POWER TRANSFER BOTTLENECKS DETERMINATION FOR THE EASTERN GRID OF BANGLADESH POWER SYSTEM

A thesis submitted to the Department of Electrical, Electronic and Communication Engineering, Military Institute of Science and Technology in partial fulfillment of the requirement for the Degree of

B.Sc. in Electrical, Electronic and Communication Engineering

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CERTIFICATION

This thesis paper titled **"Power Transfer Bottlenecks Determination for the Eastern Grid of Bangladesh Power System"** has been accepted as satisfactory in partial fulfillment of the requirements for the B.Sc. in Electrical, Electronics and Communication Engineering on December 2012.

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DECLARATION

This is to certify that the work presented in this thesis titled "**Power Transfer Bottlenecks Determination for the Eastern Grid of Bangladesh Power System"** is the result of the research and innovation carried out by the following authors under the supervision of Dr. Abdul Hasib Chowdhury, Associate Professor, Department of Electrical and Electronic Engineering, Bangladesh University of Engineering and Technology, Dhaka Bangladesh.

It is also declared that this thesis paper or any part of it has not been submitted anywhere else for the award of any degree, diploma or other qualifications.

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DEDICATION

This thesis is dedicated to our loving parents and honorable teachers.

ACKNOWLEDGEMENT

We start in the name of Allah, most gracious most merciful. At first we would like to convey our gracious gratitude to the Almighty Allah, who has made this thesis work possible.

We would like to convey our most humble and deepest gratitude and profound indebtedness to our honorable supervisor Dr. Abdul Hasib Chowdhury, Associate Professor, Department of Electrical and Electronic Engineering, Bangladesh University of Engineering and Technology, for supporting us throughout our thesis work with valuable suggestions, continuous guidance and direction. His enthusiasm, keen interest on the topic and valuable advice was essential in completing this thesis work.

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Finally we would like to convey our gratitude to our family members for their continuous support and helpfulness.

Dhaka,
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ABSTRACT

The emerging trend of deregulating power industries requires the operator to keep the transmission network congestion free when the generation companies compete to sell electricity to the distributors or wholesale purchasers. This requires the determination of various power transfer bottlenecks in the existing network. For this purpose the real-time predetermination of an index termed “Available Transfer Capability (ATC)” is required. Transfer capability of a power system also indicates how much inter area power transfer can be increased without system security violations. In case of large power systems such as that of Bangladesh, the vital information required for the planning and operation of the system are provided from the transfer capability calculations. These details provide system bottlenecks to the planners and the limits of the power transfers to the system operators. Thus power transfer bottlenecks determination of Bangladesh Power System effectively means the calculation of ATC of the system. In order to provide an effective and in depth knowledge of ATC determination, various calculation methods have been discussed in the thesis, and two of them, namely Repeated Power Flow Method and Path Dependent Network Flow model have been applied for the actual calculation procedure. As working with a large number of data makes the analysis process difficult and cumbersome, so only data from the Eastern Grid of Bangladesh Power System have been used in this research. The fact that the Eastern Grid contains about 76% of the total generation capacity, has also worked as incentive. Additionally, comparison of the results obtained from both calculation techniques are provided, which gives an in depth idea about the system capabilities and transmission bottlenecks along with directions and suggestions for improvements and future works needed in this area.

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LIST OF ABBREVIATIONS

ATC	Available Transfer Capacity
TTC	Total Transfer Capacity
TRM	Transmission Reliability Margin
CBM	Capacity Benefit Margin
CPF	Continuation Power Flow
RPF	Repeated Power Flow
KCL	Kirchhoff's Current Law
SQP	Sequential Quadratic Programming
PGCB	Power Grid Company of Bangladesh
BPDB	Bangladesh Power Development Board
REB	Rural Electrification Board
DESCO	Dhaka Electric Supply Company
DPDC	Dhaka Power Distribution Company
WZPDC	West Zone Power Distribution Company
GW	Giga-Watts
MW	Mega-Watts

CHAPTER 1

Introduction

1.1 Introduction

Amongst all types of energy, electrical energy is considered as the most convenient form of energy. It is considered as the driving force that keeps the modern civilization dynamic. Traditionally electricity is supplied over a given territory by a utility under a monopolistic framework i.e. the generation, transmission and distribution sectors are vertically integrated under a single ownership [1]. However, with increased demands recent years have witnessed participation of private companies in the generation sector. As a result the electric utilities all over the world have been subjected by the governments to the process of gradual transition from a regulated and monopolistic configuration towards a full scale deregulation. In this present open access or deregulated environment all the participants (producers and buyers of electrical energy) desire to produce or consume large amounts of energy and may force the transmission system to operate beyond one or more transfer limits or bottlenecks. This is also true for Bangladesh. The Bangladesh electricity transmission system is an extensive, interconnected network of high-voltage power lines that transport electricity from generators to consumers [2]. The transmission system must be flexible enough, every second of every day, to accommodate the nation's growing demand for reliable and affordable electricity. In order to ensure reliable and affordable electricity now and in the future it is essential to determine the transmission bottlenecks. And in order to do so, the necessity of calculation of Available Transfer Capability (ATC) in power systems rises, as this quantity has a direct impact on production and transmission cost signals. In general ATC is the limiting transfer value between two control areas that is available without any violation of the power system operating limits. The purpose of determining the ATC values is to further the open access of the bulk transmission system by providing a market signal of the capability of the transmission system to deliver energy, which could spur competitive bidding in the energy market. [3]

1.2 ATC Definitions

In order to understand the different concepts related to ATC calculation, various definitions must be taken into account.

1.2.1 Available Transfer Capability (ATC)

Available Transfer Capability (ATC) is a measure of the transfer capability remaining in the physical transmission network for further commercial activity over and above already committed uses. Mathematically, ATC is defined as the Total Transfer Capability (TTC) less the Transmission Reliability Margin (TRM), less the sum of existing transmission commitments (which includes retail customer service) and the Capacity Benefit Margin (CBM). As shown in Figure 1.1. [4]

ATC = TTC - TRM - CBM - Existing transmission commitments

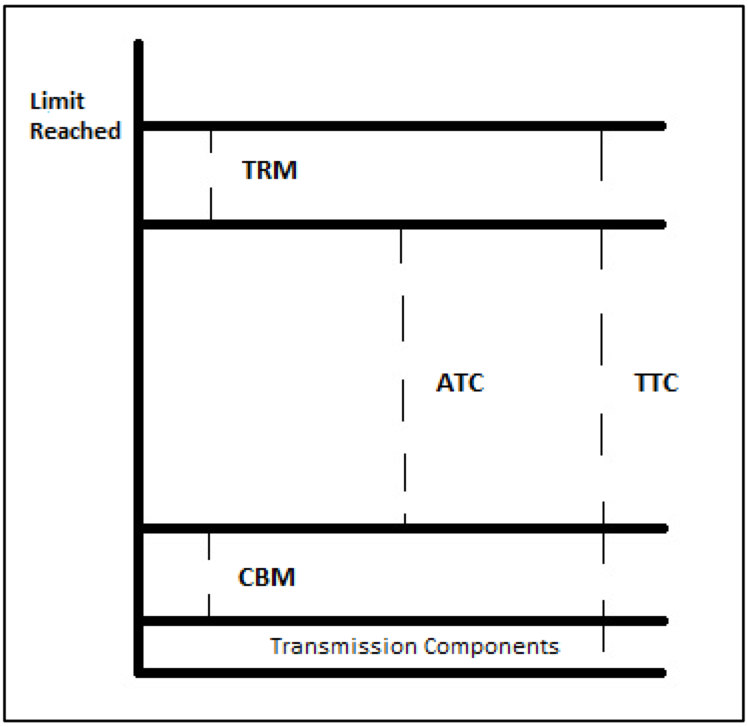


Figure 1.1 Components for Available transfer Capability Determination

1.2.2 Total Transfer Capability (TTC)

Total Transfer capability (TTC) is defined as the amount of electric power that can be transferred over the interconnected transmission network in a reliable manner while meeting all of a specific set of defined pre- and post-contingency system conditions. Mathematically,

TTC = Minimum of {Thermal Limit, Voltage Limit, Stability Limit}

TTC is an important parameter that indicates how much power transfer can take place without compromising the system security. The accurate TTC calculation is essential to ensure that power system can operate without reliability risks [4][5] . For Repeated Power Flow (RPF) method of ATC calculation, TTC is taken as the basis.

1.2.3 Transmission Reliability Margin (TRM)

Transmission Reliability margin (TRM) is defined as that amount of transmission transfer capability necessary to ensure that the interconnected transmission network is secure under a reasonable range of uncertainties in system conditions. [4]

1.2.4 Capacity Benefit Margin (CBM)

Capacity Benefit Margin (CBM) is defined as that amount of transmission transfer capability reserved by load serving entities to ensure access to generation from interconnected systems to meet generation reliability requirements. [4]

ATC and related terms are depicted graphically below.

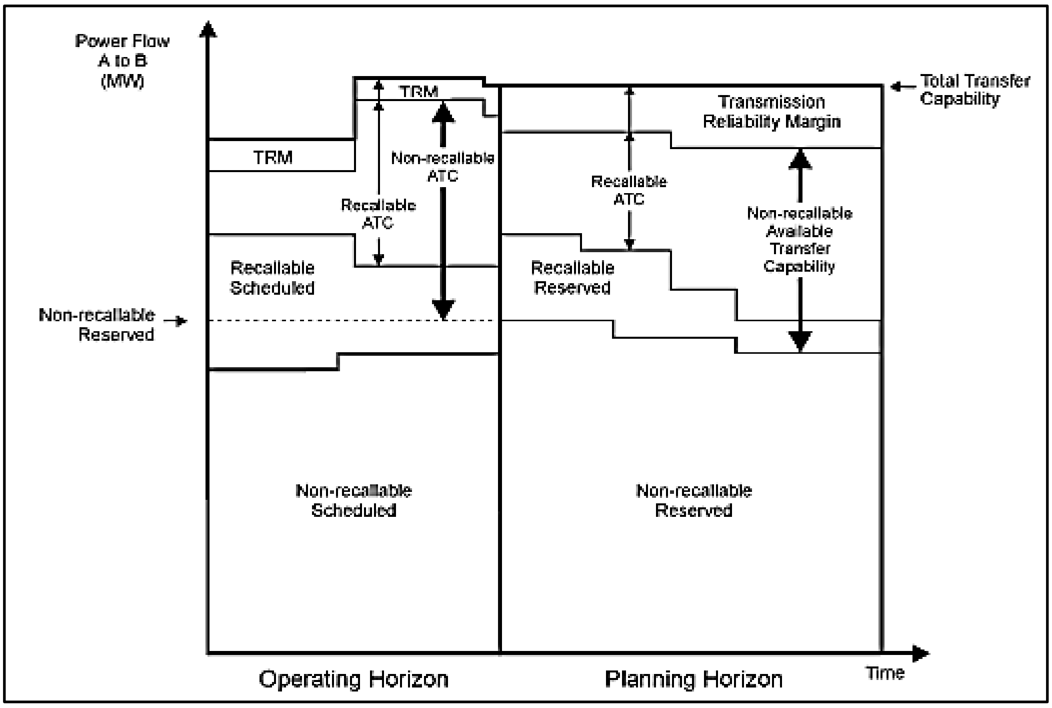


Figure 1.2 TTC, ATC, and Related Terms in the Transmission Service Reservation System.

1.3 Available Transfer Capability Principles

Certain principles must be adhered for ATC calculation which balances both technical and commercial issues. All transmission provider and user entities are required to follow these Principles. [4]

a) The results of ATC calculation must be commercially viable indicators of the transfer capabilities available to the electric power market.

b) The time-variant power flow conditions on the entire interconnected transmission network must be recognized during ATC calculation. To accurately assess the capabilities of the transmission network all system conditions, uses, and limits should be taken into consideration.

c) ATC calculations must acknowledge the dependency of ATC on the points of power injection, the directions of transfer, and the points of power extraction. All entities must provide sufficient information required for the calculation of ATC.

d) Regional or wide-area coordination is necessary to develop and post information that reasonably reflects the ATCs of the interconnected transmission network.

e) ATC calculations must observe the rules to reliability planning and operating policies by considering appropriate system contingencies.

f) The determination of ATC must accommodate reasonable uncertainties in system conditions and provide operating flexibility to ensure the secure operation of the interconnected network.

1.4 Determination of Available Transfer Capability

Many different methodologies have been applied for transfer capability studies and to determine the relationship of electric power transactions and associated power flows on the transmission network. Among the different methodologies, Repeated Power Flow (RPF) [6][26]; Continuation Power Flow (CPF) [6-10]; Optimal Power Flow (OPF) [11][12]; Path

Dependent Network Model [15]; DC load flow utilizing linear sensitivity factors [13]; Sequential Quadratic Programming [15] etc. are the most common and widely used methods. Some of these methods are discussed elaborately in Chapter 2.

