REAL TIME POWER SYSTEM OPERATION
UNDER Deregulated ENVIRONMENT

SYNOPSIS

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SYNOPSIS

1. Introduction

During the years of 1980s, almost all-electric power utilities throughout the world were operated with an organizational model in which one controlling authority i.e. the utility operated the generation, transmission, and distribution systems located in a fixed geographical area and it refers to as vertically integrated electric utilities (VIEU). There was an iota of doubt whether the monopoly organization was efficient. There is rapid change in philosophies in respect of Telecom, Air Lines, and IT Sectors, which brought a revolution in power sector also.

The present day power systems operation has assumed commercial significance and technical considerations like availability, demand and transmission adequacy, which weigh against the economic background of the countries. The electric utility introduced new concept of deregulation in this sector in order to improve availability, efficiency and derive the economic benefits. Many electrical utilities and power network companies’ worldwide have been forced to change their ways of doing business from vertically integrated mechanism to open market system. This kind of process is called as deregulation or restructuring or unbundling. At present, the power utility has been restructured as
separate entities of generation (GENCO), transmission (TRANSCO) and distribution (DISCO).

These changes in the structure of electric utilities and the creation of free markets for energy trading are bringing about a redefinition of power system operation and forcing a re-examination of the design concepts for power system control centers. Many utilities throughout the world are on the threshold of a new beginning in system operation as they enter into the arena of a free electricity market. In recent decades, several improvements have been achieved in power system operation. The evolution was mainly in the development of computational and communication systems. Both areas allowed the analysis of complex models of power system operation that resulted in a more flexible system controlled in almost real-time mode. All these improvements favoured the change of power system operation to a new environment, in which the traditionally regulated monopoly electrical system became deregulated with operations based on energy market operations. In this environment, not only security, but also the monitoring of power flow direction and the controls, represents critical issues.

The operation of the generation-transmission-distribution grid is quite complex because this large system has to operate in synchronism and because many different organizations are responsible for different portions of the grid in this new scenario. Many public and private electric power companies are interconnected. Thus, many organizations have to
coordinate to operate the grid, and this coordination can take many forms, from a loose agreement of operational principles to a strong pooling arrangement of operating together. Constant review and monitoring of all the different markets is done to track the advancement of the power market.

The other structure is open access; in which bilateral contracts transactions are directly organized between generator and consumer.

2. Organization of Thesis

This thesis is organized in seven chapters. First chapter introduces the area of Real Time Power System Operation under deregulated environment. Since the topic taken up for study is in evolving stage, a detailed literature survey is presented in second chapter. The third chapter enlightens the real time power system operation prevailing in developing countries with particular reference to Indian power sector scenario. Fourth chapter proposes Proportional Nucleolus of Cooperative Game Theory (CGT) as a model for the allocation of the transactional transmission losses in Multiple-Transaction Electricity Markets. In the fifth chapter, a detailed algorithm for Transmission loss allocation in usage-based methodology and development, application of the equivalent loss compensation concept procedure for open access environment are presented. The sixth chapter proposes a methodology for evaluating frequency linked- price and loss scheduling under deregulation market environment. Seventh chapter 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.

3. Motivation for the work

The introduction of deregulation involves many technically complicated issues ranging from system planning, operation to commercial and market areas. The introduction of deregulation and subsequent open access policy in electricity sector has brought competition in energy market. But, it also caused certain difficulties in some areas especially the transmission network loss sharing and the responsibility of Automatic Control of generation. These issues were identified and motivated to develop certain models for allocations of transmission loss and frequency regulation services.

4. Details of proposed work

The main objectives of the work reported in the thesis are:

- To Investigate of Current Trends in the Deregulated Electricity Market in developing countries with particular reference to Indian power sector under inadequate generation resources and transmission capabilities commensurate with load growth.

- To develop new methodologies for
  - Loss allocation Problem by Cooperative game theory for Multi transactions.
  - Loss allocation by usage based under open access.
o Loss compensation Scheme.

- To develop an approach for frequency regulation problem.


