STATIC AVAILABLE TRANSFER CAPABILITY ENHANCEMENT USING 'UPFC' UNDER CONTINGENCIES

A Dissertation Submitted In Partial Fulfillment of the Requirement

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MASTER OF TECHNOLOGY
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By

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DECLARATION

I hereby declare that the work, which is being presented in the report, entitled **"STATIC AVAILABLE TRANSFER CAPABILITY ENHANCEMENT USING UPFC UNDER CONTINGENCIES"** in the partial fulfilment of the requirements for the award of the degree of Master of Technology, and Submitted in Department of   Electrical Engineering **DELHI TECHNOLGICAL UNIVERSITY, DELHI** is an authentic record of my own work carried out under the supervision of   **Dr. Narendra Kumar**, professor and head, electrical engineering Department.

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This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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CERTIFICATE

This is to certify that the dissertation work entitled "**STATIC AVAILABLE TRANSFER CAPABILITY ENHANCEMENT USING UPFC UNDER CONTINGENCIES**", is being submitted by **VIKAS SINGH [Roll No: 13/P.Sy/09]** in partial fulfillment of the requirement for the award of **MASTER OF TECHNOLOGY IN (POWER SYSTEM)** at the **DELHI TECHNOLOGICAL UNIVERSITY**, has been carried out under my supervision and guidance. It is also certified that the report embodies the results of the work carried out by him within prescribed period. The matter embodied in this dissertation has not been submitted for the award of any other degree.

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ABSTRACT

A combination of lack of investment and environmental issues results in lack of building of new transmission infrastructure. This leads to a requirement for better utilization of existing transmission network. The ATC is defined as a measure of the transfer capability remaining in the physical transmission network for further commercial activity over and above already committed uses" This index is often used as a measure of additional power that can be securely transferred by a transmission network.

The Available Transfer Capability (ATC) depends on a number of factors such as system generation dispatch, system load level, load distribution in the network, power transfer between areas and the limit imposed on the transmission network due to thermal, voltage and stability considerations. The computation of ATC is very important to the transmission system security and market forecasting. While the power marketers are focusing on fully utilizing the transmission system, engineers are concern with the transmission system security as any power transfers over the limit might result in system instability

With development of power market, bilateral trade increase greatly. The higher and higher challenges to the reliable and economic operation of power grid have been posed. While Flexible AC Transmission System (FACTS) is for a new solving method, it brings an unprecedented turning point in power flow control, stability and transmission capacity and improves power system. Placement of FACTS controller may be quite effective for enhancing The ATC of power system due to their capability to improve line voltage and control power flow through lines.

Out of all the FACTS devices, placement of Unified Power Flow Controller (UPFC) seems to the more effective in enhancing available transfer capability of the transmission network due to its ability to control series and shunt parameters simultaneously.

CHAPTER 1
INTRODUCTION

1.1 GENERAL

With the movement towards the open transmission access, quantifying the transmission transfer capability of interconnected power systems is becoming an important issue of concern to both system planners and operators, which has led to the introduction of available transfer capability. The transfer capabilities must be calculated and the power system planned and operated so that the power transfers do not exceed the transfer capability.

Available Transfer Capability (ATC) of a transmission network is its unutilized transfer capacity available for further transactions to the market participants. Power transaction between a specific seller bus/area and a buyer bus/area can be committed only when sufficient ATC is available for interface to ensure the system security. The computation of ATC is very important to the transmission system security and market forecasting. While the power marketers are focusing on fully utilizing the transmission system, engineers are concern with the transmission system security as any power transfers over the limit might result in system instability

To evaluate the ATC, it is also necessary to consider the effect of contingencies on the limits of the system. It is often desirable to consider how a system is affected by a limited number of contingencies at a time. Commonly, the N-1 contingency criterion is used which considers the effect of all reasonable single contingencies occurring for bilateral and multilateral transactions in between the specified buses.