1.5 Thesis Objectives

Available transfer capability (ATC) indicates how much inter-area power transfers can be increased without compromising system security. The Bangladesh electricity transmission system is an extensive, interconnected network of high-voltage power lines that transport electricity from generators to consumers. Bangladesh Power System comprises of two major regions, namely Eastern Grid and Western Grid, geographically divided by the combined flow of rivers Jamuna, Padma and Meghna. The two areas operated in isolation until commissioning of the first double circuit East-West Interconnector between Ghorasal and Ishurdi in early 1980s. After this line another double circuit 230 kV line has been constructed between Ashuganj to Sirajganj to enhance power transmission capability from eastern to western grid [2][24]. This transmission system of the country must be flexible enough, every second of every day, to accommodate the nation’s growing demand for reliable and affordable electricity. For a country like Bangladesh with complex power transmission network accurate identification of transmission bottlenecks i.e. Transfer capabilities is vital to maintain a reliable operation for the bulk power market. While overstating ATC could necessarily endanger the network's security, an overly conservative estimate, on the other hand, could limit trades and transactions across the system. Moreover deregulation of power market has imposed great impact on the utility industry. For smooth transaction of power between the areas or paths, new technologies and computation methods are urgently needed. The vital information required for the planning and operation of the large power systems can be obtained from these transfer capability calculations. These calculations also help to determine the quantity of lost generation that can be replaced by potential reserves and limiting constraints in each circumstance. For these reasons, this thesis paper aims at calculating the Available Transfer Capability of the Eastern Grid of Bangladesh. The Generator, branch and bus data necessary for the calculation purpose were obtained from PGCB. The obtained data were divided into the Western and Eastern grid according to bus numbers and connections following PGCB regulations. The reason behind selecting data only from the Eastern grid is because Eastern

Grid contains the majority of the countries generation capacity (76%). Moreover, dividing the huge amount of data into components offers more accurate results of present transfer capabilities and provides the scope for more concentrated and reliable analysis.

1.6 Thesis Outline

The thesis is organized in five chapters. The subject matter of our thesis is described in the following chapter wise.

Chapter 1 formally introduces us to the concept of Available Transfer Capability, Principles governing ATC calculation and definitions of various terms related to ATC calculation. A brief overview of various ATC calculation methods and the thesis objective are also described in the chapter.

Chapter 2 contains in depth analysis of some ATC calculation methods.

Chapter 3 gives a clear idea about the whole power system network of Bangladesh, explaining generation, transmission and distribution methods and East-West grid connections.

Chapter 4 This chapter shows us the load flow results of Available Transfer Capability (ATC) of Eastern zone of Bangladesh and analysis and comparisons of results obtained.

Finally **Chapter 5** draws the conclusive part to our thesis work. This chapter comes with the conclusions and discussions on directions for future research.

CHAPTER 2

Techniques for ATC Calculation

2.1 Introduction

Transfer capability can be computed using different methods and these computations are evolving. The results obtained from ATC calculation depends largely on the configuration of the system. As a matter of fact the network model used in the calculation procedure has great impact on ATC determination. In general a number of methods have been employed for ATC calculation. Some of them are: Repeated Power Flow (RPF); Path Dependent Network Flow Model; Maximum Flow Problem; Continuation Power Flow (CPF); Optimal Power Flow (OPF); Sequential Quadratic Programming Method etc. This chapter discusses these methods in detail.

2.2 Repeated Power Flow Method

ATC calculation can be conducted by performing Repetitive Power Flow (RPF) solutions for increasing amounts of transfer until the first limiting condition is reached. Repeated power flow approach starts from a base case, and repeatedly solves the power flow equations each time increasing the power transfer by a small increment until an operation limit is reached. The advantage of this approach is its simple implementation and the ease to take security constraints into consideration [26]. In this thesis work, this is one of the methods used to solve TTC problem to determine ATC; in repeated power flow method, TTC determination is the basis for determining ATC [15].

2.2.1 Determination of Total Transfer Capability (TTC)

TTC represents the total amount of electric power (net of normal base power transfers plus first contingency incremental transfers) that can be transferred between two areas of the interconnected system in a reliable manner based on the following conditions:

(i) For the existing or planned system configuration, and with normal (pre-contingency) operating procedures in effect, all facility loadings are within normal ratings and all voltages are within normal limits.

(ii) The electric systems are capable of absorbing the dynamic power swings, and remaining stable following a disturbance that results in the loss of any single electric system element, such as a transmission line, transformer or generating unit.

(iii) After the dynamic swings subside following a disturbance that results in the loss of any single electric system element as described in (ii) above, and after the operation of any automatic operating systems, but before any post-contingency operator-initiated system adjustments are implemented, all transmission facility loadings are within emergency ratings and all voltages are within emergency limits.

The condition (i) is related to the static security constraints under the first contingency of the pre-contingency operating conditions while condition (iii) is concerned with the static security constraints of the post-contingency operating conditions. Condition (ii) is the typical (angle) transient stability constraint.

Due to the nonlinear nature of the interconnected electric power systems, total transfer capability between two areas and their associated binding constraints depend on the set of operating conditions. The operating conditions represent a single snapshot of the operation of the interconnected network based on the consideration of a number of factors:

- Generation dispatch
- System configuration
- Base scheduled transfers
- System contingencies
- Projected customer demand

TTC between any two areas or across particular interfaces is direction specific that is limited by the physical and electrical characteristics of the system including:

- Thermal limits (branch MVA, and loading limits)
- Voltage limits (voltage magnitude limits)

• Stability limits (voltage stability limits, and transient angle stability limit)

The limiting condition of the transmission network can shift among thermal, voltage, and stability limits as the network operating conditions change over time. Such variations further make the determination of TTC a non-trivial task.

2.2.2 Algorithm for Repeated Power Flow Method

This method involves the solution of a base case, which is the initial system conditions, and then increasing the transfer. After each increase, another load flow is solved and the security constraints tested. A conceptual framework is suggested to determine the TTC on an area inter change basis. The steps to determine the TTC from area A to area B are:

a. Start with a base case power flow.

b. Increase generation in area A and increase load in area B by the same amount.

c. Check the normal thermal, stability, and voltage constraints.

d. Evaluate the first contingency event and ensure that the emergency operating limits are met.

e. Repeat steps b, c, and d until an emergency limit is reached for the first contingency, the corresponding (pre-contingency) transfer amount from area A to area B is the total transfer capability.

After TTC is determined, then we have for ATC;

$$\text{ATC} = \text{TTC} - \text{Existing transmission commitments} \tag{2.1}$$

2.3 Path Dependent Network Flow Model

Network flow models have been studied extensively in economics. They apply to areas such as electrical and power networks, telecommunication networks, airline flight paths, gas pipelines, highway traffic, and manufacturing and distribution networks. In all of these problem domains, the aim is to move some entity (electricity, a consumer product, a person or a vehicle, a message) from one point to another in an underlying network, and to do so as efficiently as possible, both to provide good service to the users of the network and to use the underlying (and typically expensive) transmission facilities effectively. In a power transmission network, source and sink nodes correspond to buses with generation and load respectively. Arcs (or links), with flow bounds between the nodes, correspond to transmission lines with their transfer limits. The mass balance constraint is equivalent to Kirchhoff s Current Law (KCL) which applies to the transmission system. KCL requires the sum of energy flow into a node (area) to be equal to the sum of Energy out of the node (area). Flow from a node (area) in a network flow model has free choice of transmission lines. It can leave the source node (area) to the demand node (area), given that there is a direct link, or split between the areas in any desired ratio. The ATC between any two areas corresponds to the minimum interface rating on the various paths between the areas [15].

2.3.1 Path Dependent ATC Calculation

Consider the 6-area system given in Figure 2.1 [16]. The areas at the top of the diagram (1,2 and 3) are generators while the areas at the bottom (4, 5, and 6) are loads. The network has 11 arcs (branches) and each arc represents a transmission interface. The primary flow of power is from the top of the diagram to the bottom and also from left to right. The network parameters are given in. The generation at areas 1, 2, and 3 is 100 MW, 50 MW, and 60 MW respectively. The load at areas 4, 5 and 6 is 70 MW each. The capacity of each arc is 100 MW.

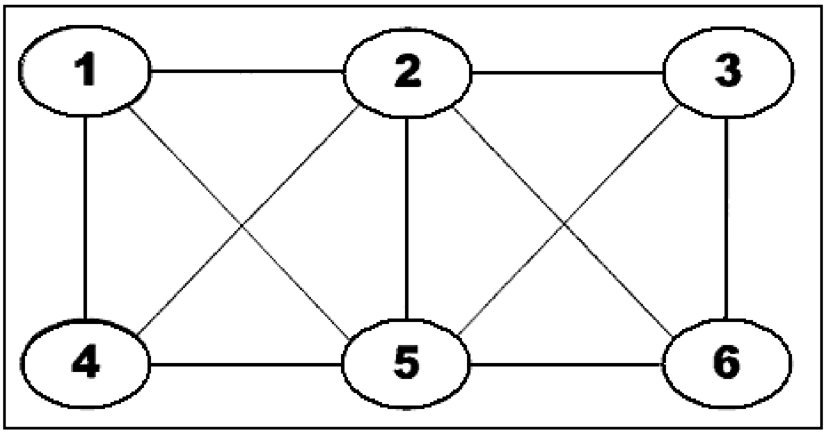


Figure 2.1 6-area system

The directed graph in Figure 2.2 (a) shows the flow on each arc and the arc's capacity in p.u., the flows and their directions were obtained from the DC power flow solution of the network. Suppose area 6 is to buy power from area 1.

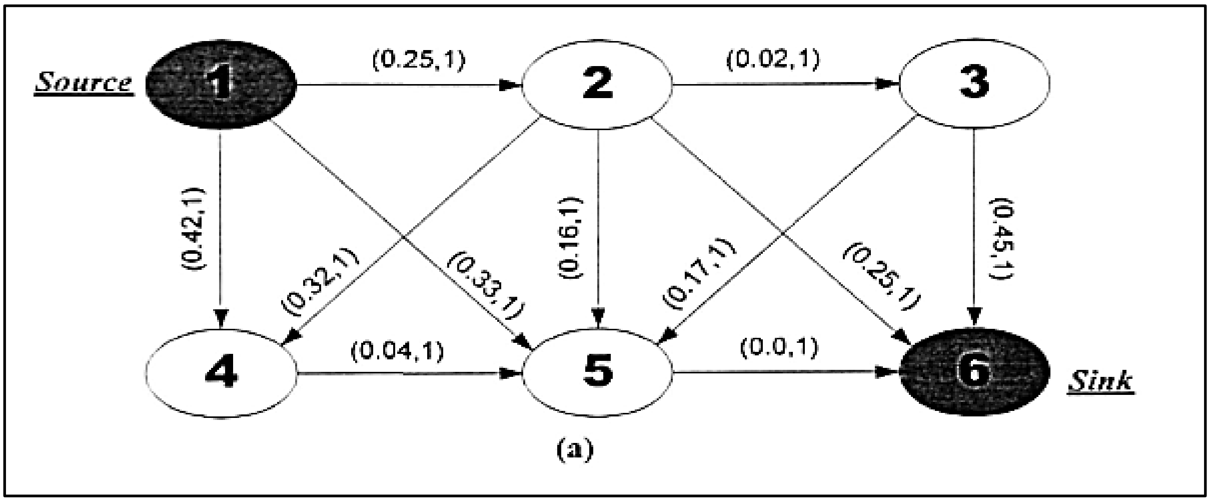


Figure 2.2 (a) Original 6-areanetwork with flow *x*

We want to determine the ATC from area 1 to area 6. To apply the augmented path algorithm, we first have to construct the residual network shown in Figure 2.2 (b). Each arc in the original network is replaced by two arcs, and the arc has a residual capacity. The residual network functions as a "remaining flow network" for carrying the incremental flow.

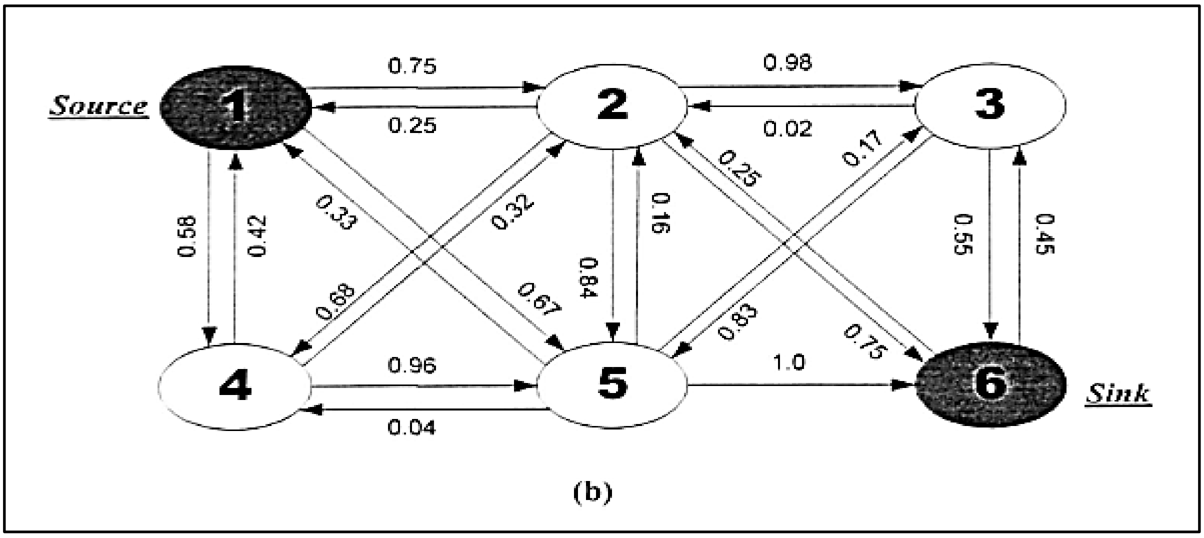


Figure 2.2 (b) Residual network for flow x

Working with the residual network is equivalent to working with the original network 2.Suppose the path 1-2-6 is selected for augmentation. The residual capacity of this path is 0.75 p.u. since both arcs have equal flows and capacities. In other words, the transfer limit between area 1 and area 6 using the contract path from area 1 to area to area 6 is 75 MW. The resulting residual network from the augmentation is shown in Figure 2.2 (c).