Power system operation becomes a difficult task for power utilities in developing countries due to common situation of inadequate generating capacity and transmission capacities commensurate with load growth in demand. In this regard, the electric energy sector today is concerned more than ever before about the issue of maintaining the quality of energy supply within acceptable limits. These limits imposed on system operation basically are frequency and voltage. In such environment, the questions of maintaining sufficient system reserve margins and the cost of reliability have become key issues in the electricity business. It implies that it is hard to manage Deregulation when there is a lack of capacity. In this research work, transition in real time power system operation prevailing in developing countries with particular reference to Indian power sector scenario is taken as up study. Identification and development of solution strategies are also discussed. Issues raised in this thesis are expected to be of practical significance in real time power trading under deregulated environment.

In late 1990’s, there was acute shortage in electricity before deregulation has taken place in India. For most of the time the Indian Regional grids used to operate at precariously low frequency of about 48 Hz., and very
low voltage of even at 300 KV (400 KV). This led to severe insecurity in the grid operation. This instability in operation of power system triggered grid contingencies very frequently, resulting in system separation and grid disturbances. This insecure and unstable grid operation caused immense financial loss to the industry and the inefficient operation of the electrical equipment led to increased electrical losses also. In addition, with multiple blackouts in Indian Power systems, Indian electricity sector experienced energy crisis along with serious financial problems. During this period, all electric power utilities throughout India were operated with an organizational model i.e. vertically integrated model. The Electrical utility as a controlling authority operated the generation, transmission, and distribution systems located in a fixed geographical area. During this period, there were wide fluctuations in the frequency and voltage in Indian power systems due to shortage of power as mentioned above. The new tariff mechanism known as Availability Based Tariff (ABT) was implemented in regional grids so as to impose the grid discipline. The ABC of ABT is presented in [1]. The rules and regulations of power system operation under this mechanism and pricing structures are documented in [2]. It came into existence for regional grids of India from the year 2003 onwards. The techno economical issues of integrated operations of practical large scale Power Systems under ABT are presented in [3-6].
These electric utilities introduced privatization in their sectors to improve efficiency. During 21st century, many electrical utilities and power network companies have been forced to change their ways of doing business from vertically integrated mechanism to open market system. The Open Access was introduced in Indian electrical environment with the help of 2003 Electricity ACT. The issues related to trading in open access environment are presented in [7-12]. The author identified some of the complex issues and variety of critical situations if the new tariff mechanism will be extended to the inner layers of the state sector and implications of the power system operations in a Real-time environment under ABT mechanism in [13].

This thesis mainly focuses on the peculiar techno-economical practical issues related to integrated operations of Power Systems existing in developing countries, which have undergone various phases of development. The transition in power system operation in developing countries with particular reference to Indian power sector scenario is described. ABT as mentioned above has been implemented in regional grids of India so as to impose the grid discipline and to regulate the wide fluctuations prevailing in the frequency. Development of such a typical power system can be divided into three phases: a) Pre ABT b) ABT c) Post ABT conditions. An attempt is also made in this thesis to synthesize the complex issues and variety of critical situations handled by the operators of State Load Despatch centers and of Generating Stations and of
Distribution Companies of State if new tariff mechanism is implemented to the inner layers of the state sectors. The power system operator cannot judge the implications of the operations on Real Time basis under ABT mechanism with practical constraints prevailing in the existing state grids in micro level. It becomes difficult for the operator to analyze the effect on operation of power system under ABT. Some of these problems are identified and suggestions are proposed in this thesis.

6. Real Time Power System Operations in Deregulated Environment in Indian Scenario

The discussion evolves around the power system issues for Genco, Transco and Discos. There are a number of factors present in the power system operation within the restructured industry. The main Deregulation should not sacrifice system operation reliability and security. However the risk does exist in developing countries like India. The main risks identified are as follows:

- Inadequate generation capacity
- The Original transmission network is not designed for market operation. Thus these weak networks and bilateral contracts will cause transmission congestion.
- There is large cross-border trading verses poor interconnected power system control coordination.
- There is shortage of reserve capacity and reactive power.
• Emergency control & protection are not ready for market operation.
• Growing uncertainties in planning and operation of power systems.
• Increased need for the exchange of data among market players.
• Software technologies and numerical methods for the power industry.

