. This work was focused on transmission loss allocation procedures and provides a detailed comparison of different loss cost allocation methodologies. These methodologies are pro-rata (PR), marginal allocation, unsubsidized marginal allocation and proportional sharing based algorithms. The transmission expansion planning is also one of the important and necessary responsibilities of power system operators. Transmission-expansion planning in deregulated environment has been considered by Xu *et al.* [18] in length. In this work, the authors have presented a market oriented approach for transmission planning in a deregulated power system. The optimum expansion planning has been obtained by using a Genetic Algorithm (GA) based optimization in this work. Maghouli *et al.* [19] introduced transmission expansion planning methodology in multi objective optimization framework. These objectives are investment cost, reliability and congestion cost in the power system. In this approach, the difficulties due to nonconvex and mixed integer nature of optimization problems have been overcomed by genetic

based NSGA-II algorithm followed by fuzzy decision making analysis. The reported work ascertains the advantages of the proposed algorithm for planner in terms of cost benefit. A transmission planning methodology considering future generation expansions in electricity market related work has been reported by Motamedi and Zareipour [20]. In this work, the optimal solution has been obtained by agent-based and search-based optimization techniques. This work also proposes the four levels of optimization problems; GenCos bidding strategies, market-clearing, generation expansion and transmission planning in deregulated power market. Later on, another work related to transmission planning with uncertainty in market operation and regulations have been reported by Munoz *et al.* [21]. This work investigates the investments at two stages of operational model, differentiating between commitments that must be made at the instant and the corrective actions that can be undertaken as new available information. The objective is to minimize the transmission and generation cost in time perspective. The work has also reported the effects of uncertainty associated with renewable electricity mandates, emission policies and fossil fuel prices in transmission planning.

1.2.2. Development of Power Market in India

The reformations of Indian electricity sector have led to shift towards worldwide existing markets. In India, the electricity is now seen as a tradable commodity, rather than just infrastructural requirement. Thus, the market oriented approach and the commercialization of electric power needs a place for various services which promotes the competition in the market. This section deals with the review of Indian power market and its chronological developments. A considerable growth in Indian power industry has taken place with the passage of time as various electricity acts have been passed by the government of India time-to-time [22-24]. The aim of these acts is to provide better service quality and to fulfill the needs of the society. Revolution in Indian power industry has come into view after the Electricity Act, 2003 [25]. The main aim of this act is to bring gain in efficiency and competition for the market participants. This act provides more freedom of business to all the participants. Some amendments in this act have been taken place in the later years.

Singh and Srivastava [26] have reported a review paper on the restructuring of Indian power industry and its future scopes. The work highlights the reformation processes of Indian power industry and also suggested a conceptual and effective model of regional/state wise wholesale electricity market. Later on, Khaparde [27] presented a detailed overview on Indian power sector reforms and restructuring. The main objective of this work was to introduce the terms open access, market pricing and transmission pricing in Indian context.

Subsequent to introduction of Electricity Act, 2003, the Indian power sector has become more efficient. This act encourages competition through appropriate regulatory involvements. On the basis of the frame work of this act, a National Electricity Policy, 2005 and Tariff Policy, 2005 have been commissioned by the Central Electricity Authority (CEA), India [28] and [29]. These policies have been amended by the CEA and state regulatory bodies. The main objective of these policies is to encourage the players for investments and provide the efficient consumer services at attractive tariffs.

A critical evaluation procedure for the methodologies and steps for the restructuring processes in India has been proposed by Sharma et al. [30]. This work provides some suggestions for re-framing of future Indian power market. Thereafter, Parida et al. [31] introduced an overview on various key issues related to ancillary services and their future in Indian power industry. This paper covers the classification of ancillary services and different approaches for procurement and remuneration in Indian perspective. A paper was reported to suggest the certain mechanism and purposes of ancillary services by which it can be introduced and implemented in the Indian electricity market [32].

The Central Electricity Regulatory Commission (CERC) India has issued various electricity regulations to promote the competitive trading in the power market [33]. These regulations have also been amended by CERC in different time frame. Some of the important regulations have been subsequently discussed in the present section. The Procedure, Terms and Conditions for Grant of Trading License and Other Related Matters Regulations, 2009 has been issued by CERC. This regulation tightened the terms and conditions for the grant of trading licenses (including the current prices of the trading power), liquidity requirement of power trading business and encourages only the

serious players in the business. The congestion management is one of the important complexities in the market operation. The CERC issued a regulation related to congestion management procedure for Indian power system as Measures to Relieve Congestion in Real Time Operation Regulations, 2009. The unscheduled interchange (UI) has frequently been used in the Indian power market and this operation affects the system security and reliability. Therefore, Unscheduled Interchange Charges and Related Matters Regulations, 2009 has been issued by CERC for the market to maintain the system security and reliability. The CERC restructured the UI regulation and some amendments were made to maintain discipline in grid management.

Now a days, both the types of business planning; long term and short term, are used in Indian power market. The inter-state transmission plays an important role in this. A regulation has been issued by CERC as Grant of Connectivity, Long-term Access and Medium-term Open Access in Inter-State Transmission and Related Matters Regulations, 2009. Later on, Power Market Regulation, 2010 was issued by CERC. This regulation provides market terminologies and operational regulations of the power market. This regulation helps the power exchangers to formulate the bye-laws, rules and business rules for power trading. The CERC issued the Indian Electricity Grid Code (IEGC) Regulation, 2010 to maintain discipline and to improve the operation of power grid. This regulation made rules, guidelines and standards for the various persons and participants in the system to plan, develop, maintain and operate the power system in the most secure, reliable, economic and efficient manner. This regulation also facilitates a healthy competition in the generation and supply of electricity. A discussion paper was reported by CERC on the improvements of market efficiency by using information dissemination through display of aggregate demand and supply day-ahead curves published by Power Exchanges.

A detailed study on Indian Power market operations have been carried out with the help of various annual reports published on CERC website in different time frame. Recently, a paper has been published by CERC on terms and conditions of tariff regulations for the period 2014-19 [34]. The paper introduced different approaches for tariff setting in the power market. These approaches are of two types; financial (hybrid) and operational norms based.

The paper also reported some additional issues such as availability of fuel and tariff application methodologies in future Indian power market.