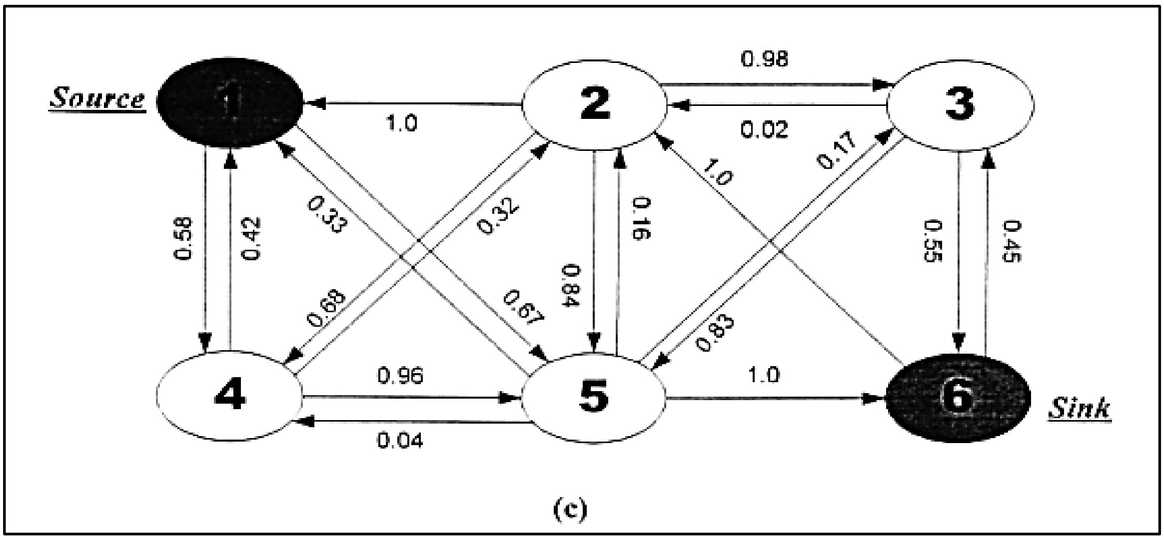


Figure 2.2 (c) Residual network after augmenting 0.75 p.u. along path 1-2-6

In the second iteration, suppose the path is 1-4-5-6. The residual capacity of this path is min {0.58, 0.96, 1.0}. Augmenting 0.58 p.u. along this path yields the residual network shown in Figure 2.2 (d).

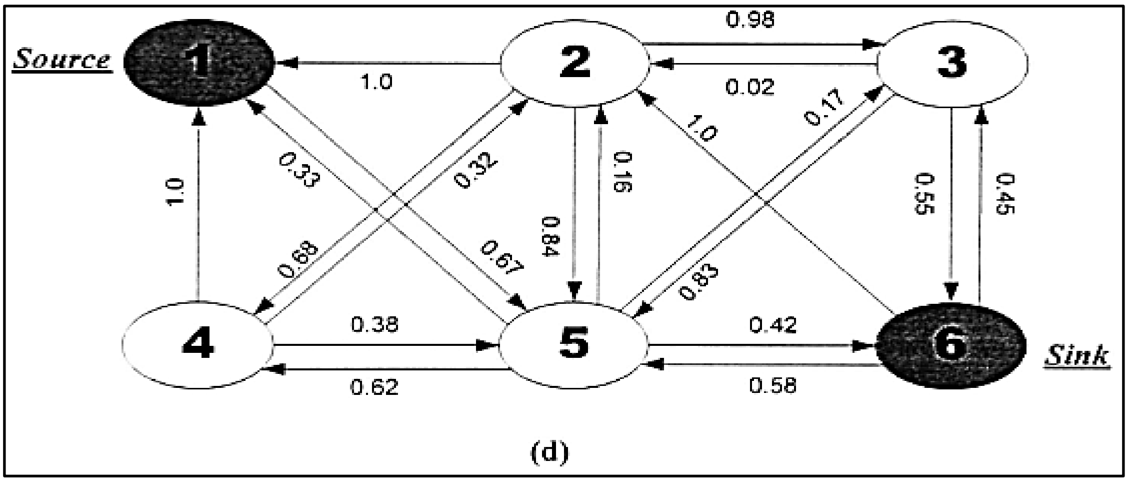
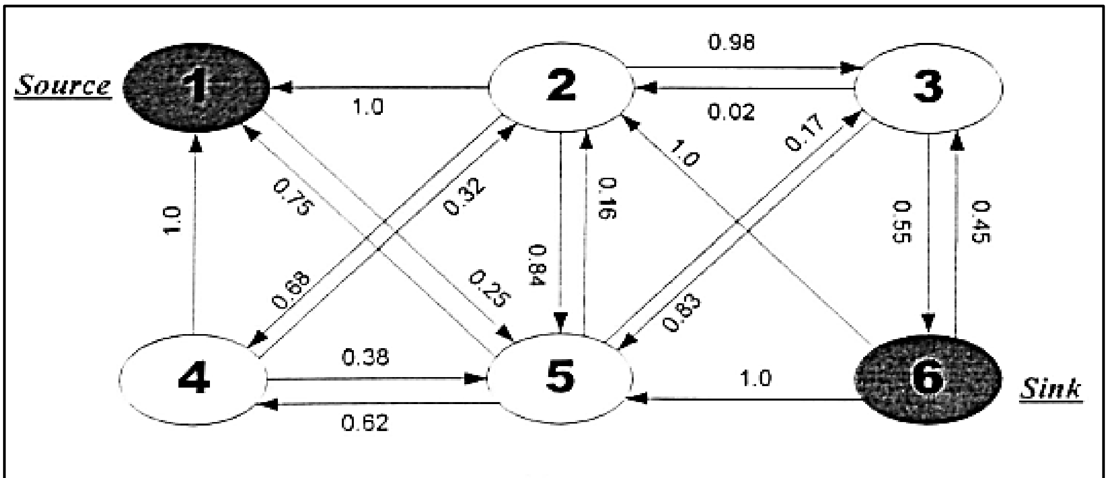


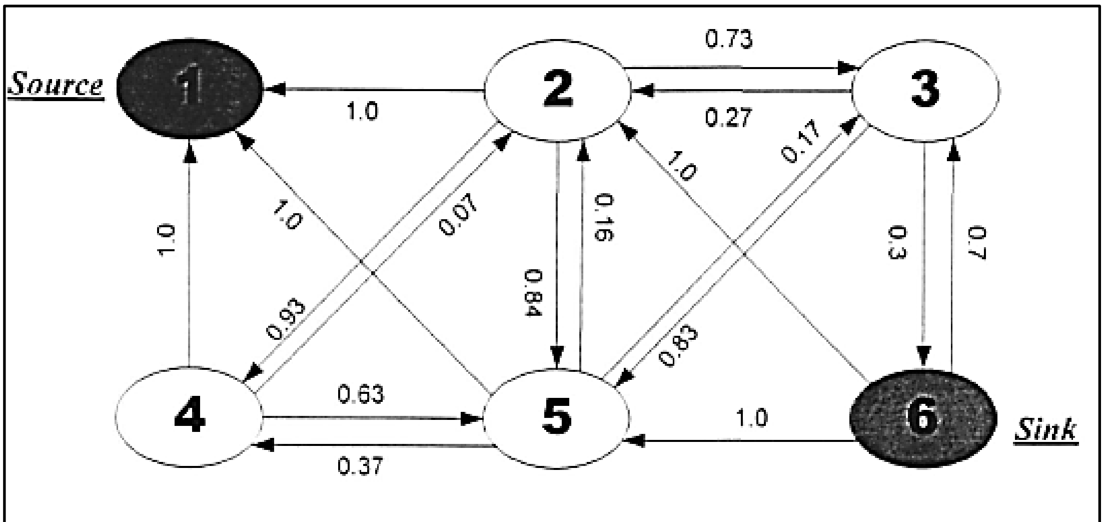
Figure 2.2 (d) Residual network after augmenting 0.58 p.u. along path 1-4-5-6

The algorithm proceeds for another two iterations, shown in Figure 2.2 (e) and 2.2 (f), and terminates because no more paths exist in the residual network.



(e)

Figure 2.2 (e) Residual network after augmenting 0.42 p.u. along path 1-5-6



(f)

Figure 2.2 (f) Residual network after augmenting 0.25 p.u. along path 1-5-4-2-3-6

The original network after the augmentation is shown in Figure 2.2(g).

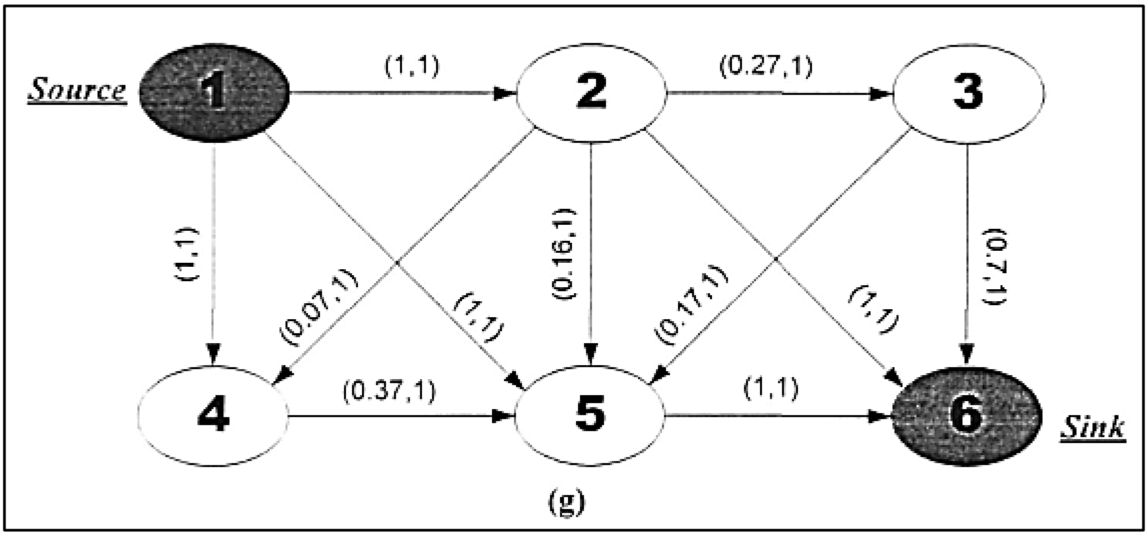


Figure 2.2 (g) Flow in the original network after augmentation

Path-dependent transfer limits are presented in Table 2.1. ATC from area 1 to area 6 is 200 MW.

Table 2.1 Path limits for the transfer from area 1 to 6 area

Path	Path transfer limit, MW
1-2-6	75
1-4-5-6	58
1-5-6	42
1-5-4-2-3-6	25

The results given in Table 2.1 are for one possible set of paths. A large number of combinations are possible without affecting the ATC value (i.e., 200 MW).

2.4 Continuation Power Flow Method

Continuation power flow (CPF) method is a comprehensive tool for tracing the steady state behavior of the power system due to parametric variation [9]. The parameters which are varied include bus real and/or reactive loads, area real and/or reactive loads and real power generations at generator or P-V buses. Continuation methods are also known as curve tracing or path following which are used to trace solution curves for general non-linear algebraic equations with a parametric variation. Conceptually, the purpose of the continuation power flow is to find a continuum of power flow solutions for a given load change scenario.

2.4.1 Continuation Power Flow Formulation

For CPF, the set of power flow equations first have to be reformulated to include a continuation (varying) parameter. The total system demand at some collection of load buses is usually taken as the varying parameter. The power flow equations are represented as:

$$P_i - V_i \sum_{j=1}^{N} V_j \left(G_{ij} \cos\Theta_{ij} + B_{ij} \sin\Theta_{ij} \right) = 0 \qquad (2.2)$$

$$Q_i - V_i \sum_{j=1}^{N} V_j \left(G_{ij} \sin\Theta_{ij} - B_{ij} \cos\Theta_{ij} \right) = 0 \qquad (2.3)$$

Where P_i and Q_i are the active and reactive power injection at bus i; $V_i < \theta_i$ is the voltage at bus i and $\theta_{ij} = \theta_i - \theta_j$; $Gij + jB_{ij}$ is the corresponding conductance and susceptance of the system Y-matrix; *N* is the total number of buses. The power injection at bus is defined as

$$P_i = P_{Gi} - P_{Li} \qquad (2.4)$$

$$Q_i = Q_{Gi} - Q_{Li} \qquad (2.5)$$

Where P_{Gi} and Q_{Gi} are the real and reactive power generation at bus i while P_{Li} and Q_{Li} are the real and reactive load at bus i.

To simulate a load change, the P_{Li} and Q_{Li} terms must be modified. This is done by breaking each term into two components: one component corresponds to the original load at bus and the other component represents a load change brought about by a change in the load parameter η [3].

Thus,

$$P_{Li} = P_{Lio} + \eta(k_{Li} S_{\Delta base} \cos\Psi_i) \tag{2.6}$$

$$Q_{Li} = Q_{Lio} + \eta(k_{Li} S_{\Delta base} \sin\Psi_i) \tag{2.7}$$

Where the load parameter $0 \le \eta \le \eta_{critical}$. When $\eta=0$, this corresponds to the base load and $\eta=\eta_{critical}$ corresponds to the critical load. P_{Lio} and Q_{Lio} are the original loads at bus *i* (active and reactive respectively). k_{Li} is a multiplier designating the rate of load change at bus i as η changes. Ψ_i is the power factor angle of load change at bus i. $S_{\Delta base}$ is a given quantity of apparent power which is chosen to provide appropriate scaling of η.