7. Loss Allocation Problems
The thesis presents a model for the allocation of losses using CGT where several transactions are jointly maintained in Multi-Transaction Electricity Market environment and a usage-based methodology for transmission loss allocation in deregulated Power Systems under open access are presented.

There has been a lot of change in many aspects of the electricity business, including the pricing of electricity by introduction of the new concept of deregulation in the electricity market. In this deregulated market, participants must require a fair and equitable pricing structure that reflects both the share of power Generated/Consumed in the network and the cost of power loss, based on losses that they cause. These allocations influence on decision-making of the electricity market participants for their financial commitments and their profits, i.e., these changes have resulted in a radical shift in the way losses are distributed among market participants and have gained financial significance. The Market participants must be charged for the losses in a way, which
reflects their use of the network. Many different loss allocation schemes have been proposed in literature in this area, but no method has gained universal acceptance. The problem of allocating the transmission losses among the power system users has become more important with the increase in the competition level in electricity markets.

The evaluation of the loss allocations by various procedures has been widely discussed in many papers [14]-[24]. Reviews of Cost Based Transmission Losses Allocation Methods are presented in [25]. These methods have been suggested to allocate the system losses to generators and loads in a pool market or to individual transactions in a bi-lateral contracts market.

7.1 Modeling Loss Allocation Problem by Applying CGT

Game theory looks at rational behaviour when each decision maker’s well being depends on the decisions of others as well as his or her own. Game theory comprises of cooperative and non-cooperative game theory. In cooperative game, it is assumed that the decision makers (or, “players”) are able to sign legally enforceable contracts with each other. Non-cooperative game theory does not make this assumption. It is a discipline that is used to analyze problems of conflict among interacting decision makers. It may be considered as a generalization of decision theory to include multiple players or decision makers.
Cooperative games have the following ingredients

i) A set of players

Let \( N = \{1, 2, \ldots, n\} \) be the finite set of players and let \( i \), where \( i \), runs from 1 through \( n \), index the different numbers of \( N \).

ii) A characteristic function, specifying the value created by different subsets of the players in the game, is denoted by \( \nu \). The Characteristic function is a function expressed as a number and is associated with every subset \( S \) of \( N \), denoted by \( \nu(S) \). The number \( \nu(S) \) is interpreted as the value created when the members of \( S \) come together and interact.

Into to, a cooperative game is a pair \((N, \nu)\), where \( N \) is a finite set and \( \nu \) is a function mapping subsets of \( N \) to members of the game.

iii) Imputation:

For a Given Cooperative Game \((N, \nu)\), an allocation \( X = (x_1, x_2, x_3, \ldots, x_n) \) is called as an imputation.

iv) A key concept in cooperative game theory is the core of the game. The Core is defined as a set of imputations satisfying the following conditions.

\[
x_i \geq \nu\{i\} \quad \text{(Individual rationality)}
\]

\[
\sum_{i \in S} x_i \geq \nu(S) \quad \text{(Coalition rationality)}
\]

\[
\sum_{i \in N} x_i = \nu(N) \quad \text{(Collective Rationality)}
\]

For a game is in coalition form \((N, \nu)\) the core is denoted as \( C(N, \nu) \).
The allocation methods can be broadly classified into three categories, i.e. Classical, New, and Variants of Nucleolus (Core Solutions). In this thesis, two points are focused during the modeling of loss allocation problem: the structure of the game and the concept of fairness behind it. The allocation concept of these CGT methods for loss allocation is systematically analyzed, compared and calculations have been performed considering various standard power system networks. The Proportional Nucleolus is shown to be among the most plausible concept. A power flow (PF) procedure is applied to calculate power losses for each transaction.