Flexible AC Transmission System (FACTS) controllers offer an effective means to enhance the power transfer capability of the network. However, the extent to which a FACTS controller can enhance Available Transfer Capability (ATC) depends on its optimal location in the system. Flexible AC Transmission Systems (FACTS) controllers are emerging as an effective and promising alternative to enhance the power transfer capability and stability of the network by redistributing the line flows and regulating the bus voltages.

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1.2 THESIS ORGANIZATION

The thesis has been organized in following five chapters.

Chapter-1 presents a general introduction to the voltage stability problem, importance of ATC and its enhancement using FACTS devices.

In Chapter-2 a brief literature survey in the relevant areas and has set the motivation behind the work carried out in this thesis.

In Chapter-3 a general introduction to the ATC and its determination under contingency for bilateral and multilateral transactions has been presented. A criterion for static ATC determination has been proposed in this chapter. The effectiveness of the proposed method of static ATC determination has been tested on IEEE 14-bus system under different outage conditions.

In Chapter-4 a criterion for optimal placement of UPFC to enhance static ATC has been proposed. The effect of UPFC in static ATC enhancement has been studied on IEEE 14-bus system under contingency for bilateral and multilateral transactions.

Finally Chapter-5 concludes the main finding of the dissertation work and brings out future scope of investigations in this area.

CHAPTER 2
LITERATURE SURVEY

2.1 LITERATURE SURVEY

ATC of a transmission system is a measure of unutilized capability of the system at a given time. The ability of a system to reliably transfer power is constrained by one or more of the following limits: thermal, bus voltage and stability. Voltage stability refers to the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition [4]. Voltage collapse is the process by which the sequence of events accompanying voltage instability leads to a blackout or abnormally low voltages in a significant part of the power system [1], [3], [4]. Several incidences of voltage collapse throughout the world have given major impetus for analyzing the problem with increased interest. Fast advances in computer analysis of power systems have enabled appearance of extensive knowledge related to general power system control and stability.

Voltage stability is threatened when a disturbance increases the reactive power demand beyond the sustainable capacity of the available reactive power resources. While the most common form of voltage instability is the progressive drop of bus voltages, the risk of over voltage instability also exists and has been experienced at least in one system [6].

A method has been proposed in [9] for determining the ATC between any two locations in a transmission system (single-area or multi-area) under a given set of system operating conditions like system generation dispatch, system load level, load distribution n the network, power transfer areas, network topology and the limits imposed on the transmission due to thermal, voltage and stability.

Many technical challenges including total transfer capability calculation, transient stability constraint handling, transmission capability margins and probabilistic ATC calculation has been presented in [16].

For reliable and secure power transaction it is necessary to calculate ATC under contingencies .In [20] N-1 contingency criterion is used to evaluate ATC for the system.

In [18], a new set of AC distribution factors has been defined for ATC determination under system intact and line outage conditions.

A novel formulation of the ATC problem based on full AC power flow solution to incorporate the effects of reactive power flows, voltage limits and voltage collapse as well as the traditional line flow (thermal loading) effects has been considered [7].

The evaluation of multi-area ATC using power transfer distribution factors in a combined economic emission dispatch environment is described in [23]. An application of bifurcation criteria is proposed for available transfer capability (ATC) determination in a competitive power market having bilateral as well as multilateral transactions [15].The Hopf bifurcation limit has been considered for determination of the dynamic ATC [15]. Taking into account the limits on the line flows bus voltage magnitude, generator reactive power, voltage stability, as well as the loss of line contingencies, a method for multi-area power system total transfer capability (TTC) computation is presented [21].

The Flexible AC Transmission System (FACTS) [8] has received much attention in the last two decades. It uses high-current power electronic devices to control voltage, power flow, stability etc. FACTS devices can be connected to a transmission line in series, in shunt or in a combination of series and shunt. FACTS technologies allow for improved transmission system operation with minimal infrastructure investment, environmental impact and implementation time compared to the construction of new transmission lines [11].