1.2.3. Centralized/Decentralized Decision Supports and Social Welfare or Benefit Maximization in Deregulated Power Market

The main purpose of this review is to establish the concepts of social welfare and effects of centralized/decentralized decision support in power markets. The term Social Welfare in the power system has been used by Wu and Varaiya [35] to propose the new operating paradigm in the power system. In this work, the economic decisions have been taken for private multilateral trades among generators and consumers. This work shows that the coordinated multilateral trading models can also exist with the traditional models and provides non-discriminatory services to both the customers; transaction and direct access customers. Ferrero and Ramesh [36] reported a paper on maximization of the individual benefits of participants by cooperating with the power pool to obtain the maximum system wide benefits. In this paper, the game theory has been used to simulate the decision making process for offered prices in a deregulated environment. The contingency analysis in deregulated power market is also carried out in this work. The results show that the benefits of all the participants maximize during the contingency condition. Thereafter, Weber *et al.* [37] have reported a work on social welfare maximization by including the consumer's benefit functions in OPF formulation. In this work, the problem has been developed in such a way that the objective function includes the price-dependent load models in the problem formulation of social welfare maximization. The work investigated the impact of price-dependent loads on systems with transmission congestion, increased fuel costs and voltage problems. Another work of individual welfare maximization in electricity spot markets has also been represented by these authors [38].

Nishimura *et al.* [39] have reported a base for benefit optimization in centralized and decentralized multi-transaction power system. This work shows that the generation cost minimization is not a necessary criterion for benefit maximization. The demands could also contribute in the problem objective to provide the system benefits. A decentralized control method which provided more economical independence to the market players has been reported by Anvar [40]. In this work, the feasibility of control method has been validated by

the state-space decomposition method. Similarly, Botterud *et al.* [41] have reported a model of centralized and decentralized decision support based optimal investment in power generation under uncertainty conditions. The optimal generation investment calculation and their strategies have been shown in this model using centralized and decentralized support. The main objective of this work is to compare the effects of centralized and decentralized decision support in the generation investments.

Correia [42] has presented a paper on decentralized decisions based solution for unit commitment problems in the power market. This paper reported a strategic problem through a probabilistic dynamic programming based model. The optimal solution in this work has been obtained by direct Monte-Carlo method with Nash equilibrium strategies. Thereafter, Sood *et al.* [43] reported a work to show the effectiveness of Locational Marginal Pricing (LMP) based approach on social benefits in the power system. This work represents that the LMP pricing method provides social benefit to all GenCos and load centers depending upon their allocation in the transmission network. The results obtained using this approach shows that the load centers have to pay even less than their bidding price and the GenCos get even more amount than their bidding cost. It has also been reported in this work that the transmission and congestion costs reduce using LMP pricing based method. Soroudi *et al.* [44] have introduced hybrid immune genetic algorithm based benefit maximization for distribution network operators and distributed generation owners. This work investigates the effects of benefit sharing decisions on distribution generators. A market oriented approach with inter-transactions power exchanges has been proposed by Aguado and Quintana *et al.* [45]. The main objective of this work is to minimize the overall production costs while preserving dispatch independency of the involved utilities. This work also proposes an efficient algorithm for the decomposition of optimization problem in inter-utility exchanges using duality theory. Thereafter, Bikas and Bakirtzis [46] have presented a paper on decentralized security constrained based DCOPF of interconnected power system. In this paper, the solutions of security constrained optimal power flow (SCOPF) sub-problems of the different areas have been obtained by coordination through a pricing mechanism.

1.2.4. Various Methodologies of Security Constraints Optimal Power Flow in Deregulated Power System

The optimal power flow (OPF) based market operation plays a significant role in deregulated power market. In the present section, a review has been reported on security constraints based optimal power flow (SCOPF) and their various methodologies in deregulated power market. Mostly, the curtailment of active power is one of the frequently used operational strategies for secure and reliable operation of power system. A work has been reported by Jianhua [47] on transaction curtailment based operation in a cross region deregulated power market. The power transfer distribution factor (PTDF) has been used as a sensitivity factor in this work, wherein the computational error of PTDF calculation has been reduced by Fuzzy curtailment set. A novel technique for identification of system security constraints in competitive electricity markets has been presented by Milano *et al.* [48]. In this work, the voltage stability constraints are used for the formulation of OPF problem with continuous power flow (CPF). This CPF analysis provides the maximum loading parameters and then they are used in the OPF problem based on N-1 contingency criterion. Later on, Alsac and Stott [49] presented a steady state SCOPF methodology that incorporates the exact outage-contingency constrains in the OPF formulations and provides an exact steady-state secure operating points of the system. A detailed survey on OPF methods and dispatching methodologies has been reported by Huneault and Galiana [50].

After deregulation in the power system, OPF and security assessment problem in the power system becomes an important issue among the system operators. Chang *et al.* [51] have reported a paper on study of bilateral contracts with steady-state security in a deregulated environment. In this paper, a linear programming based approach has been used to study the complex relationships of bilateral contracts and system security. In the same way, David and Fang [52] reported a work on rescheduling of transactions based on security constraints. Thereafter, Condern *et al.* [53] presented an objective of the system operation including the minimization of expected total cost and security costs of the system. The work has compared the total operating costs in pre-contingency and post contingency conditions. The model

has also incorporated the cost of ramping of generators and interrupting customers load during contingency conditions. Lin *et al.* [54] reported an OPF model for competitive deregulated market during transient conditions. The OPF method is also useful to operational problem of distributed generation (DG) in the power system. Dent *et al.* [55] have reported a paper on use of OPF in distributed generation capacity analysis of power network. In this work, the voltage steps are considered as a constraint and the OPF solution has been obtained by using AIMMS optimization tool with CONOPT solver. Thereafter, the optimality and reliability in power system under uncertainty have been achieved by Zang and Li [56] using probabilistic analysis in OPF formulation. This analysis has been carried out by using Monte-Carlo simulation with the combination of deterministic optimization. Later on, Fadil *et al.* [57] formulated a security constrained power dispatch problem for a lossy power system area with non-convex functions. In this case, the solution is obtained by a sub-gradient algorithm based on feasible values and common pseudo scaling factor for limited energy supply of the thermal units. All equality and inequality constraints in the non-linear optimization model of a subinterval are functions of bus voltage magnitudes and phase angles (the off-nominal tap setting). These constraints have been taken as independent variables, except for those belonging to the reference bus. The load flow equations are also added to the model as equality constraints.

The renewable energy resources and there grid interfacing is one of the current issues among the power system operators. Therefore, the operational constraints associated with renewable energy based system have also been incorporated with OPF model of power market. Yu and Rosehart [58] proposed an algorithm of OPF to achieve robust operations by considering the load and renewable generation uncertainties in the power market. In this work, the operations of the probabilistic distributions of load and renewable energy output are derived from Taguchi's orthogonal array testing. Later on, Gyame and Topcu [59] reported a work on OPF with storage integration at large scale in power networks. The charging and discharging dynamics of energy storage devices have been added in OPF formulation of this work. The results show that the energy storage and demand based cost functions significantly reduces the generation costs and compress the generation profits.