An extension of the Core Solution Concept is presented for handling the empty-core situations and its advantage along with the supportive mathematical proofs are presented in [26]. If core is nonempty, the concept of extended core always coincides with core. The unique allocation belongs to this extended core, i.e. Proportional Nucleolus is proposed as selection device. How the Proportional Nucleolus allocation is better than other allocations such as Shapley and Nucleolus etc is dealt in [27]. The various methods in CGT, the application of testing the convexity and additivity functionalities and comparison of allocation methods in CGT are extensively dealt in [28-29]. The application of CGT methods applied to the deregulated environment is presented in [30]-[31].
Traditionally, agreement over allocation of losses is reached through discussions between participants and these losses can be divided without any assistance from knowledge of game theory. It remains a challenge to electricity business to select allocation concepts or methods for total losses and distribute it among the participants in Multi-Transaction Electricity Markets. This is because the participants do not have knowledge about the fair allocation concepts to be accepted.

This Thesis suggests that CGT application is an effective approach for the solution of the problem. First, it shows that the loss allocation problem is identical to the problem of computing the value of an n-person cooperative game. A case study shows why some allocation methods in CGT, failing to satisfy the mandatory properties, have to be rejected. The cooperative game theoretic ideas are attentively implemented for loss allocation in this thesis and also compared with the approach presented in Transmission Loss Allocation in a Multiple-Transaction Frame work [15]. Then, the thesis proposes Proportional Nucleolus method as it has unique solution even if the core is empty and compares the variants of Nucleolus and Shapley from cooperative game theory.

7.2. Loss Allocation in Open Access by Usage Based Methodology

The losses are always present in transmission lines and transformers due to resistances. A total active power loss in transmission system typically amounts only to the extent of 3-5% of the total generation. Even
though this figure is small, it is significant in terms of accumulated effect on revenue. Any proposal for restructuring without a solution to the problems due to losses is incomplete and unacceptable. The loss allocations have influence on decision-making of the electricity market participants for their financial commitments and their profits. There is a need to find the contribution of losses by each generator and distribute the same among market participants. The market participants must be charged for the losses in a way, which reflects their use of the network. In general, each trade should include its share of transmission losses. In other words, the net generation should equal to the sum of the demand and the transmission losses caused by the trade. The total transmission losses caused by all the trades on the network can either be measured or calculated.

The problem of allocating the transmission active power losses among the power system users has become more important with the increase in the competition level in open access electricity markets. The commercial issues related to charges for power losses are taken into consideration, subject to negotiations between consumers/distribution utilities and Generating companies.

A method to allocate transmission losses for simultaneous bilateral transactions in open access is proposed on utilization basis. This approach uses a standard Power Flow solution program and calculates the injected power flow at each node. Based on this, it calculates the
portion of real power loss contributions by individual generators and allocation to loads using (i) the amounts of generation utilized by consumers and (ii) the standard loss formula as function of injected powers at the nodes [36]. There are no additional approximations assumed in the proposed approach, resulting in avoidance of inaccuracies induced during the formulation stages of method. The standard power network loss formula [36] is expressed in terms of amounts of power utilized by Discom Companies/Consumers from individual generators. The proposed method illustrates the splitting of total losses as contributions from each generator and to the loads.

The methodology starts from a converged load flow solution which gives the entire information pertaining to the network such as bus voltages, complex line flows, slack bus power generation and Total Transmission losses etc. Once a load flow solution is obtained, this result is then used in the proposed methodology to allocate transmission losses to generators and loads.

The allocation method is in fact derived on the basis of exact loss formula. The system loss is then decomposed into components corresponding to individual generators and loads. The loss compensation scheme for active power is also presented in this thesis.

7.3. Loss Compensation Scheme

In open access system, a non-profit organization known as Independent Grid Operator (IGO) usually is responsible for the operation of the
system. In addition to the operation and control of a system, typical tasks of an IGO may also include accepting schedules from generators, providing access to the successful consumers and allocating transmission loss among the generators and consumers. An IGO also plays the role of a supervisor for system operation and security. It would keep track of all information related to the trading and computes the transmission usage for each generator.

This model is based on the principle that free market competition is a route to economic efficiency. In this model, suppliers and consumers independently arrange trades, setting by themselves the amount of generation and consumption and the corresponding financial terms, with involvement or interference by the Independent Grid Operator. Coordination is necessary because physical laws dictate how power flows from the generators to the consumers in a transmission network. The IGO coordinates among the independent trades, which cannot lead to a violation of transmission network constraints. Also, power flows must be balanced throughout the network and transmission losses must be included in power balance. The energy loss in the transmission network is a function of the aggregate trades, and therefore the trades have to account for their own losses.