Additionally, the active power generation term can be modified to

$$P_{Gi} = P_{Gio}(1+\eta k_{Gi}) \tag{2.8}$$

Where P_{Gio} is the active generation at bus i in the base case and k_{Gi} is a constant used to specify the rate of change in generation as η varies. By substituting this values,

$$P_i = P_{Gio}(1+\eta k_{Gi}) - P_{Lio} - \eta(k_{Li} S_{\Delta base} \cos\Psi_i) \tag{2.9}$$

$$Q_i = Q_{Gio} - Q_{Lio} - \eta(k_{Li} S_{\Delta base} \sin\Psi_i) \tag{2.10}$$

A generic formulation for the whole set of the parameterized power flow equation can be expressed in the form

$$f(y, \eta) = 0 \tag{2.11}$$

where y is the vector of state variables (bus voltage angles and bus voltage magnitudes).Above equation means that the active and reactive power demand at a load bus (or some collection of load buses); and the real power generation at one generator bus (or collection of generator buses) vary, and their variations can be parameterized while the others remain fixed. However, only a very specific variation of load and generation is allowed as η changes. To solve the problem, the continuation method starts from a known solution and uses a predictor-corrector scheme to find subsequent solutions at different load levels. In principle, continuation methods have four basic elements [9]:

1) Predictor: Its purpose is to find an approximation for the next solution. Several different predictors have been proposed namely, ODE (Ordinary differential equation) based methods and polynomial extraction based methods. The tangent method is a first order ODE based method which uses the current solution and its derivative to predict the next solution. The secant is a polynomial-based predictor which uses the current solution and the previous one to predict the next solution.

2) Parameterization: Parameterization is a mathematical way of identifying each solution along the solution curve being traced so that the next solution and the previous one can be quantified. Arc length and local parameterization are the most popular types of parameterization. In general, each parameterization scheme augments the system of nonlinear equations and makes them regular at the critical point.

3) Corrector: Since the predictor has produced an approximation for the next solution, the corrector is needed to modify the solution before the error accumulates. Usually the Newton method to the augmented system of equations serves as the corrector. The structure of the augmented Jacobean depends on the chosen parameterization.

4) Step length control: Constant step length or adaptive step length control can be implemented. It depends, however, on the investigation problem.

Continuation methods have been used widely in power systems for optimal continuation power flow [17], and maximum transfer capability computation [18].

2.5 Optimal Power Flow Method

In a power system, the generation and distribution of power must be accomplished at minimum cost but with maximum efficiency. This involves the real and reactive power scheduling of each power plant in such a way as to minimize the total operating cost of the entire network [29]. In other words, the generator's real and reactive powers are allowed to vary within certain limits so as to meet a particular load demand with minimum fuel cost.

This is called the Optimal Power Flow (OPF) or sometimes known as the Optimal Power Dispatch or Economic Dispatch (ED) problem [30]. Optimal Power Flow (OPF) widely used to determine ATC in power corridors of the system. However these optimization methods are suitable in case of open access system where there is a possibility of power transactions occurring from any point to any point.

The basic concept of OPF (Optimal power flow) approach is to formulate the TTC calculation as an optimization problem, with equity constraints of power flow, inequality constraints from basic operation and equipment limits to more detailed approximation of transient stability security requirements.

The objective function is the maximum power flow on the specified transmission route. To determine the total transfer capability the objective is to maximize the power transfer between the two areas subjected to the conditions that there is no voltage or thermal or stability limit violations.

2.5.1 Optimal Power Flow Formulation

OPF is formulated mathematically as a general constrained optimization problem.

Minimize a function

$$F(u,x) \tag{2.12}$$

Subject to

$$h(u,x) = 0 \tag{2.13}$$

$$(u,x) \geq 0 \tag{2.14}$$

Where,

u = the set of controllable quantities in the system.

x = set of dependent variables.

F(u,x) = an objective function which is scalar.

Equality constraints of equation (2.13) are derived from conventional power balance equation. And inequality constraints of equation (2.14) are the limits on control variables u and the operating limit on the other variables of the system.

Total transfer capability problem formulation can be explained as follows.

Minimize

$$P_i = \sum_{j \in i} P_{kj} \tag{2.15}$$

Subjected to,

Active power balance equation:

$$P_{Gi} - P_{Di} - V_i \sum_{j=1}^{N} V_j (G_{ij}\cos\Theta_{ij} + B_{ij}\sin\Theta_{ij}) = 0 \tag{2.16}$$

Reactive power balance equation:

$$Q_{Gi} - Q_{Di} - V_i \sum_{j=1}^{N} V_j (G_{ij}\sin\Theta_{ij} - B_{ij}\cos\Theta_{ij}) = 0 \tag{2.17}$$

Here, i=1,2,3,…….,N

Active power generation limits:

$$P_{Gi,min} \leq P_{Gi} \leq P_{Gi,max} \tag{2.18}$$

Reactive power generation limits:

$$Q_{Gi,min} \leq Q_{Gi} \leq Q_{Gi,max} \tag{2.19}$$

Here, i=1,2,3,……,NG

Voltage limits:

$$V_{Gi,min} \leq V_{Gi} \leq V_{Gi,max} \tag{2.20}$$

Transformers tap setting limits:

$$T_{Gi,min} \leq T_{Gi} \leq T_{Gi,max}, \ i=1,2,\ldots,NT \tag{2.21}$$

Line loading limits:

$$|S_{Li}| \leq S_{Li,max},\ i=1,2,\ldots\ldots, NL \qquad (2.22)$$

Where,

P_{Di}= Active power demands at bus i

Q_{Di}= Reactive power demands at bus i

P_{Gi} = Total active power generation at bus i

Q_{Gi}= Total reactive power generation at bus i

V_i = Voltage magnitudes at buses i

V_j = Voltage magnitudes at buses j

G_{ij} = Real parts of the ij-th element of the admittance matrix (Y-bus)

B_{ij} = Imaginary parts of the ij-th element of the admittance matrix(Y-bus)

Θ_{ij} = Difference of voltage angles between buses i and j

T_i = tap setting of the i-th transformer

$|S_{Li}|$= Line loading in MVA at line i

N, NL, and NT are the total numbers of buses, lines, and transformers

The subscripts (x_{max}) and (x_{min}) are the upper and lower limits of variable x

The objective functions can be varied so as to maximize TTC or the maximization of active power flow over tie lines [31].

2.6 Sequential Quadratic Programming Method

The advanced Sequential Quadratic Programming (SQP) method is employed to solve the ATC problem since it was proven to be a highly effective method for constrained nonlinear programming [23][28]. In fact, approximating programming methods, such as SQP, are considered in modern mathematics as the most efficient ones for solving nonlinear programming problems since quadratic approximation provides a much more accurate representation than its linear approximation like.

SQP models the nonlinear problem at a given approximate solution x^k by a quadratic programming (QP) sub problem, then uses the solution to this sub problem to construct a better approximation x^{k+1}. This process is iterated to create a sequence of approximations that eventually converges to the final optimal solution. The method first constructs the Lagrangian function of the problem then converts it to a quadratic programming (QP) sub problem. Based on the first-order Karush-Kuhn-Tucker (KKT) conditions of optimality, the QP sub-problem is solved by Quasi-Newton method performing a line search to update the Hessian matrix H_k of the QP sub-problem. Some merit function is reduced along the search direction to ensure convergence from any starting point.

2.6.1 Structure for SQP

For the generic nonlinear programming problem (here x= $[y^{tT}u^T]^T$) we get by minimize f(x) Subject to,

$$g_i(x) = 0 \qquad (i=1,2,\ldots,p) \qquad (2.23)$$

$$h_j(x) \leq 0 \qquad (j=1,2,\ldots,m) \qquad (2.24)$$

The associated Lagrangian function is

$$L(x,\lambda) = f(x) + \sum_{i=1}^{p} \lambda_i g_i\,(x) + \sum_{j=1}^{m} \lambda_{p+j} h_j\,(x) \qquad (2.25)$$

Where λ_i, (i=1,2,…..,p+m) is the Lagrangian multiplier for the active i-the quality and inequality constraint. We can define an approximate quadratic sub-problem whose optimality conditions are identical to the original problem. The quadratic sub-problem will have the following form:

Minimize

$$\nabla f^T(x^k)S^k + \frac{1}{2}S^{kT}[H_k]S^k \qquad (2.26)$$

Subject to

$$g_i(x^k) + \nabla g_i^T(x^k)S^k = 0 \,, \; (i=1,2,\ldots,p) \tag{2.27}$$

$$h_i(x^k) + \nabla h_j^T(x^k)S^k \leq 0 \,, \; (j=1,2,\ldots,m) \tag{2.28}$$

Where *k* is the iteration number and $[H_k]$ is the Hessian of the Lagrangian. The constraints are linearized to form the approximate quadratic sub problem but second order information on the constraint functions is maintained in the objective function via the Hessian of the Lagrangian. The particular QP sub problem is solved to obtain the search direction *s* which is used to compute x^{k+1} as:

$$X^{k+1} = x^k + \alpha s^k \tag{2.29}$$

Where *k* is the iteration number and ά is the step length along the search direction *s*t hat is used to assure the algorithm would converge from an arbitrary initial point to a local minimum. To do that, a merit function φ(α) whose reduction implies progress towards a solution, is constructed in such a way that the unconstrained minimum of φ(α). The merit function is given as;

Minimum

$$\varphi(\alpha) = f(x^{k+1}) + \sum_{i=1}^{p} \lambda_i \, |g_i(x^{k+1})| + \sum_{j=1}^{m} \lambda_{p+j} \, . \max[0, h_j(x^{k+1})] \tag{2.30}$$

On completion of the line search, a Quasi-Newton update of the Hessian adopting the popular BFGS update is used as follows

$$H_{k+1} = H_k - \frac{H_k^T d_k d_k^T H_k}{d_k^T H_k d_k} + \frac{\gamma \gamma^T}{d_k^T d_k} \tag{2.31}$$

Where,

$$d_k = x^{k+1} - x^k \tag{2.32a}$$

$$\gamma = Q_k + (1-\Theta)H_k d_k \tag{2.32b}$$

$$Q_k = \nabla_x L(x_{k+1}, \lambda_{k+1}) - \nabla_x L(x_k, \lambda_k) \tag{2.32c}$$

$$\Theta = f(x) = \begin{cases} 1.0 & (if\ d_k^T Q_k \geq 0.2 d_k^T H_k d_k) \\ \frac{0.8 d_k^T H_k d_k}{d_k^T H_k d_k - d_k^T Q_k} & (otherwise) \end{cases} \tag{2.32d}$$

Where L is a constant and it can be changed between 0.2 and 0.8 based on numerical experience.

The SQP method has excellent convergence properties [19]. In addition, the SQP is not a feasible-point method; i.e., neither the initial point nor any of the subsequent iterates need to be feasible. This is a major advantage since finding a feasible point when there are nonlinear constraints is as difficult as solving the original nonlinear problem itself. For power system applications, the SQP has been used in a reduced form in the optimal power flow problem [20]. The equality constraints were eliminated using a load flow and the resulting problem is solved using the SQP algorithm.

2.7 Conclusion

All the transfer capability calculation techniques mentioned in this chapter have their individual strengths and limitations. There is no hard and fast rule of what method or technique should be followed, as it depends on network configuration and requirements. Besides, these methods are continuously evolving and new techniques are being introduced which provide improved results. It is to be noted that the methods mentioned above are only some of the available ATC calculation techniques and they do not represent the only methods of calculation available. Based on system configuration and ease of analysis, this thesis employs RPF and Path Dependent methods for ATC calculation.

CHAPTER 3

Bangladesh Power System Network

3.1 Introduction

Bangladesh has small reserves of oil and coal, but potentially very large natural gas resources. Commercial energy consumption is around 71% natural gas, with the remainder almost entirely oil (plus limited amounts of hydropower and coal). Only around 18% of the population (25% in urban areas and 10% in rural areas) has access to electricity, and per capita commercial energy consumption is among the lowest in the world. Noncommercial energy sources, such as wood, animal wastes, and crop residues, are estimated to account for over half of the country's energy consumption. Consumption of wood for fuel has contributed to deforestation and other environmental problems in Bangladesh. [24]

Bangladesh's installed electric generating capacity in 2000 was 3.8 gig watts (GW), of which 94% was thermal (mainly natural-gas-fired), and the remainder hydroelectric, at 18 power stations. With only around 18% of the population connected to the electricity grid, and with power demand growing rapidly (10% annually from 1974-1994; 7% annually from 1995-1997), Bangladesh's Power System Master Plan (PSMP) projects a required doubling of electric generating capacity by 2010. [25]

The Padma-Jamuna-Meghna river system divides Bangladesh into two zones, **East** and **West**. The East contains nearly all of the country's electric generating capacity, while the West, with almost no natural resources, must import power from the East. Electricity interconnection from the East to the West was accomplished in 1982 by a new, 230-kilovolt (kV) power transmission line. The vast majority of Bangladesh's electricity consumption takes place in the East, with the entire region west of the Jamuna River accounting for only 22% of the total. Greater Dhaka alone consumes around half of Bangladeshi electricity. [2]

3.2 Bangladesh Power System Network

The responsibility for formulating policy relating to power and supervise, control and monitor the developmental activities in the power sector of the country lies with the Power Division of Ministry of Power, Energy and Mineral Resources of Bangladesh government. To implement its mandate the Power Division is supported by a number of organizations, related with generation, transmission and distribution. A graphical view of the organizational linkage for Bangladesh power system is shown in figure 3.1. [24]

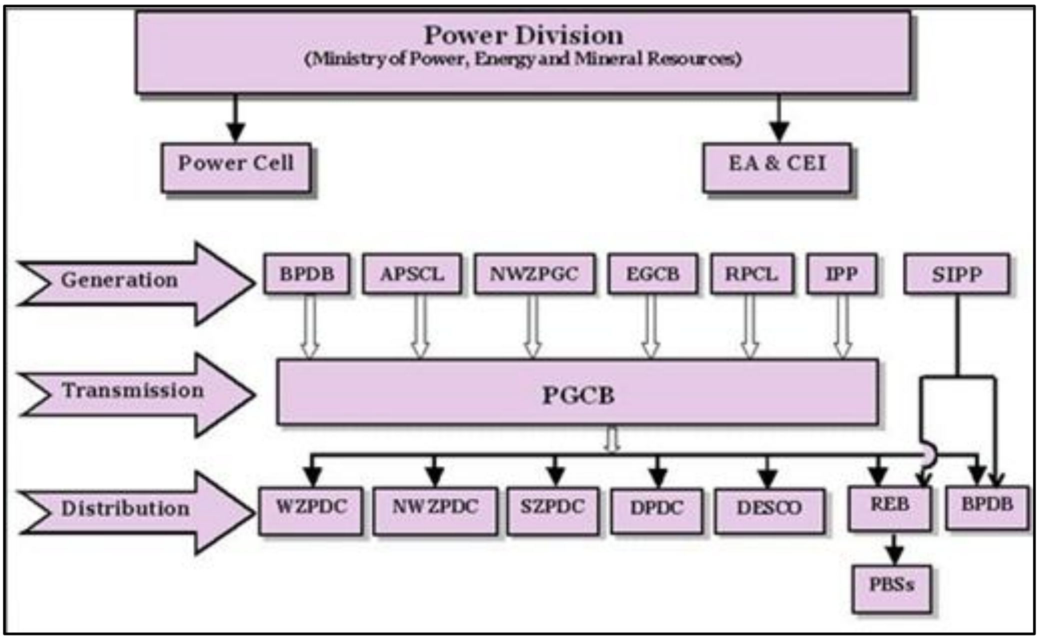


Figure 3.1 Organizational linkage for Bangladesh Power System

In order to fully understand the Bangladesh Power System Network infrastructure, detailed discussion for Generation, Transmission and Distribution system of the network is required.