The centralized and decentralized decision based operations with OPF are also very useful methodologies in the case of multi-area power systems. A decentralized DC optimal power flow (DCOPF) based solution for the multi-area coordinated system has been reported by Conejo and Aguado [60]. In this work, the Lagrangian-Relaxation decomposition procedure has been used to achieve the economical optimum solution of the system. The work has also derived the optimal energy pricing rates of the traded energy in the inter connections. Later on, Bikas *et al.* [61] had reported a discussion on network of work stations based transmission operations using decentralized DCOPF. In this work, an individual work station has been assigned to each regional transmission system operator (TSO). These TSOs manage the transmission operations of their region as well as cross-border exchanges with neighboring regions. In this work, the transmission system information has been shared among all the TSOs to solve the regional OPF sub-problems, until the global OPF solution is reached. Bikas and Bakirtizis [62] have also presented a decentralized OPF based work for large multi-area power systems. In this work, decoupling of first order Karush Kuhn Tucker (KKT) conditions based decomposition method has been used to solve the independent sub-problems of decentralized OPF problem of the system. Similarly, a decentralized solution for interconnected power system using DCOPF has been reported by Bakirtizis and Biskas [63] wherein the overall OPF problem is decomposed into multi-area independent OPF sub-problems.

The various optimization techniques have been applied in OPF solutions. Sun *et al.* [64] have proposed modifications in the classical OPF problem using explicit Newton approach for the non-separable objective functions. This solution method provides some key ideas for the inclusion of inequality constraints in the problem objectives. Similarly, Yuryevich and wong [65] proposed an evolutionary programming based methodology for the OPF solution. An enhanced genetic algorithm (EGA) for the solution of OPF with continuous and discrete control variables is proposed by Bakirtzis *et al.* [66]. In this work, the authors considered the continuous control variables for unit active power outputs and generator bus voltage magnitudes, while the discrete control variables are transformer-tap settings and suitable shunt devices. Other operating constraints such as voltage limits, line limits, etc are included as penalties in the EGA fitness function. In this work, the effectiveness of

genetic algorithm (GA) has been enhanced using 4-bit chromosome area for encoding each control variable. Also, a sequential GA solution scheme is employed to achieve acceptable control variable resolution.

A novel method for dynamic optimal power flow (DOPF) in deregulated power market using Benders decomposition model has been reported by Yamin *et al.* [67]. Accurate and fast solutions for DOPF problem has been reported in this work. An evolutionary programming based security constrained OPF has been reported by Somasundaram *et al.* [68]. This work investigates the relatively simple, reliable, effective and suitable form of algorithm for on-line applications of OPF. Later on, a new dynamic bacterial foraging algorithm (DBFA) based OPF for dynamic environment has been presented by Tang *et al.* [69]. The property of reproduction and self adaptability of E. coli bacteria has been incorporated with OPF problem formulation to solve the dynamic behaviour of the power system. Thereafter, overviews on major computational issues with OPF formulation and a brief summary of major computation intelligent tools have been discussed by AlRashidi and El-Hawary [70]. In the presented text, detailed coverage of OPF related research work and use of modern computational intelligent techniques have been reported. The security constraint unit commitment (SCUC) problem in OPF solution has been solved by Bai and Wei [71] using a semi-definite programming (SDP) model. The reported work shows that the proposed SCUC problem can be solved by SDP because of its excellent convergence and ability to handle the non-convex integer variables. In SDP, model decomposition and initial relaxations are not required.

Capitanescu and Wehenkel [72] reported a sensitivity based approach for OPF computation with discrete variables. This work proposes three iterative approaches for handling the discrete variables in OPF computations. These approaches are: sensitivity based objective and inequality constraints with respect to discrete variables; mixed-integer linear programming (MILP) based solution using merit functions and lagrange multipliers corresponding to discrete variables bound constraints based approach. The results obtained by these approaches have concluded the importance of discrete constraints based OPF solutions. Recently, the on-line applications of OPF computation has also been involved in market operations. Dolan *et al.* [73] reported a work on on-line application of market operations. This work was reported the state-of-art of

distributed generation in U.K. and presents a novel technique for online OPF using automatic power flow management (PFM).

The OPF also provides a better approach towards some other issues such as voltage stability issues in power systems. A novel technique has been introduced by Milano *et al.* [74] to represent the market-clearing algorithm model and voltage stability constrains based OPF including system security constraints. The system sensitivities are also considered in the solution procedure in this work. The sensitivities have been calculated by continuous power flow (CPF) method to find out the maximum loading conditions on the system. This is a known fact that the initialization procedure affects the performance of the evolutionary programming based OPF algorithm. Todorovski and Rajicic [75] reported an initialization procedure for Genetic Algorithm (GA) methods. In this reported work, GA has been initialized with new voltage angles at generator buses as control variables in place of selections of random control variables. The result shows that the computation time reduces considerably as compared to random selections. Thereafter, a voltage security assessment based reactive power and voltage control methodologies have been reported by Yoshida *et al.* [76]. In this work, the problem formulation of reactive power and voltage control is based on mixed-integer optimization problem. The voltage security assessment is based on continuous power flow (CPFLOW) technique and fast voltage contingency selection method.

Verbic and Canizares [77] presented an algorithm for OPF on two-point estimate method (2PEM) including the uncertainties of OPF. In the reported work, the uncertainties have been calculated by probability based computation technique. Thereafter, Bath *et al.* [78] offered a stochastic multi-objective OPF solution including security constraints for deregulated power system. This work considered some other constraints apart from usual constraints such as gaseous emission coefficients, power demands and statistical uncertainties in the thermal power generation cost coefficients. The fuzzy set theory has been exploited to evaluate the different objectives and it is quantified by defining their membership functions. Further, transient stability constrained OPF using differential evolutionary (DE) algorithm for the solution of OPF problems has been reported by Cai *et al.* [79]. The authors reported that the DE base optimization provides more accurate solutions for nonlinear and non-convex problems. In the same way, Jabr [80] presented a paper on OPF using extended

conic quadratic formulation for deregulated power system. The author reported that this method is easily integrated within optimization routines that require the evolution of second order derivatives as well as improve the numerical conditioning for linear programming. During the same period, Lin *et al.* [81] represented a hybrid current-power based OPF technique for power networks. The economic dispatch in the system has also been achieved by LMP calculations. Usually, the LMP calculations have been obtained by two methods; DCOPF and ACOPF. Li and Bo [82] reported a comparison of these two methods. In this work, a methodology of fictitious nodal demand (FND) algorithm has also been incorporated for DCOPF based LMP calculations. Simultaneously, Wang *et al.* [83] enlighten the important computational issues for market based OPF formulations and proposed some new OPF formulations and algorithms to overcome the reported issues. These new methodologies are based on trust-region-based augmented Lagrangian method (TRALM), step-controlled primal-dual interior point method (SCIPM) and constrained cost variable (CCV) based OPF formulations. The results obtained using these methods are compared with some previously reported works.