The main other concern of the IGO, with respect to transmission loss, is to allocate loss either to the generators or consumers. Based on the allocation of transmission losses computed as per methodology given
in above section and as per previously agreed terms, a generator or consumer is required to either compensate or pay its share of loss. In either case, the allocation of transmission loss is a debatable issue for the simple fact that transmission loss is a complex non-linear function of power provided by the generators and sensitive to system state.

The objective is to recover more accurately power loss subject to the terms and conditions of agreement. IGO employs the proposed loss compensation approach to balance the difference between the total system loss and the recovered loss. The ISO is equivalent to IGO.

The transmission loss compensation schemes considered as ancillary services are presented in [32]-[35]. A non-profit organization known as Independent System Operator (ISO) usually is responsible for the operation of these ancillary services.

8. Design of Frequency Regulation Service Markets

An attempt has been made to develop a model for the frequency-regulated systems by considering the frequency as an additional variable in load flow procedure. Optimal pricing structure is proposed for frequency-regulated systems.

This thesis proposes a general model for multi-area AGC, suitable for deregulated electricity market under steady state condition. A model is developed considering the interface variable like frequency of the areas and the bilateral contracts between Disco (or buyer) in any of the areas and Gencos (or seller) in the same or in a different area. It is assumed
that participation of any Genco or Disco in frequency regulation market depends on their bids. It is proposed here that the generators offer for primary regulation service based on their droop characteristics.

The main objective of the new approach proposed in this work is to establish frequency regulation services in competitive markets under steady state condition. The frequency deviations due to unscheduled interchanges are established under steady state and calculated the optimal prices in ancillary services. This approach has been revisited with modifications of the reference [37] and assuming that all network parameters can be considered as constant for small frequency deviations to simplify the problem.

The model presented is considered new and innovative. The governor characteristic of generator is taken into consideration in load flow method and modified accordingly so as to compute the frequency deviations due to unscheduled interchange.

The proposed model replicates the actual power system in which each generator shares the load and accounts for the losses according to the governor characteristic. Representation of governor characteristics of the generator in the modeling of power system is towards actual replica of practical power system. In short, the approach proposed and algorithm described in this thesis performs concurrent analysis of power flow along with frequency variations.
9. Main Contributions of Thesis

The following are the contributions of the present thesis.

1. The evolution of transition in real time power system operation prevailing in developing countries with particular reference to Indian power sector scenario is taken up for study. Identification and development of solution strategies are discussed. Issues raised in this thesis are expected to be of practical significance in the study of real time power trading under deregulated environment.

2. The challenge faced is how to allocate the transmission loss and what should be the criterion for charging utilities in new deregulated environment. In general, Utilities look for consistency, simplicity, accuracy and predictability in loss allocation method. Not only accurate calculations are necessary, but also fair and equitable allocation of the losses to all the participants in trading is also important. There exists no ideal or standard loss allocation method as all the existing methods require time consuming process and, therefore found limited acceptance by the industry.

   i) Mathematical Models are developed by using Cooperative Game Theory (CGT) to the allocation of the transactional transmission losses in Multiple-Transaction Electricity Markets. The Proportional Nucleolus model is found to be the most plausible concept.
ii) A new model is developed for allocating losses to individual generators and loads according to their usage in Open Access environment. The method uses (a) amounts of generation utilized by consumers and (b) the standard loss formula as function of injected powers obtained at each node from standard power flow program to the nodes without any approximations.

iii) Development and application of the equivalent loss compensation concept procedure for open access environment.

3. An approach for frequency linked price is modeled for deregulation market environment. This model takes into consideration: Governor Characteristics and frequency characteristics using modified load flow method. The pricing methodology for the deviations in scheduled power with respect to the deviation of frequency has been evaluated. The arbitrary prices of the imbalances due to differences between schedules on account of contracted amount and actual drawls have been calculated by using this model.
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