3.2 Generation

Significant efforts aimed at adding new generation capacities characterized the power sector of Bangladesh in recent years. As a result, installed capacity and evening peak electricity generation have increased over the period of 1994-2011. Compound Annual Growth Rates (CAGR) during this period were 5.81 percent, 7.17 percent and 5.62 percent for installed capacity, derated capacity and evening peak generation respectively. A significant portion of this addition in generation came from liquid fuel based (Diesel, HFO) power plants rising the overall contribution of liquid fuels in power generation to 12.6 percent in 2011 compared to only 5 percent in 2010. However, the addition in installed capacity is not reflected in terms of proportional increase in power generation. More power plants have become non-operational in recent years resulting in huge gap between derated capacity and evening peak generation since FY 2005-2006. Moreover, increase in generation costs resulted in huge budgetary subsidy. The government has also estimated USD 366 million as subsidy in the energy sector for the fiscal year 2011-12 which is 333.33 percent higher than that of the FY 2009-10. The government has proposed to allocate USD 872 million in the power sector as the development budget for FY 2011-12 which is 340 percent higher than that of FY 2009-10. Installed, derated capacity and evening peak generation as of December 31, 2011 was 8,033 MW, 7,413 MW and 4,728 MW respectively. Figure 3.1 illustrates graphs for installed capacity and Evening Peak generation FY 1994-2008 in MW. [24][25]

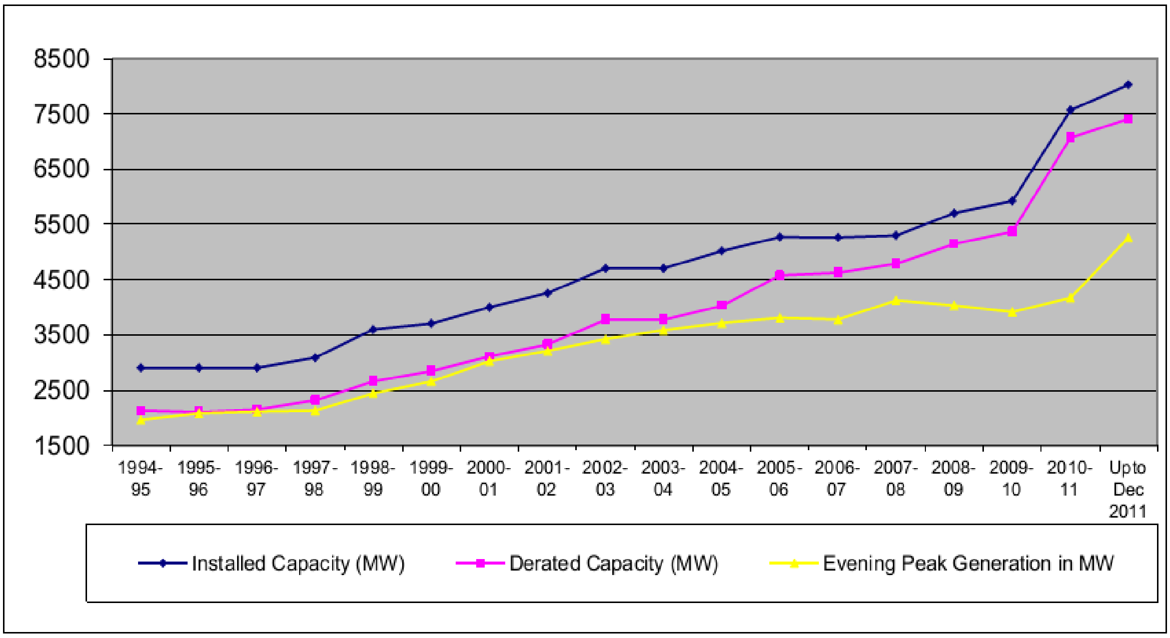


Figure 3.2 Installed Capacity and Evening Peak Generation 1994-2008 (in MW)

In line with the increase in generation capacity, average daily electricity generation has increased steadily from 25.26 M kWh in FY1994-1995 to 72.26 M kWh in 2009-2010 This represents a CAGR of 7.70 percent over the period. [25]

Electricity generation in Bangladesh is overwhelmingly gas based. (FY 2011) More than 82 percent of evening peak electricity is generated by using natural gas (Figure 3.3). This is followed by liquid fuel and coal with generation shares of 12.61 percent and 2.49 percent respectively. Hydro accounts for 2.78 percent of generation.

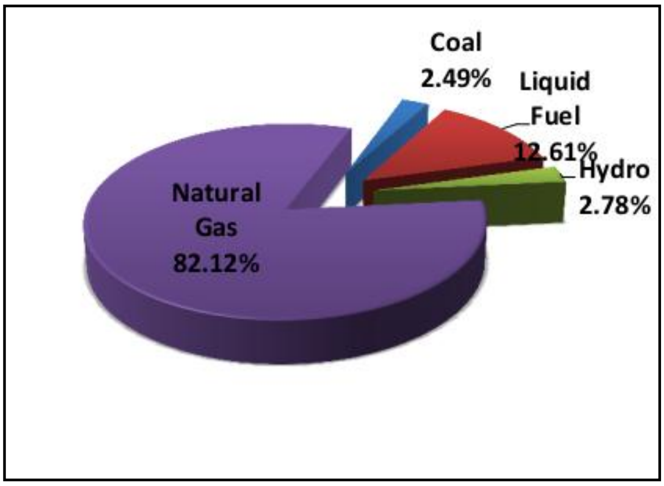


Figure 3.3 Energy Generation (FY 2011): 31,355 M kWh

Compared to previous year's (2010) power generation mix, contribution of natural gas decreased by approximately 8 percent and contribution of liquid fuel increased by 152 percent in the mix of total generation of electricity. Around 1,169.88 M kWh of electricity generated in 2010 was attributed to coal whereas in 2011, only 780.74 M kWh of electricity was generated from coal based power plants. [25]

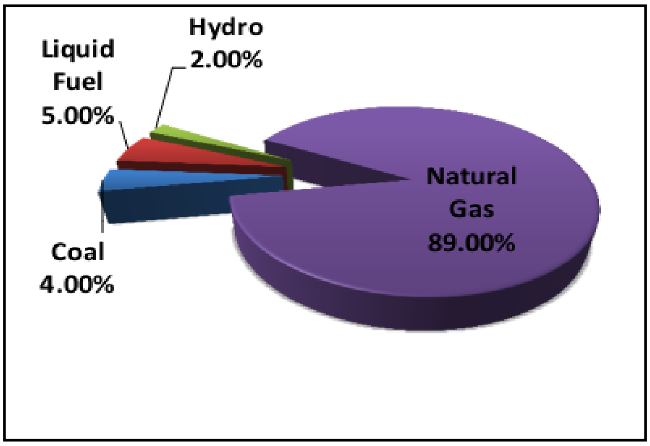


Figure 3.4 Energy Generation (FY 2010): 29,247 M kWh)

3.3 Transmission

Power Grid Company of Bangladesh Ltd. (PGCB) is responsible for operation, maintenance and development of transmission system all over the country. Presently power generated in various power plants in Bangladesh is transmitted to the national grid through 230 kV and 132 kV transmission lines.

PGCB receives power from BPDB and private sector power generation companies and transmits the electricity to BPDB, REB and 3 other distribution companies. The power generated by different power plants all over the country is evacuated and transmitted through PGCB's integrated grid system by 230 kV and 132 kV transmission lines and substations. Currently, 400 kV transmission lines are under construction to expand the transmission network in the country between Aminbazar and Meghnaghat.

At present there are 2647.3 Circuit km of 230 kV lines and 6015 Circuit km of 132 kV lines throughout Bangladesh under PGCB (total 8662.3 Circuit km). From the table below it can be seen that in 2011 amongst the two types of substations, there are thirteen 230/ 132 kV substations with the capacity of 7225 MVA and eighty one 132/33 kV substations with the capacity of 10492 MVA. Therefore, the total current substation capacity is 17,717 MVA. The Transmission Network is summarized in Table 3.1. [2]

Table 3.1 PGCB Transmission Network

Transmission line as on June 2011	
230kV	2647.3 circuit km
132kV	6015 circuit km
Substation as on June, 2011	
230/132kV	13 Nos: 7225MVA
132/33kV	81 Nos: 10492 MVA
Present Manpower on 31 may,2011	1992

The total grid network of PGCB is shown in Figure 3.5 [2]

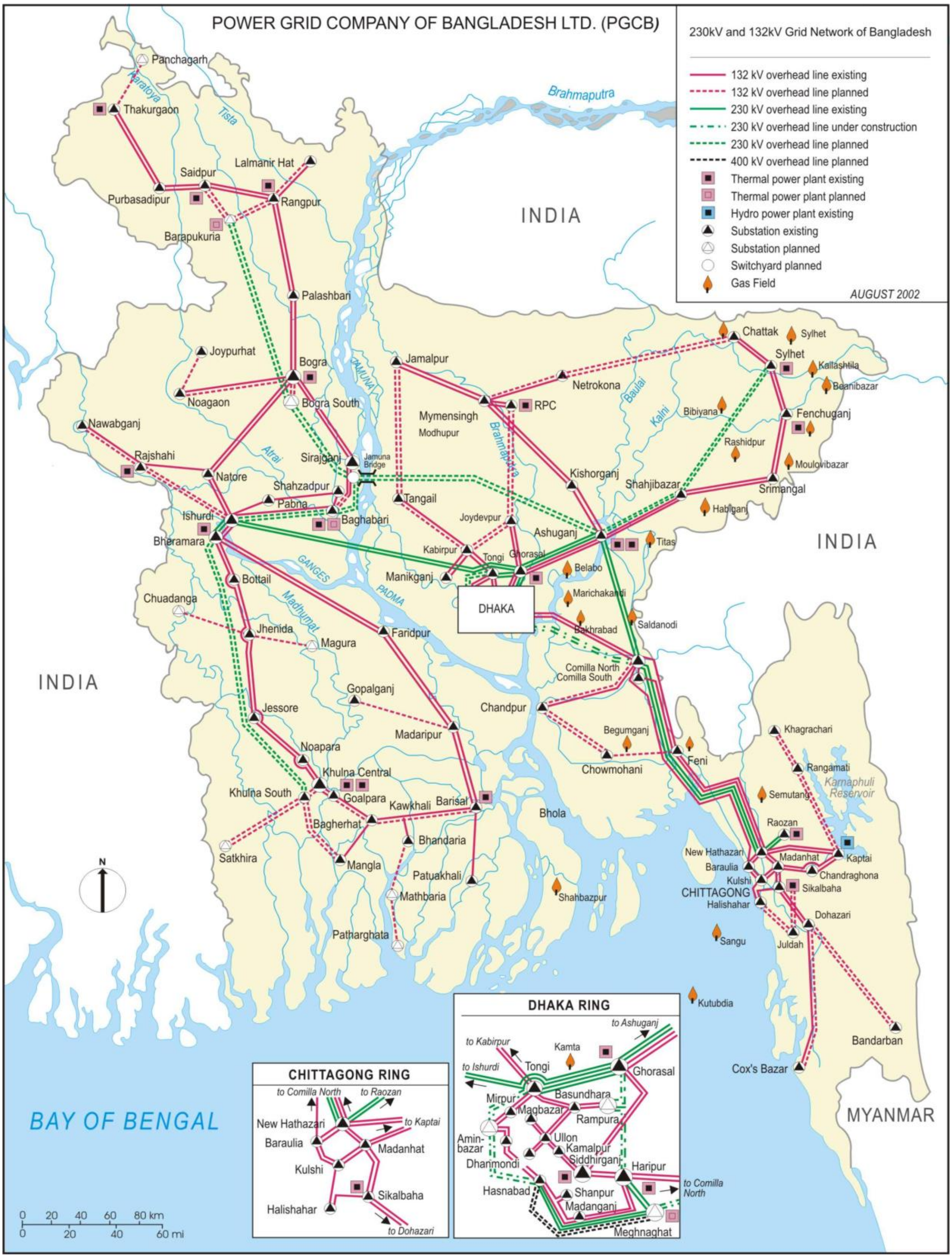


Figure 3.5 230 KV and 132 KV Grid Network of Bangladesh

3.3.1 East-West Grid Interconnection

Most of the electricity generation capacity of the country is located in the eastern region, mainly due to the proximity to available of gas reserves. Of the total installed generation capacity, 6613 MW is located on the eastern side of the Jamuna river and the remaining 1866 MW on the western side. An East-West interconnector of 400 MW was introduced to transfer any surplus electricity from the Eastern side to the Western side. A second East-West interconnector of 1000 MW capacity was also added in 2009. Together with the old interconnector and currently a combined capacity of 1400MW, there is no transmission constraint in transferring surplus electricity from the eastern regions to the western regions. A line Diagram of Grid connections is shown in Figure 3.6. [2][24]