Now a days, the Flexible AC Transmission devices (FACTS) are frequently used by various existing power markets for secure and stable operations of system during dynamic contingent conditions. Lehmkoster [84] introduced the integration of control capability of FACTS with OPF which provides some significant results in terms of reduced power loss as well as cost of power transmission. The author has taken various cases of sequential quadratic programming (SQP) based optimization problem including models of FACTS devices in objective function model. Later on, FACTS devices with SCOPF based work have been presented by Berizzi and Delfanti [85]. The paper reported the use of FACTS devices as control variables in a compact and reduced SCOPF formulation. The work is also focused on the definition of their control regions and on a new procedure to find a global solution without sticking local minima. The proposed idea has been tested on a real Italian EHV system. The role of FACTS devices in OPF has been represented by Mihano *et al.* [86]. The goal of this work is to obtain an appropriate security level procedure during re-dispatching using FACTS devices models in OPF formulation.

1.2.5. Congestion Management Methodologies in Deregulated Power System

Congestion in a power network is a critical problem of a deregulated power market. Therefore, the congestion management becomes a central issue among the power system operators in competitive deregulated electricity market. This section provides a review on congestion management methodologies for a deregulated power market. Wang *et al.* [87] have proposed an optimal dispatch methodology for a mixed power market. In this, the balancing mechanism has been used to solve the problems of congestion management and optimal dispatch associated with system operation. All the three types of electricity contracts; bilateral energy, pool energy and ancillary services contracts have been taken into account in this work. Thereafter, Christie *et al.* [88] presented an invited paper that covers the detailed procedure for transmission management as well as the effect of congestion on transmission system operations. The work has also presented the different management schemes used by various power markets worldwide. In addition, Doll and Verstege [89] proposed some corrective measures for congestion management in deregulated environment. These corrective measures are adjustment of the network elements like transformer taps or shunt elements, corrective switching, corrective re-dispatch of generators, etc. The main objective of inclusions of these corrective measures in the problem formulation is to obtain an undisturbed status of dispatch in power system. Later on, Gan and Bourcier [90] reported a paper on locational market power screening and congestion management. The paper proposed two new approaches for locational market power screening; based on zonal network model and nodal transmission model. Furthermore, a bibliographical survey on congestion management methodologies in competitive power market has been reported by Kumar *et al.* [91]. The survey presents detailed information about congestion management methodologies. A paper on generation rescheduling and load shedding based congestion management scheme with a simple heuristic computational based method has been presented by Talukdar *et al.* [92]. This method considered both the cost and line sensitivities in the problem formulation. This enables the operators to reschedule the selected generators and load buses in economical and sensitive way. The authors claimed that in

most of the cases the cost of generation rescheduling and cost of load shedding is less where both sensitivity and cost are taken into account for ranking the buses.

Shayested *et al.* [93] introduced an approach for congestion management by demand side management. The paper proposed emergency demand response program (EDRP) and day-ahead response program (DADRP) models based on load elasticity to meet the transmission capacity limits and mitigate transmission congestion in a least cost manner by considering uncertainties in demand values and power system conditions. The results obtained indicate that the congestion management by generation and demand re-dispatch can considerably reduce the congestion costs. During the same period, Bikas and Bakirtzis [94] reported a paper on decentralized solution for congestion management in large scale multi-area interconnected system with cross border re-dispatching coordination. The coordination is performed through pricing mechanism using Lagrangian relaxation. Similarly, Hao and Shirmohammadi [95] introduced an Ex-Ante pricing based congestion management scheme in decentralized electricity market. The models proposed by them are based on relations between transmission congestion prices and electricity commodity prices which are useful for optimal solution. The main aim of this work is to determine clearing prices and schedules of forward electric energy and reserve markets. A decentralized approach based congestion management and pricing of congestion in the interconnected power system have been reported by Wei *et al.* [96]. In the reported work, each participants of power market tries to maximize their own profits independently in this work. Also, in this work, the results obtained by decentralized approach have been realized by the centralized approach.

A new interregional congestion management with trading has been introduced by Aguado *et al.* [97]. The authors have proposed an alternative approach by combining the forward market with a decentralized optimization-based mechanism to manage the real-time interregional congestion where the interaction of adjacent TSOs are efficiently taken into account in order to achieve system-wide efficiency. Mendez and Rudnick [98] have presented a work on Flow Gate Right (FGR) based congestion management in deregulated centralized market. Fundamentally, the FGR is used for decentralized market operations. However, in the reported work, it has been used in centralized

market to find out the advantages over FTR. Moreover, Hao [99] reported a decentralized decision based congestion management for inter-market. This paper discusses congestion path price and MW capacity allocation based decompositions by which all the regional transmission operators (RTOs) and administrators act as transmission coordinators to utilize the congested transmission lines efficiently for all regions. In the congestion path price decomposition, the congestion price signals have been realized by transmission coordinators to attract transmission demand responses. In MW capacity allocation based decomposition, transmission capacities are directly allocated to the markets.

Liu *et al.* [100] introduced the congestion management scheme for multilateral transactions based decentralized market using optimal resource allocation (ORA). The capacity of possible congested transmission lines are optimally allocated to individual transactions for maximizing the social welfare in this work. The mathematical model and its proof show the equivalence of the proposed decentralized approach with the centralized approach. In general, in decentralized power markets, the communication and exchange of information are based on synchronous models. Huang *et al.* [101] presented an asynchronous decentralized method for interconnected power markets. In the reported work, the solutions of the individual optimization problems are coordinated through an asynchronous communication model until they converge to the global optimal solution of the combined markets. The authors reported that the total operational time to reach the final solution reduces using this algorithm. Similarly, a covariance matrix adaptation evolution strategy (CMAES) based decentralized congestion management for multilateral transactions based power market has been reported by Visalakshi and Baskar [102]. The problem formulation in the reported work is based on ORA methodology as reported in ref. [100]. However, the optimal solution for congestion management has been obtained by CMAES algorithm using AC load flow (ACLF) method.

A physical flow based congestion management allocation mechanism for multiple transaction networks have been reported by Tao and Gross [103]. In this paper, a multiple transaction network frame-work was constructed to characterize the transmission congestion and then on the basis of physical flows, the contribution of congestion effects on each transaction was

determined. The counter flows were also explicitly addressed in this work. Later on, Alomoush and Shahidehpour [104] reported a zonal congestion management scheme with fixed transmission rights by transactions. This work has enlightened the congestion management in interconnected area with inter zonal lines. This work has basically combined zonal and fixed transmission rights (FTR) scheme to manage the congestion in transmission lines. Congestion management of interconnected regions using OPF formulation with Lagrangian relaxation based algorithm of decomposition has been presented by Wang *et al.* [105]. The main advantage of this method is that dummy generators or loads are not required similar to other existing methods.

A model of decentralized solution using DC load flow (DCLF) scheme for transmission management in interconnected power system has been reported by Bakirtizis and Biskas [106]. In the presented work, the original large set of the linear sparse DCLF equations have been transformed into number of smaller sparse quadratic programming (QP) problems for each area. These small programs are iteratively solved using auxiliary problem principal (APP), until they converge to the original problem solution. The results shown in this work illustrates that only limited information regarding boundary node voltage phase angle and injection must be exchanged between adjacent regions. The decentralized power transfer distribution factor (PTDF) and line outage distribution factors (LODF) are also calculated in this work. The necessity of tradable physical flow gate rights (FGR) in multiple regions based system model for economical congestion relief has been proposed by Oren and Ross [107]. The approximate pricing of transmission from a realistic adjustment process has been demonstrated in this work. In fact, in this work, a systematic random search of cost functions and network parameters are identified. This work highlights the strength of competing approach based physical tradable flow gate rights. The nonlinearities due to the AC characteristic of the system must also be recognized in design of interregional transmission load relief (TLR). A report on congestion management requirements, methodologies and performance indices has been reported by Kirby and Dyke [108]. The report provides detailed concepts of various congestion management methodologies and there functional tools for power market in United States (US). These features of congestion management open some new opportunities of business

in power market. Some suggestions had been given by the authors for the congestion management and its future scope in US electricity market.

Kumar *et al.* [109] presents a zonal/cluster-based congestion management approach for the market. In this work, the zones are identified on the basis of real and reactive power transmission congestion distribution factor based sensitivities. The most sensitive generators in a zone are identified and rescheduled on the basis of sensitivity indexes for congestion management. Cross-border congestion management scheme for European electricity market has been reported by Athanasiadis *et al.* [110]. The main objective of this work was to analyze the various features of coordinated auction technique in European market with congestion management schemes. Two techniques have been applied in this work for congestion management using FACTS devices; coordination auctioning (CA) and border capacity (BC). The analysis of these schemes shows the superiority of CA technique over BC technique in EU market. This work also reported that in day-ahead stage of market, the UPFC provides effective congestion management and increases the total transfer capability (TTC) of the transmission line, keeping the security constraints within the limits.

One of the other operational issues of voltage profile management coordination with congestion management in market operation has been considered by Yamin and Shahidehpour [111]. This paper described a generalized iterative algorithm based on Benders decomposition for the active/reactive coordination between GENCOs and the ISO for congestion and voltage profile management in the day-ahead power market wherein the GENCOs are taking the risk of committing their units and the ISO is responsible for the system transmission and voltage security. The cost and sensitivity based congestion management not only ensures transmission system security and reliability but also it ensures the voltage stability of the system. Conejo *et al.* [112] introduced voltage stability criterion in the power system. The result shows that the proposed voltage stability criterion enforces transmission capacity limits related to stability which is computed off-line. Another work on voltage security based congestion management has been reported by Esmaili *et al.* [113]. In the proposed work, the congestion relives considering voltage stability into account using effective bids. The raw bids are obtained from consumers and generators of the congested market. These are

combined with their voltage stability margin (VSM) sensitivity factors to ascertain that the contributions of risky bidders are less.

Singh *et al.* [114] proposed a congestion management scheme associated with transmission constraints and congestion costs in an electricity market. This paper examines the effect of congestion management in both the market structures; pool and bilateral. Thereafter, a review on congestion management schemes and associated pricing mechanism used by grid operators has been reported by Bompard *et al.* [115]. This paper establishes a unified frame work of market dispatch and re-dispatches among network operators to solve the congestion management problem. This work also compared the effectiveness and efficiency of various congestion management schemes.

The bidding strategies in electricity market are also one of the major operational issues. These strategies are affected due to congestion in the system. Peng and Tomsovic [116] have reported a paper on influence of congestion problem on bidding strategies in the power market and proposed a game theory based mathematical formulation for congestion management. Thereafter, Liu and Gross [117] introduced a financial tool for evaluating the congestion charges. This is known as congestion revenue rights (CRR). The holder's reimbursement of congestion charges are incurred in day-ahead market using CRR in this method. The CRRs are calculated using injection shift factors (ISF) and PTDFs.

Acharya and Mithulananthan [118] presented the effects of thyristor controlled series compensator (TCSC) based congestion management on transmission pricing in electricity market. In this work, the authors studied the behaviour of power system with and without TCSC at various loading conditions. The result shows the effect of bilateral transaction variations on the system dynamics. It has been reported in this work that the wheeling charges reduce in transactions using TCSC. The load variation also affects the transmission and congestion costs in the electricity market. Li and Bo [119] reported a congestion and price prediction methodology with load variations. In the proposed work, a systematic approach of the congestion management with load variations has been obtained without running the multiple optimization algorithms. This work also includes the biding limits, critical load levels, set of marginal generators and prices to calculate and predict the new critical load

levels. Another work was reported by Acharya and Mithulananthan [120] for the allocation of series FACTS devices for congestion management. The authors have proposed the uses of LMP differences and congestion rents in congestion management.

1.2.6. Interior Point Optimization and its Application to Power System

Different optimization techniques have been used to solve power system optimization problems. The Interior Point Method (IPM) based optimization is one of the efficient techniques among them. The fast convergence of IPM attracts the researchers to use this in the power system applications. In this section, a survey has been carried out on applications of IPM in power system. A new-polynomial-time algorithm for linear programming was first introduced by Karmarkar [121]. The objective of this work was to discuss the main ideas and mathematical foundation of IPM. Thereafter, Vargas *et al.* [122] reported security constrained economic dispatch (SCED) using IPM. Tutorial descriptions on computational challenges and convergence methodologies were reported in this work. Comparison of IPM with simplex method was also carried out in this work. Later on, Yan and Quintana [123] reported a work based on Predictor-Corrector IPM (PC-IPM) for nonlinear SCED optimization problems.

Wu *et al.* [124] presented an algorithm of IPM using primal and dual variables with Predictor-Corrector strategy to solve the OPF problems. In this work, some computational adjustments had been made in the selection of barrier parameter, Newton step size, starting point and stopping criterion to improve the efficiency of IPM. Subsequently, Yan and Quintana [125] had reported an infeasible IPM to solve the OPF problems without assuming the initial feasibility in IP algorithm. This assumption was made to reduce the computational time during iteration as it did not require the derivation of Hassian matrix. An IP based solution of nonlinear OPF problem using voltage rectangular coordinates in constraint handling has been reported by Torres and Quintana [126]. In this work, the authors explored the advantages of rectangular forms in higher order matrix setup in predictor-corrector procedure.

Wei *et al.* [127] reported a nonlinear IP programming algorithm for OPF problems based on perturbed KKT conditions of the primal problem. This work

also presented a novel data structure based algorithm to rearrange the correction equations of IPM. Thereafter, Momoh and Zhu [128] reported an improved IPM for solving OPF problems. The main advantage of this method was to provide a faster solution with general starting points (rather than good points) as compared to quadratic IPM. This method is useful for the multi-objective optimization with global solution. Similarly, Jabr *et al.* [129] reported a study on SCOPF problems using simplified homogeneous and self-dual (SHSD) linear programming (LP) based IPM. In this work, both the security conditions, N-1 and N-2 of power networks were considered. Thereafter, a model of electricity market clearing system and a solution approach for daily energy and spinning reserves of power system was presented by Madrigal and Quintana [130]. In this wok, the energy supply and spinning reserves, bid for demand of energy and re-scheduled bilateral contracts were considered as objectives of optimization problems and the solutions were obtained using IPM.