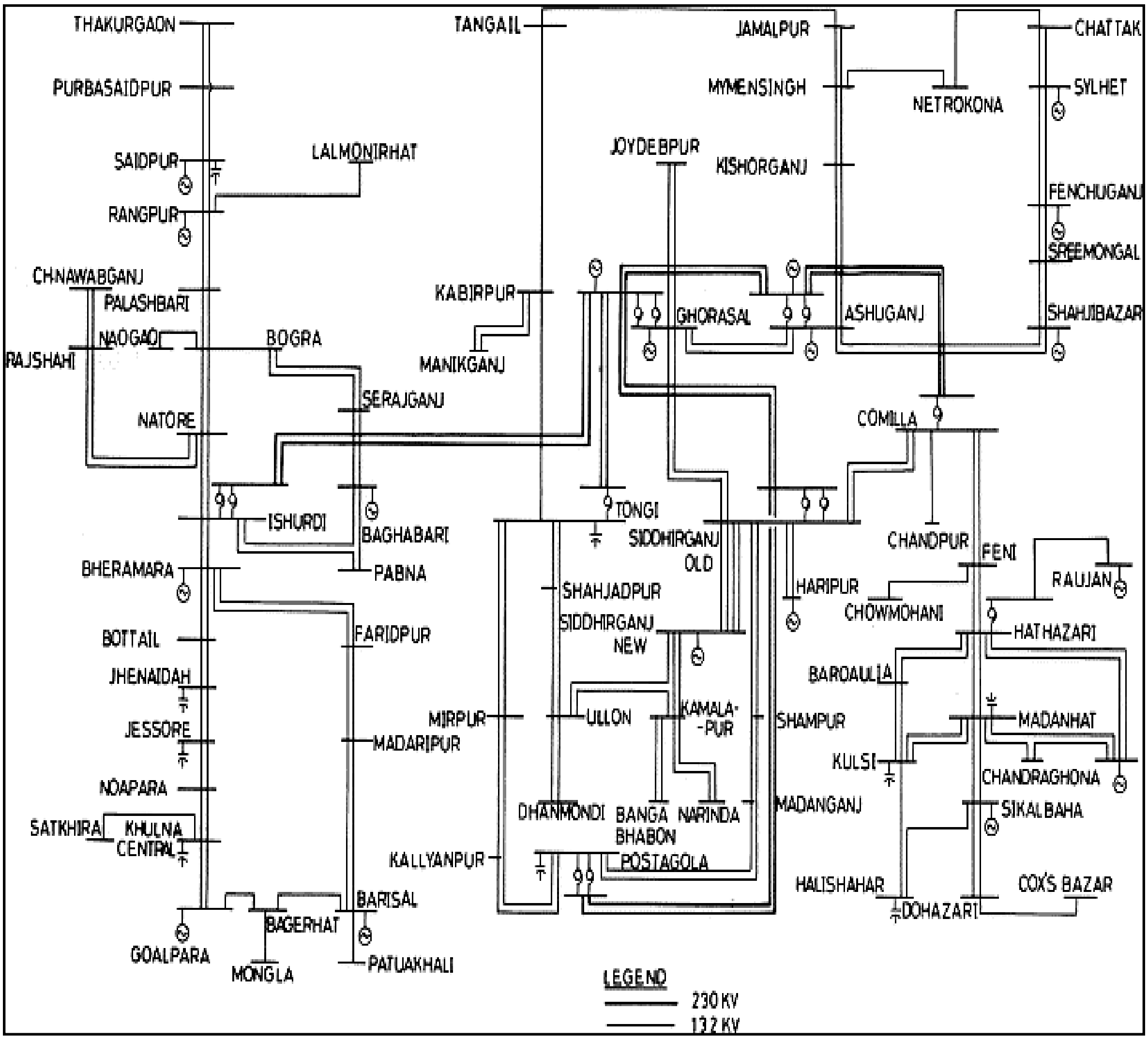


Figure 3.6 Line Diagram of East-West Grid Connection of Bangladesh

3.4 Distribution

Bangladesh power Distribution system contains a number of distribution entities with the objective of bringing commercial environment including increase of efficiency, accountability and dynamism with the aim of reaching electricity to all citizens by 2021. In order to increase and improve power generation and customer service with an aim to bring a greater mass under electrification, major integrated power distribution programs have been undertaken. Presently the following five organizations are responsible for the distribution of power: [24]

1. Bangladesh Power Development Board (BPDB)
2. Rural Electrification Board (REB)
3. Dhaka Power Distribution Company (DPDC)
4. Dhaka Electric Supply Company (DESCO)
5. West Zone Power Distribution Company (WZPDC)

Bangladesh Power Development Board (**BPDB)** is responsible for distribution of electricity in most of urban areas in Bangladesh except Dhaka Metropolitan City and its adjoining areas under DESA and DESCO, areas under West Zone Power Distribution Company Limited (WZPDCL) and some of the rural areas under Rural Electrification Board (REB). At present only 42.09% of the population is served with electricity and per capita electricity consumption is only 169.92 KWh (FY -2006). Presently BPDB's distribution network comprises of 33 KV, 11 kV and 11/0.4 KV lines. Total distribution line in the country is about 2,09,932 km of which 46,599 km belongs to BPDB and total number of consumer of different category is about 15,18,891 at the end of FY 2006. The Distribution Zones of BPDB are Chittagong, Comilla, Sylhet, Mymensingh Rajshahi and Rangpur. [25]

The **Rural Electrification Board (REB)**, is a semi-autonomous agency which is charged with the responsibility of planning, developing, financing and construction of rural distribution networks, promoting the establishment of Rural Electric Cooperatives (Palli Bidyut Samities or PBS), and assisting the PBSs to operate and maintain the rural networks and monitoring their financial performance. The REB has so far constructed over 46,000 Km of distribution lines and provided over 950,000 consumers connections in the rural areas. [33]

Dhaka Power Distribution Company (**DPDC)** succeeded DESA on 1st July 2008 and henceforth started commercial operation on the date of taking all assets and liabilities of DESA through transfer agreement. The company is created to provide electricity to the consumers of Dhaka city corporation area (excluding DESCO area) including Narayangonj town, Siddirgonj, Fatullah and Mokterpur under Narayangonj district. [34]

Dhaka Electric Supply Company (**DESCO)** was constituted to provide uninterrupted & stable power supply, better consumer service, in September 24, 1998 by taking over of Mirpur area from DESA. Area of coverage under DESCO are Gulshan Circle including Mirpur Area bounded by Balu River in the east, Turag River in the west and Turag and Balu River in the North and Mirpur Road, Agargaon Road, Rokeya Sarani, Progoti Sarani, New Airport Road, Maymenshing Road, Mohakhali Jeel, Rampura Jheel connected with Balu River in the South. [35]

The **West Zone Power Distribution Company (WZPDC)** was established in order to reduce system loss, increase efficiency through accountability and ensure better services in November 1998 and started functioning from April, 2005. The area under coverage of WZPDC contains total 21 districts, ten from Khulna Division, six from Barisal Division and five from Dhaka Division. [36]

3.5 Conclusion

Through this chapter, a clear view of the whole Bangladesh power system network can be obtained. As Eastern grid consists of the majority of generation capacity and it is the main concern of the paper, so bus data, generator data and branch data of eastern zone of the power system network has been taken under consideration. For the simplification of the network the generators connected to the same bus has been lumped for ATC calculation. In case of bus data Eastern zone covers seventy nine buses which are aligned with the Western zone buses as presented in the line diagram of east-west grid connection. The bus data and generator data has been lumped in accordance to their “from bus” and “to bus” of the network which helps to calculate the ATC and determine system bottlenecks in a simple and systematic way.

CHAPTER 4

Analysis and Results

4.1 Introduction

In this dissertation, in order to determine the Available Transfer Capability of the Eastern Grid, two methods were used. They are Repeated Power Flow (RPF) method and Path Dependent Network Flow model. The Simulation tool used for this purpose was MATPOWER which is a package of MATLAB® M-files for solving power flow and optimal power flow problems [27]. The data necessary for simulation purpose were obtained from PGCB, which contained Generator, Bus and branch information. The data provided by PGCB contained information for both Eastern and Western grid, which was separated according to bus numbers and their connections. The data used are attached in Appendix.

4.2 MATPOWER Simulation Tool

The primary functionality of MATPOWER is to solve power flow and optimal power flow (OPF) problems. This involves the following functions:

(1) Preparing the input data defining the all of the relevant power system parameters;

(2) Invoking the function to run the simulation

(3) Viewing and accessing the results that are printed to the screen and/or saved in output data structures or files.

The input data for the case to be simulated are specified in a set of data matrices packaged as the fields of a MATLAB struct, referred to as a “MATPOWER case" struct and conventionally denoted by the variable “mpc”. This struct is typically defined in a case file, either a function M-file whose return value is the “mpc” struct or a MAT-file that defines a variable named “mpc” when loaded; here the input data used were generator, bus, branch and transformer data obtained from PGCB. The codes used for simulation are attached in Appendix. [32]

4.3 Calculation of ATC of Definite Areas in Eastern Grid

The simulation results provided the Available Transfer Capability (ATC) values for all areas of the Eastern Grid, among which ATC values of some definite areas are given in Table 4.1

Table 4.1 ATC of some definite areas in Eastern grid

Bus name (From Bus)	Bus name (To Bus)	Bus number (From Bus)	Bus number (To Bus)	ATC in RPF method (MW)	ATC in path dependent ATC computation method (MW)
Tangail	Kishorgonj	1128	1202	68.1276	68.1276
New_Tongi	Savar	1445	1451	46.873	46.873
Chandpur	**Haripur**	**1032**	**1101**	**377.7342**	**377.5656**
Ulon	Shiddhirganj	1105	1102	52.9872	52.9872
Aminbazar	**Sylhet**	**1134**	**1215**	**442.7250**	**442.7550**
Joydevpur	**Mymensingh**	**1132**	**1203**	**32.2957**	**28.2757**
Raojan	Comilla_N	2001	2005	219.7816	219.7816
Raojan	Feni	2001	1120	95.7732	95.7732
Jamalpur	Chatak	1204	1216	102.5982	102.5982
Mnikganj	Tangail	1127	1128	58.3689	58.3689
Munshiganj	Brahmanbaria	1456	1035	84.1674	84.1674
Chowmuhini	Shiddhirganj	1021	1102	38.2145	38.2145
Chandroghona	Coxsbazar	1102	1009	69.4049	69.4049
Fenchuganj	Bhulta	1213	1133	414.2506	414.2506
Hathazari	Coxsbazar	2002	1009	75.3871	75.3871
Uttara	Matuail	1123	1109	101.8677	101.8677
Sikalbaha	Madanhat	1106	1105	43.5553	43.5553
Hasnabad	Meghnaghat	2013	2014	87.6858	87.6858
Mirpur	Jamalpur	1120	1204	130.5218	130.5218

4.4 Comparison of ATC Results Calculated in Different Methods

From the table, ATC calculation of different buses has been obtained both in RPF method and path dependent method. In most of the cases ATC values are same for both methods. But in the following cases there are slight differences in ATC values.

- **Jydevpur to Mymensingh:** In RPF method the ATC is 32.2957 MW and 28.2757 MW in Path Dependent method, so the difference is 4.02 MW.
- **Comment:** Path dependent method calculates ATC in every possible path. As a result theoretically the value of ATC observed in path dependent ATC computation method is more authentic than repetitive method.

- **Chandpur to Haripur:** In RPF method the ATC is 377.7342 MW and 377.5656 MW in Path Dependent method, so the difference is 0.1686 MW.
- **Comment:** Path dependent method calculates ATC in every possible path but repetitive method calculates ATC in one path. As a result theoretically the value of ATC observed in path dependent ATC computation method is more reliable than repetitive method.

- **Aminbazar to Sylhet:** In RPF method the ATC is 442.7250 MW and 442.7550 MW in Path Dependent method, so the difference is 0.03 MW.
- **Comment:** As mentioned before, RPF method calculates ATC in one path only, but for Path dependent method of calculation, all available paths are considered. So theoretically the value of ATC observed in path dependent ATC computation method is more reliable than repetitive method.

CHAPTER 5
Conclusion

5.1 Conclusion

This dissertation contains an extensive and thorough investigation for determining existing transmission bottlenecks for the Eastern grid of Bangladesh Power System, which was identified as the calculation of Available Transfer Capabilities for the system. The work done can be summarized as follows:

1) An in depth idea about ATC is provided in the thesis, by discussing, its definition, related terms, and various calculation methodologies.

2) Among various methodologies, 5 methods of ATC calculation have been discussed thoroughly.

3) The whole Bangladesh Power System network was discussed for the sake of ATC Calculation. In this paper the results reflects the ATC calculation for Eastern grid only by calculating bus data, generator data and branch data for this region.

4) The Repeated Power Flow (RPF) method of ATC calculation was employed for simulation as it ensures the accuracy of total available transfer of the network. It reflects linear characteristic of ATC calculation in a best possible manner maintaining all the functions under consideration.

5) In order to make a comparison between the results of ATC calculation, Path Dependent network flow model has also been used as an alternative method. The results in this method are mostly similar with slight differences, but it allowed us to differentiate between the methods and compare them.

6) ATC i.e. transmission bottlenecks has been calculated for individual buses as well as the whole Eastern network in both calculation methods which gives a better picture in case of comparison of ATC values.

5.2 Future Works

Identification of transmission bottlenecks in the network i.e. the calculation of the available transfer capability (ATC) in the deregulated power system environment is a very stimulating issue particularly because of the new operating paradigm dictated by the deregulation process. Some of the topics that can be addressed in the future are:

1) RPF method and Path Dependent method of ATC calculation provide a fairly accurate picture of existing Transfer Capability conditions and transmission bottlenecks, but more advanced and complicated methods can also be applied to reduce error margin.

2) Similar methods of ATC calculation can be employed to determine the ATC values in the Western grid of the power system network. This will offer an idea about ATC values for the whole network and will also provide scopes for comparisons.

3) The quantification of the uncertainties associated with ATC calculation is an interesting issue. These uncertainties are attributed to the unexpected topology changes, generation unavailability, weather conditions etc. There are scopes for development of new ATC calculation framework for implementing the probabilistic approach for the steady state and dynamic security assessment.

4) Improvement of ATC values can be obtained by the use of FACTS controllers, TCSCs, and SVCs in transmission networks. The impact of these devices on ATC calculation in terms of modeling and analysis can be investigated in further works.

5) External network modeling can reduce the computational requirements of ATC calculation methods. It is also compatible with the new decentralized environment where individual entities may not have access to the network topological details. Thus the influence of external network modeling on ATC values can be investigated in future works.

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APPENDIX-A

List of Buses in the Eastern Grid

Bus Name	Bus No.	Bus Name	Bus No.
Ghorasal	1130	Manikgonj	1127
Joydebpur	1132	Ghorasal	1130
Bhulta	1133	Joydebpur	1132
Aminbazar	1134	Bhulta	1133
Ashuganj	1201	Aminbazar	1134
Kishargonj	1202	Ashuganj	1201
Mymemsingh	1203	Kishargonj	1202
Netrokona	1205	Mymemsingh	1203
Shahjibazar	1211	Netrokona	1205
Sreemongol	1212	Shahjibazar	1211
Fenchugonj	1213	Sreemongol	1212
Fenchugonj-ps	1214	Fenchugonj	1213
Shylet	1215	Fenchugonj-ps	1214
Chatak	1216	Shylet	1215
Bheramara	1310	Chatak	1216
Madaripur	1314	Bheramara	1310
Comilla_S	1031	Madaripur	1314
Chandpur	1032	Bangbabhaban	1446
Brahmanbaria	1035	Munshigonj	1456
Haripur	1101	Daudkandi	1457
Shiddhirgonj	1102	Meghnaghat	1458
Magbazar	1103	Brahmmanbaria	1459
Maniknagar	1104	Meghhnaghat	1460
Ulon	1105	Keranigonj	1461
Rampura	1107	Raozan	2001
Matuail	1109	Hathazari	2002
Shyampur	1111	Cumilla_N	2005
Madangonj	1112	Ashuganj	2008
Hasnabad	1113	Ghorashal	2010
Sitalakhya	1114	Tongi	2011
Kamrangirchat	1118	Haripur	2012
Mirpur	1120	Meghnaghat	2014
Kalyanpur	1122	AES360	2015
Uttara	1123	Rampura	2016
Bashundhara	1124	Aminbazar	2034
Tongi	1125	Shiddhirganj230	2043
Kabirpur	1126		

APPENDIX-B

Code For RPF Method

```
clear all;
clc;
A=loadcase(caseBPG);

% %checking load data
% bus=A.bus
% gen=A.gen
% branch=A.branch
%% identifying source and sink buses
[I,J]=size(A.bus);
[K,P]=size(A.gen);
[M,N]=size(A.branch);
for i=1:I
ifA.bus(i,11)==2
source=i;
source_bus_no=A.bus(i,1);
else
ifA.bus(i,11)==3
sink=i;
sink_bus_no=A.bus(i,1);
end
end
end
%% finding Source generator from gen data and extracting source gen data
for i=1:K
ifA.gen(i,1)==source_bus_no
gen_no=i;
        PG=A.gen(i,2);
        QG=A.gen(i,3);
Qmax=A.gen(i,4);
Qmin=A.gen(i,5);
Pmax=A.gen(i,9);
end
end

 %% Finding line limit from the branch data for power transfer
for i=1:M
ifA.branch(i,1)==source_bus_no&&A.branch(i,2)==sink_bus_no
Source_sink_branch_no=i;
end
end
Vlimit=A.branch(Source_sink_branch_no,6);
%% Determining the step size of increment of power in the selected source
delta=50; %step size
iteration=80; %max iteration number
Vmax=1.6;  %max allowable voltage
Vmin=0.5; %min allowable voltage

%% First run
fprintf('for the first run check');
[MVA_base,results,success,etc]=runpf_ttc(caseBPG);
```

```
[branch]=printpf_tc(results);

%%
[X,Y]=size(branch);
for i=1:X
if branch(i,1)==source_bus_no&& branch(i,2)==sink_bus_no
index=i;
end
end
%% CBM Calculation
CBM_P=branch(index,14);
CBM_Q=branch(index,15);
%% Creating backup for comparing
B=results;
%% for checking purpose to see if B=results
% count=0;
% mismatch=0;
% for i=1:K
%     for j=1:P
%     if(results.gen(i,j)==B.gen(i,j))
%         count=count+1;
%     else
%         mismatch=mismatch+1;
%     end
%     end
% end

%% TTC calculation
for L=1:iteration
%checking for overflow in the buses
overflow=0;
for i=1:I
ifresults.bus(i,8)<=Vmax&&results.bus(i,8)>Vmin
overflow=overflow+1;
end
end

if  overflow==I  &&  branch(index,14)<=Vlimit%if  no  overflow  occurs  then
execute

%Updating bus and generator P and Q
%     for i=1:I
%         for j=1:J
%             if results.bus(i,j)>B.bus(i,j)
%                 B.bus(i,j)=results.bus(i,j);
%
%             end
%         end
%     end
%     for i=1:K
%         for j=1:P
%             if results.gen(i,j)>B.gen(i,j)
%                 B.gen(i,j)=results.gen(i,j);
%             end
%         end
%     end
%     for i=1:M
%         for j=1:N
%             if results.branch(i,j)>B.branch(i,j)
```

```
%                  B.branch(i,j)=results.branch(i,j);
%
%              end
%          end
%      end
B=results;
% Adding power to the source and increasing the demand to the sink
results.bus(sink,3);
results.bus(sink,3)=results.bus(sink,3)+delta;
results.gen(gen_no,2);
results.gen(gen_no,2)=results.gen(gen_no,2)+delta;

C=results;  %creating a running point
[MVA_base,results,success,etc]=runpf_ttc(C);
[branch]=printpf_tc(results);

else
delta=delta/2;
results=B;

end
if delta==0
break;
end
end
[branch1]=printpf_tc(B)
%% After exceeding the line limit (Vlimit)
% TTC_P=branch(index,14);
% TTC_Q=branch(index,15);
% TTC=sqrt(TTC_P.^2+TTC_Q.^2);
% TRM_P=TTC_P*0.1;
% TRM_Q=TTC_Q*0.1;
% ATC_P=TTC_P-TRM_P-CBM_P;
% ATC_Q=TTC_Q-TRM_Q-CBM_Q;
% fprintf('ATC P (MW)=');
% ATC_P
% fprintf('ATC Q (MVAR)=');
% ATC_Q
%% AT the nose point
TTC_P=branch1(index,14);
TTC_Q=branch1(index,15);
TTC=sqrt(TTC_P.^2+TTC_Q.^2);
TRM_P=TTC_P*0.1;
TRM_Q=TTC_Q*0.1;
ATC_P=TTC_P-TRM_P-CBM_P;
ATC_Q=TTC_Q-TRM_Q-CBM_Q;
fprintf('ATC P (MW)=');
ATC_P
fprintf('ATC Q (MVAR)=');
ATC_Q
```

APPENDIX-C

MATLAB Case File (Case60)

Bus Data

```
%% bus data
%	bus_i	type	Pd	Qd	Gs	Bs	area	Vm	Va	baseKV	zone	Vmax	Vmin
mpc.bus = [
	1001	2	0	0	0	0	1	1	0	132	1	1.1	0.9;
	1002	1	15	7.7	0	0	1	1	0	132	1	1.1	0.9
	1003	1	39	19.5	0	0	1	1	0	132	1	1.1	0.9;
	1005	1	20.5	10.25	0	0	1	1	0	132	1	1.1	0.9;
	1006	2	16.5	8.25	0	0	1	1	0	132	1	1.1	0.9;
	1008	1	34	17	0	0	1	1	0	132	1	1.1	0.9;
	1009	1	26	13	0	0	1	1	0	132	1	1.1	0.9;
	1011	2	74	52	0	0	1	1	0	132	1	1.1	0.9;
	1013	1	88	44	0	0	1	1	0	132	1	1.1	0.9;
	1015	1	42	21	0	0	1	1	0	132	1	1.1	0.9;
	1016	1	80	40	0	0	1	1	0	132	1	1.1	0.9;
	1017	1	9	4.5	0	0	1	1	0	132	1	1.1	0.9;
	1018	1	0	0	0	0	1	1	0	132	1	1.1	0.9;
	1020	2	44	22	0	0	1	1	0	132	1	1.1	0.9;
	1021	1	69.9	34.95	0	0	1	1	0	132	1	1.1	0.9;
	1030	1	20	10	0	0	1	1	0	132	1	1.1	0.9;
	1031	2	120	60	0	0	1	1	0	132	1	1.1	0.9;
	1032	1	45	22.5	0	0	1	1	0	132	1	1.1	0.9;
	1035	2	0	0	0	0	1	1	0	132	1	1.1	0.9;
	1101	2	57	28.5	0	0	1	1	0	132	1	1.1	0.9;
	1102	2	80	40	0	0	1	1	0	132	1	1.1	0.9;
	1103	1	92	46	0	0	1	1	0	132	1	1.1	0.9;
	1104	1	70	35	0	0	1	1	0	132	1	1.1	0.9;
	1105	1	99	49.5	0	0	1	1	0	132	1	1.1	0.9;
	1106	1	85.2	42.6	0	0	1	1	0	132	1	1.1	0.9;
	1107	1	0	0	0	0	1	1	0	132	1	1.1	0.9;
	1108	2	91	45.5	0	0	1	1	0	132	1	1.1	0.9;
	1109	1	15	7.7	0	0	1	1	0	132	1	1.1	0.9;
	1111	2	3.6	1.8	0	0	1	1	0	132	1	1.1	0.9;
	1112	2	50	25	0	0	1	1	0	132	1	1.1	0.9;
	1113	1	146	73	0	0	1	1	0	132	1	1.1	0.9;
	1114	1	52.2	26.1	0	0	1	1	0	132	1	1.1	0.9;
	1116	1	117.4	58.7	0	0	1	1	0	132	1	1.1	0.9;
```

1118	1	70	35	0	0	1	1	0	132	1	1.1	0.9;
1120	1	107.5	53.75	0	0	1	1	0	132	1	1.1	0.9;
1122	1	141	70.5	0	0	1	1	0	132	1	1.1	0.9;
1123	2	81.3	40.65	0	0	1	1	0	132	1	1.1	0.9;
1124	1	54	27	0	0	1	1	0	132	1	1.1	0.9;
1125	2	48	24	0	0	1	1	0	132	1	1.1	0.9;
1126	1	68	34	0	0	1	1	0	132	1	1.1	0.9;
1127	1	32	16	0	0	1	1	0	132	1	1.1	0.9;
1128	2	65	32.5	0	0	1	1	0	132	1	1.1	0.9;
1130	2	56	28	0	0	1	1	0	132	1	1.1	0.9;
1132	1	70.2	35.1	0	0	1	1	0	132	1	1.1	0.9;
1133	2	23	11.5	0	0	1	1	0	132	1	1.1	0.9;
1134	1	0	0	0	0	1	1	0	132	1	1.1	0.9;
1201	2	58.3	20.5	0	0	1	1	0	132	1	1.1	0.9;
1202	1	45	22.5	0	0	1	1	0	132	1	1.1	0.9;
1203	1	99	49.5	0	0	1	1	0	132	1	1.1	0.9;
1204	1	82.2	41.1	0	0	1	1	0	132	1	1.1	0.9;
1205	1	34	17	0	0	1	1	0	132	1	1.1	0.9;
1211	2	55.8	27.9	0	0	1	1	0	132	1	1.1	0.9;
1212	1	31	15.5	0	0	1	1	0	132	1	1.1	0.9;
1213	2	53.3	26.65	0	0	1	1	0	132	1	1.1	0.9;
1214	2	0	0	0	0	1	1	0	132	1	1.1	0.9;
1215	2	108.4	54.2	0	0	1	1	0	132	1	1.1	0.9;
1216	1	35	17.5	0	0	1	1	0	132	1	1.1	0.9;
1444	2	20.3	10.15	0	0	1	1	0	132	1	1.1	0.9;
1445	1	34	17	0	0	1	1	0	132	1	1.1	0.9;
1446	1	19.84	9.92	0	0	1	1	0	132	1	1.1	0.9;
1451	1	22	11	0	0	1	1	0	132	1	1.1	0.9;
1456	1	0	0	0	0	1	1	0	132	1	1.1	0.9;
1457	1	12	6	0	0	1	1	0	132	1	1.1	0.9;
1458	1	0	0	0	0	1	1	0	132	1	1.1	0.9;
1459	1	43	21.5	0	0	1	1	0	132	1	1.1	0.9;
1460	2	0	0	0	0	1	1	0	132	1	1.1	0.9;
1461	2	0	0	0	0	1	1	0	132	1	1.1	0.9;
2001	2	21.5	10.75	0	0	1	1	0	230	1	1.1	0.9;
2002	1	39	19.5	0	0	1	1	0	230	1	1.1	0.9;
2005	1	20	10	0	0	1	1	0	230	1	1.1	0.9;
2008	2	48	15	0	0	1	1	0	230	1	1.1	0.9;
2010	3	0	0	0	0	1	1	0	230	1	1.1	0.9;
2011	1	48	24	0	0	1	1	0	230	1	1.1	0.9;
2012	1	57	28.5	0	0	1	1	0	230	1	1.1	0.9;
2013	1	146	73	0	0	1	1	0	230	1	1.1	0.9;