Jabr *et al.* [131], [132] have reported their work on PD-IPM for OPF dispatching problems. The main objective of these papers was to enhance the performance of convergence process of PDIPM by some amendments using filter technique to guide the choice of step length and an altered search direction in order to avoid convergence to non-minimization stationary points. In the same way, Patra and Goswami [133], [134] have also reported papers on nonlinear IPM for OPF solution with some difference in the solution process. In both the work, instead of logarithmic barriers, a smoothing function was used to handle the complementary conditions in the solution process. The main advantage of this selection was to overcome the limitations of variables in the interior of the feasible space throughout all iteration. This selection also avoids the necessity of heuristic during the smoothing parameter updating. Similarly, Zheng *et al.* [135] reported a work on nonlinear IPM based solution of OPF with current mismatch formulation in the rectangle coordinates. The basic advantage of this formulation was that the derivatives of the intermittent variables become zero or constant which makes the computer code simpler.

A comparative study on different IP techniques for the various classical OPF problems such as minimization of generation cost, loss minimization, maximum loadability and load curtailments were reported by Capitanescu *et al.* [136]. These techniques are Primal-Dual IPM (PDIPM), Predictor-corrector (PCIPM) and multiple centrality corrections (MCC) based IPM. The results

obtained by these techniques showed that the MCC technique is superior to other techniques. Farhat and El-Harway [137] presented a paper on optimum operation scheduling of electric power systems based on IPM. In this paper, variety of IP algorithms have been applied to many areas of power system operations such as economic dispatch, unit commitment and hydrothermal coordination. Basically, this paper offers a literature survey in order to highlight the guidelines of system operations. An efficient algorithm for online application of automatic differentiation (AD) in IP for OPF solution has been reported by Jiang *et al.* [138]. In this proposed algorithm, the AD has been added as a subroutine into the IPM to identify the entire constant first order and second order derivative. These derivatives have been updated by AD tool in each iterationw to enhance the performance and flexibility of IPM. Thereafter, another work on transient stability constraints OPF (TSOPF) problem has been solved by Jiang and Geng [139]. In this work, the computational burden of numerical discrtaization has been relived using reduced memory space technique with PCIPM. The dynamic OPF solutions for an interconnected power system have been reported by Chung *et al.* [140]. This work was based on decomposition in PCIPM. In this work, the iterative process, slack variables and Lagrange multipliers of dynamic constraints are predicted and corrected and thereafter other variables are also predicted and corrected. The parameters of step length and barrier have estimated independently for each sub-system.

The interior point method based optimization had played an important role in pre-deregulation paradigm for solving power system optimization problems over the years. In post deregulation period, some new objectives have involved in the electricity market such as incentive based pricing mechanism, tariff allotment and privatization of the power market. The IPM based optimization techniques have been playing a significant role in this environment. Xie *et al.* [141] reported a work on optimal spot pricing in deregulated market using IPM based decomposition method. In this work, a technique of optimal nodal specific real-time prices for active/reactive powers has been proposed. The decomposition of problem objective into different components such as spinning reserve, voltage control and security controls corresponding generation, loss and other selected ancillary services have also been reported in this work. Consequently, Granville [142] reported an optimal reactive power dispatch method in deregulated power system using Primal-

Dual (PD) algorithm based IPM, wherein the effectiveness of IPM was shown. Later on, Momoh *et al.* [143] introduced an Extended Quadratic Interior Point (EQIP) optimization method to solve the power system optimization problems. This work included the nonlinearities of the system in problem objectives of economic dispatch and reactive power planning. The EQIP method creates some feasible interior points during iterations which helps the solution process to find the feasible solutions for the problem objective. Subsequently, Liu *et al.* [144] have reported a paper on reactive power optimization using PDIPM with extended nonlinearity in the power system. In this work, the discretization process of the control variables in PDIPM algorithm has been performed using penalty functions. The main advantage of this is to obtain a reduced number of non-zero fill-in elements during convergence. A work on formulation of maximum loadability in power system using non-linear IPM algorithm has been proposed by Irisarri *et al.* [145]. In this work, the algorithm was tested on a large system with 4000 buses and 6000 lines.

1.2.7. Particle Swarm Optimization and its Application in Power System

Initially, Kennedy and Eberhart [146] proposed a new concept for optimization of nonlinear functions using particle swarm methodology. This described the relation of PSO with artificial life and GA. Thereafter, AlRashidi and Hawary [147] and [148] reported two papers on survey of PSO applications in power system optimization problems. This report highlighted the key features and advantages of PSO in various optimization problems such as economic dispatch (ED), neural network training, power system controller design, OPF and reactive power control in comparison to other optimization techniques. Vlachogiannis and Lee [149] compared three new PSO algorithms with state of art of PSO for optimal steady-state performance of power systems. These new algorithms are GPAC, LPAC and coordinated aggregation (CA) based PSO. The results of these algorithms have also been compared with conventional interior point and classical PSO methods. Thereafter, a detailed report on PSO concepts, its variants and application in power system was reported by Valle *et al.* [150].

The selection of starting parameters is also one of the strategically important problems in PSO applications. Shi and Eberhart [151] introduced a new parameter of inertia weight in the optimization process of PSO. The

simulation work of this work shows the effectiveness of this new parameter on PSO. Another work on empirical study on PSO has also been reported by these authors [152]. This work analyzed the convergence behaviour of PSO. Richards and Ventura [153] presented a paper on choice of starting configuration for PSO. This paper shows that the performance of initialize PSO over standard PSO. This paper suggested that the centroidal voronoi tessellations (CVT) initialization improves the performance of PSO for high dimensional spaces. The problems of premature convergence of PSO have been solved by Chaturvedi *et al.* [154]. In this work, a self-organizing hierarchical PSO was used to solve the nonconvex ED problems. The performance of proposed algorithm has been further improved by inclusion of time-varying acceleration coefficients. Abido [155] presented a paper on OPF solution using PSO. In this paper, different objectives such as fuel cost minimization, voltage profile improvement and voltage stability enhancement have been considered. Also, the results obtained by PSO have been compared with the results of other reported methods. Later on, the problem of transient-stability constrained based OPF has been solved by Mo *et al.* [156]. In this work, the rotor angel has been considering as an additional inequality constraint for OPF problems. Another work on security constraints OPF has been proposed by Yumbla *et al.* [157]. In this work, the security constraints are embedded with OPF problem. The reconstruction operators with PSO algorithm (PSO-RO) has been used as the optimization tool in this work. These operators are used for improving the feasible space, computational time and quality of solution during search mechanism.