Generator Data

```
%% generator data
%	bus	Pg	Qg	Qmax	Qmin	Vg	mBase	status	Pmax	Pmin	Pc1Pc2
Qc1min	Qc1max		Qc2min	Qc2max		ramp_agc		ramp_10		ramp_30
	ramp_q	apf
mpc.gen = [
1001	163	190	190	0	1.05	100	1	179.3	0;
1213	164	217	217	0	1.05	100	1	180.4	0;
1214	29	24	24	0	1.05	100	1	32	0;
1211	209	174	174	0	1.05	100	1	230	0;
1444	203	180	180	0	1.05	100	1	223.3	0;
2008	421	422.55	422.55	0	1.05	100	1	463.1	0;
1006	36	48	48	0	1.05	100	1	39.6	0;
1035	72	80.55	80.55	0	1.05	100	1	79.2	0;
1031	128	113.5	113.5	0	1.05	100	1	140.8	0;
1020	30	30	30	0	1.05	100	1	33	0;
1011	8	41.4	41.4	0	1.05	100	1	8.8	0;
2001	140	130	130	0	1.05	100	1	154	0;
1215	54	40	40	0	1.05	100	1	59.4	0;
2015	348	303.75	303.75	0	1.05	100	1	382.8	0;
1201	209	171.50	171.50	0	1.05	100	1	229.9	0;
2008	421	422.55	422.55	0	1.05	100	1	463.1	0;
1130	263	288.3	288.3	0	1.05	100	1	289.3	0;
2010	550	444.6	444.6	0	1.05	100	1	605	0;
1101	208	251.25	251.25	0	1.05	100	1	228.8	0;
1112	83	75	75	0	1.05	100	1	91.3	0;
2014	420	352	352	0	1.05	100	1	462	0;
1460	94	75	75	0	1.05	100	1	103.4	0;
1133	38	44.5	44.5	0	1.05	100	1	41.8	0;
1111	36	37.5	37.5	0	1.05	100	1	39.6	0;
2043	54	131	131	0	1.05	100	1	59.4	0;
1102	147	172	172	0	1.05	100	1	161.7	0;
1123	16	28	28	0	1.05	100	1	17.6	0;
1128	22	20	20	0	1.05	100	1	24.2	0;
1125	105	97	97	0	1.05	100	1	115.5	0;
```

Branch Data

```
%% branch data
%	fbus	tbus	r	x	b	rateA	rateB	rateC	ratio	angle	status
	angmin	angmax
mpc.branch = [
1001	1002	0.00464	0.01888	0.0039	660	0	990	0	0	1
	-360	360;
1001	1003	0.01334	0.05428	0.0112	660	0	990	0	0	1
	-360	360;
1001	1005	0.0174	0.0708	0.0146	660	0	990	0	0	1
	-360	360;
1002	1005	0.01798	0.07316	0.0151	660	0	990	0	0	1
	-360	360;
1003	1005	0.00261	0.01062	0.0022	660	0	990	0	0	1
	-360	360;
1003	1015	0.00348	0.01416	0.0029	660	0	990	0	0	1
	-360	360;
1003	1020	0.02581	0.10502	0.0216	660	0	990	0	0	1
	-360	360;
1005	1006	0.00377	0.01534	0.0031	660	0	990	0	0	1
	-360	360
1005	1013	0.00377	0.01534	0.0031	660	0	990	0	0	1
	-360	360;
1006	1008	0.01015	0.0413	0.0085	660	0	990	0	0	1
	-360	360;
1006	1016	0.00116	0.00472	0.0009	660	0	990	0	0	1
	-360	360;
1006	1017	0.0029	0.0118	0.0024	660	0	990	0	0	1
	-360	360;
1006	1018	0.00261	0.01062	0.0022	660	0	990	0	0	1
	-360	360;
1008	1009	0.02523	0.10266	0.0211	660	0	990	0	0	1
	-360	360;
1011	1013	0.00406	0.01652	0.0034	660	0	990	0	0	1
	-360	360;
1011	1017	0.00464	0.01888	0.0039	660	0	990	0	0	1
	-360	360;
1013	1015	0.00754	0.03068	0.0063	660	0	990	0	0	1
	-360	360;
1013	1016	0.00116	0.00472	0.0009	660	0	990	0	0	1
	-360	360;
1017	1018	0.00203	0.00826	0.0017	660	0	990	0	0	1
	-360	360;
1020	1021	0.00928	0.03776	0.0078	660	0	990	0	0	1
	-360	360;
1020	1030	0.01856	0.07552	0.0155	660	0	990	0	0	1
	-360	360;
1021	1032	0.02175	0.0885	0.0182	660	0	990	0	0	1
	-360	360;
```

1030	1031	0.00464	0.01888	0.0039	660	0	990	0	0	1	-360	360;
1030	1457	0.0145	0.055	0.013	660	0	990	0	0	1	-360	360;
1031	1032	0.03538	0.14396	0.0296	660	0	990	0	0	1	-360	360;
1457	1458	0.00928	0.0352	0.0083	660	0	990	0	0	1	-360	360;
1459	1211	0.0145	0.055	0.013	660	0	990	0	0	1	-360	360;
2001	2002	0.00115	0.006555	0.02355	750	0	1125	0	0	1	-360	360;
2002	2005	0.008305	0.05738	0.1155	1000	0	1500	0	0	1	-360	360;
2005	2008	0.004345	0.03002	0.0604	1000	0	1500	0	0	1	-360	360;
2005	2014	0.00232	0.01595	0.061	1500	0	2250	0	0	1	-360	360;
1211	1212	0.01044	0.03978	0.0094	660	0	990	0	0	1	-360	360;
1212	1213	0.01421	0.054145	0.0127	660	0	990	0	0	1	-360	360;
1213	1214	0.00116	0.00442	0.00105	660	0	990	0	0	1	-360	360;
1214	1215	0.00841	0.032045	0.0075	660	0	990	0	0	1	-360	360;
1215	1216	0.00928	0.03536	0.0083	660	0	990	0	0	1	-360	360;
1202	1203	0.01711	0.065195	0.01535	660	0	990	0	0	1	-360	360;
1203	1204	0.01595	0.060775	0.01435	660	0	990	0	0	1	-360	360;
1203	1205	0.00986	0.03757	0.00885	660	0	990	0	0	1	-360	360;
1203	1444	0.00725	0.027625	0.0065	660	0	990	0	0	1	-360	360;
1101	1102	0.00058	0.0022	0.0005	660	0	990	0	0	1	-360	360;
1101	1104	0.00348	0.0132	0.0031	660	0	990	0	0	1	-360	360
1101	1109	0.0058	0.022	0.0052	660	0	990	0	0	1	-360	360;
1101	1111	0.01856	0.0704	0.0166	660	0	990	0	0	1	-360	360;
1101	1112	0.00754	0.0286	0.0068	660	0	990	0	0	1	-360	360;
1101	1130	0.02552	0.0968	0.0229	660	0	990	0	0	1	-360	360;
1101	1133	0.01392	0.0528	0.0125	660	0	990	0	0	1	-360	360;

1101	1458	0.00609	0.0231	0.00545	660	0	990	0	0	1	-360	360;
1102	1105	0.00464	0.0176	0.00415	660	0	990	0	0	1	-360	360;
1103	1105	0.00348	0.0132	0.0031	660	0	990	0	0	1	-360	360;
1103	1107	0.0029	0.011	0.0026	660	0	990	0	0	1	-360	360;
1104	1109	0.00928	0.0352	0.0083	660	0	990	0	0	1	-360	360;
1104	1446	0.00145	0.0055	0.0013	660	0	990	0	0	1	-360	360;
1105	1107	0.00232	0.0088	0.0021	660	0	990	0	0	1	-360	360;
1107	1124	0.00319	0.0121	0.00285	660	0	990	0	0	1	-360	360;
1111	1113	0.01102	0.0418	0.0099	660	0	990	0	0	1	-360	360;
1112	1114	0.00348	0.0132	0.0031	660	0	990	0	0	1	-360	360;
1112	1456	0.00116	0.0044	0.00105	660	0	990	0	0	1	-360	360;
1113	1114	0.00696	0.0264	0.0062	660	0	990	0	0	1	-360	360;
1113	1461	0.00206	0.00781	0.00185	660	0	990	0	0	1	-360	360;
1118	1122	0.00696	0.0264	0.0062	660	0	990	0	0	1	-360	360;
1120	1123	0.00754	0.0286	0.0068	660	0	990	0	0	1	-360	360;
1120	1125	0.0087	0.033	0.0078	660	0	990	0	0	1	-360	360;
1120	1134	0.0029	0.011	0.0026	660	0	990	0	0	1	-360	360;
1122	1134	0.00087	0.0033	0.0008	660	0	990	0	0	1	-360	360;
1123	1125	0.00522	0.0198	0.0047	660	0	990	0	0	1	-360	360;
1124	1125	0.00232	0.0088	0.0021	660	0	990	0	0	1	-360	360;
1125	1126	0.00667	0.0253	0.006	660	0	990	0	0	1	-360	360;
1125	1445	0.00087	0.0033	0.0008	660	0	990	0	0	1	-360	360;
1126	1127	0.00957	0.0363	0.0086	660	0	990	0	0	1	-360	360;
1126	1128	0.01479	0.0561	0.01325	660	0	990	0	0	1	-360	360;
1126	1132	0.00435	0.0165	0.0039	660	0	990	0	0	1	-360	360;

1130	1132	0.00754	0.0286	0.00675	660	0	990	0	0	1
	-360	360;								
1130	1133	0.0116	0.044	0.0104	660	0	990	0	0	1
	-360	360;								
1130	1201	0.01247	0.0473	0.0112	660	0	990	0	0	1
	-360	360;								
1134	1451	0.00377	0.0143	0.0034	660	0	990	0	0	1
	-360	360;								
1201	1035	0.00667	0.0253	0.006	660	0	990	0	0	1
	-360	360;								
1201	1202	0.01508	0.0572	0.0135	660	0	990	0	0	1
	-360	360;								
1201	1211	0.03074	0.1166	0.0276	660	0	990	0	0	1
	-360	360;								
1201	1459	0.00667	0.0253	0.006	660	0	990	0	0	1
	-360	360;								
1460	1458	0.001565	0.00594	0.0014	660	0	990	0	0	1
	-360	360;								
1461	1118	0.00226	0.00858	0.002	660	0	990	0	0	1
	-360	360;								
1461	1122	0.00632	0.02398	0.0057	660	0	990	0	0	1
	-360	360;								
2008	2010	0.0033	0.01694	0.0327	753.07	0	1129.6	0	0	1
	-360	360;								
2008	2036	0.0056	0.0385	0.0413	1500	0	2250	0	0	1
	-360	360;								
2010	2011	0.002025	0.010395	0.0201	753.07	0	1129.6	0	0	1
	-360	360;								
2010	2016	0.00345	0.01771	0.0342	753.07	0	1129.6	0	0	1
	-360	360;								
2010	2020	0.01335	0.06855	0.0370	753.07	0	1100	0	0	1
	-360	360;								
2011	2034	0.002485	0.00942	0.0205	1500	0	2250	0	0	1
	-360	360;								
2012	2014	0.00048	0.0033	0.01265	1500	0	2250	0	0	1
	-360	360;								
2012	2015	0.00011	0.00076	0.00155	1500	0	2250	0	0	1
	-360	360;								
2012	2016	0.00104	0.00715	0.02745	1500	0	2250	0	0	1
	-360	360;								
2012	2043	0.00022	0.00152	0.0031	1500	0	2250	0	0	1
	-360	360;								
2013	2014	0.00104	0.00715	0.0274	1500	0	2250	0	0	1
	-360	360;								
2013	2034	0.00696	0.0264	0.00625	1500	0	2250	0	0	1
	-360	360;								

Data for Voltage Regulating Transformer

```
% voltage regulating transformer

%fbus   tbusr x b rateA rateB rateC ratio angle status angmin angmax

2002   1003  0   0.0193   0   660   0   990   1.7424  0  1  -360  360;
2005   1030  0   0.058    0   660   0   990   1.7424  0  1  -360  360;
2008   1201  0   0.029    0   660   0   990   1.7424  0  1  -360  360;
2010   1130  0   0.029    0   660   0   990   1.7424  0  1  -360  360;
2011   1125  0   0.0193   0   660   0   990   1.7424  0  1  -360  360;
2012   1101  0   0.0193   0   660   0   990   1.7424  0  1  -360  360;
2013   1113  0   0.0193   0   660   0   990   1.7424  0  1  -360  360;
2016   1107  0   0.0193   0   660   0   990   1.7424  0  1  -360  360;
2034   1134  0   0.0193   0   660   0   990   1.7424  0  1  -360  360;
2020   1401  0   0.0193   0   660   0   990   1.7424  0  1  -360  360;
2030   1412  0   0.0193   0   660   0   990   1.7424  0  1  -360  360;
2040   1440  0   0.029    0   660   0   990   1.7424  0  1  -360  360;
2042   1442  0   0.029    0   660   0   990   1.7424  0  1  -360  360;
2032   1332  0   0.029    0   660   0   990   1.7424  0  1  -360  360;
];

% %%-----  OPF Data  -----%%
% %% area data
% %     area     refbus
% mpc.areas = [
%       1        5;
% ];
%
% %% generator cost data
% %     1        startup shutdown    n        x1       y1       ...      xn       yn
% %     2        startup shutdown    n        c(n-1)   ...      c0
% mpc.gencost = [
%       2        1500     0        3        0.11     5        150;
%       2        2000     0        3        0.085    1.2      600;
%       2        3000     0        3        0.1225   1        335;
% ];
```