The PSO is also one of the efficient optimization methods which has been used for solving the problem of congestion in the power systems. Hazra and Sinha [158] presented an efficient method for congestion management using multi-objective PSO (MOPSO). This method is based on realistic frequency and voltage dependent load flow method which considered the voltage and frequency dependent loads and generators regulation characteristics. The proposed method provides a set of optimal solutions for any congestion problem. The optimal rescheduling of generators using PSO has been proposed by Dutta and Singh [159]. The main objective of this work is to reduce the number of participating generators and reschedule their outputs for congestion management in a power pool with minimum rescheduling cost. This work explored the ability of PSO for congestion management.

Onate *et al.* [160] presented a paper with objective of minimization of overall operating cost while satisfying the power flow equations, system security and equipment operating limits. The overall operating cost comprises the generation costs, transmission cost and consumers benefits. The solution has been made by PSO in this work. Gaing [161] proposed a PSO for economic dispatch problem of power system. In this work, the effects of generator characteristics such as ramp rate limits, prohibited operating zones and non smooth cost functions have been analyzed. The results have also been compared with results of GA in the reported work. Park *et al.* [162] reported a paper on economic dispatch in power system with non-smooth cost functions using PSO. In this paper, the modified PSO is used for treatment of equality and inequality constraints. The dynamic process has been used to accelerate the convergence. In the same lines, Jeyakumar *et al.* [163] presented various solutions for ED problems using PSO. These problems are multi-area ED problems with line limits, multiple fuel options, environmental effects and generators prohibited zones. Thereafter, Selvakumar and Thanushkodi [164] reported a solution for nonconvex economic dispatch problems in power system using PSO. In this work, the split-up cognitive behaviour based modification was carried out in PSO. This modification helps in exploring the search space. A simple local random search (LRS) procedure was integrated in this modification. Baskar and Mohan [165] reported a work on ED problems with security constraints in thermal units. This work proposes an improved PSO (IPSO) method in which a new velocity strategy equation was formulated. This method was effectively used in large-scale power system problems. A paper on improved coordinated aggregation-based PSO (ICA-PSO) algorithm to solve the ED problems has been presented by Vlachogiannis and Lee [166]. In this algorithm each particle in the swarm retains a memory of its best position encountered. Then the particle is attracted only by other particles with their better achievements and consequently the said particle moves randomly. Mahadad *et al.* [167] proposed ED with discontinuous fuel cost functions in power systems using improved parallel PSO. In this work, the range of partial power demand corresponding to the partial output powers near the global optimal solution is determined by a flexible decomposed network strategy and then finds the optimal solution using parallel PSO. The swarm intelligent based solution has also been frequently used in the electricity market operations. Bajpai *et al.* [168] proposed a strategic bidding method for competitive

electricity markets. In the reported work, single supplier's decision-making problem has been solved by PSO for bid and linear bid electricity market methods.

A variety of improved and hybrid PSO was reported by various researchers in different time frames. Victoire and Jeyakumar [169] present an efficient method for solving the economic dispatch problem (EDP), by integrating the PSO technique with the sequential quadratic programming (SQP) technique. In this work, the PSO is the main optimizer and the SQP is used to fine tune for every improvement in the solution of the PSO run. The effectiveness of the proposed method is validated by carrying out extensive tests on three different EDP with incremental fuel cost function and takes into account the valve-point loadings effects. The proposed method out-performs and provides quality solutions compared to other existing techniques for EDP considering valve-point effects. Later on, Esmin *et al.* [170] presented a PSO and hybrid particle swarm optimizer with mutation based solutions for loss reduction problems. This study caries tangent vector technique for identification of critical area in system and PSO/HPSOM are used to optimize the amount of shunt reactive power compensation at each bus. Liu *et al.* [171] presented a hybrid swarm optimization algorithm with chaos. In this method, an adaptive inertia weight factor (AIWF) was introduced in PSO to effectively balance the exploration and exploitation abilities. The PSO with AIWF and chaos are hybridized to form a chaotic PSO (CPSO), which reasonably combines the population based evolutionary ability and searching behaviour of PSO. Victoire and Jeyakumar [172] introduces an application of hybrid-PSO and sequential-quadratic programming technique (hybrid-PSO-SQP) guiding the Tabu search (TS) method for solving the unit-commitment problem. At the same way, Yare *et al.* [173] presented a work on optimal generator maintenance scheduling using a modified discrete PSO. This modified PSO provides a feasible solution and overcomes the limitations of the conventional methods such as extensive computational efforts. An improved PSO (I-PSO) based work was proposed by Park *et al.* [174]. This work proposes a solution for non-convex ED problems in the system. The work is based on I-PSO employing chaotic sequences combined with conventional linearity decreasing inertia weights and adopting a crossover operation scheme to increase both the exploration and exploration capability of the PSO. Another work based on

hybrid quantum mechanics inspired PSO has been proposed by Chakraborty et al. [175]. In this work, the economic load dispatch problems with valve-point effects have been solved by this hybrid PSO method. In this proposed PSO, a fine balanced has been maintained in between local and global searching point. A paper was reported by Gaing and Lin [176] on the contingency-constrained OPF solutions by a simplex-based-chaotic PSO. The results of this algorithm have been compared with other classical PSOs. Hoballah and Erlich [177] presented a paper on online market-based rescheduling strategy to enhance the power system stability. The objective of this work is to solve the online transient and oscillatory stability constrained ED problem using a mixture of modified PSO and artificial neural network (ANN). Nikman *et al.* [178] reported multi-objective OPF considering the cost, loss, emission and voltage stability indexes. The solutions of these problems have been solved by I-PSO. In this work, a fuzzy decision based mechanism was used to select the best compromise solution of Pareto set which is obtained during the solution procedure. Furthermore, to improve the quality of solution, particularly to avoid trapped in load optima; a self-adaptive concepts based I-PSO has been proposed and used in this work. Zhao et al. [179] reported a paper on multi-agent based PSO approach for optimal reactive power dispatch. In this work, all agents live in a lattice-like environment where each agent fixed on a lattice point. In order to obtain the optimal solution quickly, each agent competes and cooperates with neighbours and it also learns by using its knowledge.

The PSO has also been utilized for solving the some other operational issues of power system such as generation expansion planning, maximum loadability and unit commitment (UC) problems. Kannan *et al.* [180] presented a work on generation expansion planning at least cost. In this work, virtual mapping procedure (VMP) has been used to enhance the performance of PSO. The numbers of infeasible solutions have been reduced by penalty function approach. Apart from simple PSO, many variants approach such as constriction factor, Lbest model, hybrid PSO, stretched PSO and composite PSO have been applied on the test system and compared the results with dynamic programming in terms of speed and efficiency. A paper was reported by Shunmgalatha and Slochanal [181] for maximum loadability limit of the system using hybrid PSO. This work incorporates the breeding and subpopulation process of GA in PSO. The unit commitment (UC) problem of

power systems have been solved by Jeong *et al.* [182] using Quantum-Inspired Binary PSO (QBPSO). In this method, the quantum computing has been used to formulate the PSO algorithm. This modification improved the search capability of the PSO for UC problems.

Recently, a work on the elastic behaviour of demand consumption jointly used with distributed generation (DG) has been proposed by Faria *et al.* [183]. In the proposed work, the PSO based methodology is used to support the minimization of optimal cost of a virtual power player that manages the resources in the distribution network and the network.

1.3. OBJECTIVE AND SCOPE OF THE THESIS

The main objective of the thesis is to alleviate network congestion in multi-transaction power system with social welfare maximization for the region or country. A new operating paradigm in which the decision mechanism regarding economics and security of the system are considered for the problem. The economic decisions are carried out by bilateral/multilateral contracts among generators and consumers for trading of power. In this work, the congestion management in a multi-transaction power market model is considered as a security issue and social welfare maximization is considered as optimization problem among the transmission operators. The sensitivity index information is coordinated through the power system operators. On the basis of this information, all the transactions schedule their generators and loads at demand buses to make profitable trades with secure transmission loading limits in the power market.

This thesis work proposes a decentralized optimal power flow (DOPF) based decision support in multi-transaction power market based on AC load flow (ACLF) technique. The formulation of the objective function of DOPF is based on Optimal Resource Allocation (ORA) methodology in this work. Further, the results obtained by DOPF are compared and validated with the results of centralized optimal power flow (COPF) based decision support. In DOPF, each transaction optimizes its own schedules under the transfer limits of transmission lines which are allocated by ISO. The transmission line capabilities for individual transaction is determine with the help of Resource

Allocation Weighting Matrix (RAWM) indices. The congestion management issue is also carried out by the help of these indices.

The congestion in the system can be managed by various methods. The rescheduling of generations and loads are one of the efficient methods among them without adding any external tool such as FACTS and compensation devices in the system. In other words, rescheduling does not require any additional cost of external component with system installation cost. Thus, in the present thesis work, the generators and consumers are coordinated by some contracts and make groups inside the system structure. These groups are known as transactions which have some numbers of generators and consumers and these groups' frames a market structure in the power system. These transactions utilize the RAWM indices to optimize the welfare of the system which is termed as social welfare in contingent conditions. The optimal schedules of generators and consumers demands in transactions are obtained by OPF solution. In this work, the two approaches, centralized optimal power flow (COPF) and decentralized optimal power flow (DOPF) based decision are used to solve the scheduling problems. The formulation of mathematical models for COPF and DOPF are given in this work. The power losses and their cost due to transactions are also carried out in this thesis work. This is a known fact that the losses have been allocated on the slack bus in ACLF analysis. Therefore, in this work the cost of power losses via transactions are also calculated by inclusion of slack bus generation cost coefficients corresponding to loss in each transaction for obtaining the actual social welfare of the market. Thus, it can be stated that a fair competition in the power market can be established by this analysis.

The congested system is modeled as the optimization problem and the three optimization techniques are used to solve the problem objective of congestion management with social welfare in multi-transaction power market with COPF and DOPF approaches. Among the three optimization techniques, two are the suggested techniques, interior point (IP) and particle swarm optimization (PSO) techniques and third is a proposed technique which is interior point initialized particle swarm optimization (IP-PSO) as a hybrid PSO. The major advantage of IP technique is to provide a fast convergence of solution of OPF as compared to other conventional optimization techniques. This feature can be utilized for real-time scheduling of generators and demands for

congestion management. A major drawback of IP technique is the need of derivatives in the solution process which is difficult to evaluate. Also, this method does not guarantee the global solution for the optimization problems. Therefore, to mitigate these problems, the present work uses PSO to solve the problem objective and compared the results with IP solution. The PSO provide an optimal and global solution for OPF problems. In the present thesis work, the PSO is applied on the multi-transaction system with COPF and DOPF based approaches to obtain the global solution for the problem objective.

Although, the PSO produces global optimal solutions which is better than IP technique, but it gives slower convergence if initial particles are far away from global optimal solution. With the intention of taking benefits of both the methods, the solution obtained by IP has been used as one of the particles/solutions among the initial particles. In the present thesis work, a hybrid PSO is proposed as IP-PSO. In this technique, the solution starts with the solution obtained by IP and then followed by solutions obtained by PSO. This results into a fast search mechanism. The accuracy of the proposed IP-PSO based COPF and DOPF approaches have been been authenticated by comparing the results with IP and PSO based COPF and DOPF approaches. Modified IEEE-30 bus and modified IEEE-118 bus systems are chosen to demonstrate the performance of the proposed study. The test results reveal that the proposed DOPF approach provides more social welfare as compared to COPF. At the same time it is also finds that the IP-PSO yields better results as compared to IP and PSO based OPF solutions and produces more social welfare and requires less computational time as compared to results reported in [102].

1.4. ORGANIZATION OF THE THESIS

This thesis is organized in six chapters. First chapter (Chapter I) introduces the background of the problem undertaken in this thesis. This chapter presents a brief review of literature related to the topic. This is followed by the objective and scope of the thesis.

Chapter II deals with the basic concepts of social welfare in the power markets and congestion management process in the terms of definition and alleviation process for deregulated power systems. This chapter also includes

the general description on operations and services of worldwide established deregulated system environment.

The mathematical formulation of optimal power flow with centralized and decentralized decision support for congestion management with social welfare in power market is proposed in Chapter III. The centralized and decentralized decisions have been implemented using centralized and decentralized optimal flow based mathematical formulations for the problem objective. This formulation emphasizes mainly on congestion alleviation process by economic rescheduling of power generators and loads of consumers demands in multi-transaction market. The optimization problem is formulated on the basis of optimal rescheduling of all the participants using system sensitivities PTDF and RAWM indices.

In chapter IV, the social welfare maximization based congestion management problem is solved for coordinated bilateral/multilateral power market. Optimal generations and demands rescheduling have been found by IP and PSO based optimization methods. The performance of the algorithm is studied on the modified IEEE-30 bus and modified IEEE-118 bus systems. The obtained results of IP and PSO are compared to show the effectiveness of PSO over IP method.

In Chapter V, the proposed IP-PSO based optimization method has been applied for the problem objective using COPF and DOPF and the results are compared with results of IP, PSO and CMEAS methods. Same system models of modified IEEE-30 bus and modified IEEE-118 bus systems are selected to demonstrate the effectiveness of IP-PSO method for problem objective. Detailed studies on comparisons of social welfare and computational behaviour have also been reported in this chapter.

Chapter VI concludes with the summary of contributions of thesis with scope for further work in this new area of specialization. A comprehensive bibliography of documented literature on this topic of research is given in references.