FACTS controllers have been established as an effective means in improving the system stability including voltage stability, enhancing power transfer capability of the transmission system and also providing voltage control. However, due to high cost and, for maximum enhancement in voltage stability margin, these are to be optimally placed in the system.

Standard stability evaluation technique has been used to identify the optimum place for the implementation of FACTS devices and the effects of FACTS on system load ability has been studied and presented in [10].

An optimal power-flow-based ATC enhancement model is formulated to achieve the maximum power transfer of the specified interface with FACTS control [12]. Reference [18] focuses on the evaluation of the impact of FACTS devices on Available Transfer Capability (ATC) and its enhancement.

Generic algorithm is used for optimization process of the best location of SVC: as a FACTS device. The evaluation of the impact of IPFC (Interline Power Flow Controller) on ATC is presented in [22]. In order to increase ATC, voltage improvement as well as minimum capital cost the deployment of UPFC is suggested [23]

In [26] a sensitivity based approach for the determination of optimum location of UPFC is presented based on continuation power flow. So that placement of UPFC at optimum location results in significant enhancement in ATC.

UPFC is a device which can control transmission line impedance, voltage and phase angle. This controller offers substantial advantages for the static and dynamic operation of power system. The steady state injection model of UPFC is suggested in [17].

2.2 MOTIVATION

From the literature survey presented in the previous section, it seems that very limited efforts have been made to calculate and enhance ATC based on voltage stability criterion.

In the competitive electricity markets each generating company may try to earn maximum benefit without bothering about the safety of the grid. This may result in overloading of some of the transmission lines violation of some of the operating constraints of the power system, thus posing danger to grid failure. For safe operation of the grid a maximum limit has to be put for future transaction between seller and buyer buses.

To fulfill the demand of increasing load, new generating stations have been installed, but to build up new transmission system is a quite tough task due to lack of investment and limited right of way (ROW). Therefore special care with transmission capacity expansion and the development of efficient operation techniques to best use the system's capabilities is crucial. The power industry restructuring process has introduced a number of factors that have increased the possible sources of system disturbances, leading to a less robust, more unpredictable system as far as the operation is considered. The lack of new transmission facilities, cutbacks in system maintenance, workforce downsizing, unpredicted power flow patterns, just to name a few, are some of the important factors that affect the security of power systems.

The enhancement of Available Transfer Capability (ATC) in deregulated power system should take into account thermal limits, transient, steady-state and dynamic angle stability as well as the voltage stability limits. The consideration of voltage stability in the determination of ATC, however, was usually neglected.

On the other hand, under the power market environment, voltage instability becomes a more important consideration in many countries in recent years, especially when following a large disturbance in a heavily stressed power systems over long distances.

For transferring the more additional power through the transmission system, it is necessary to increase the static available transfer capability of the transmission system, so that a good compromise can be obtained between the security of the system and maximum utilization of the system.

In the FACTS family, the Unified Power Flow Controller (UPFC) seems to be the most powerful for voltage stability enhancement due to its ability to control line impedance, voltage magnitude and voltage angles, simultaneously. UPFC can be used as a powerful tool to increase the available transfer capability of the system.

Therefore, the motivation behind the work presented in this thesis has been to determine ATC based on static criterion and to see the impact of UPFC in enhancement of available transfer capability.

CHAPTER 3
STATIC ATC DETERMINATION

3.1 GENERAL

The Indian power sector, like what happened in most of countries, is gradually moving towards a deregulated or re-regulated framework under process of power reforms. In general, the restructuring of generation utilities and power grid corporations is taken as the first step. Under such a deregulated environment, besides the system operator, certain real-time information of the transmission grid is also required to be known by its user especially the generating companies (GENCOs), so as to schedule their generation under secure operation and try to gain more profit. Real-time Available Transfer Capability (ATC) is one of the most pivotal data to be published on the Open-Access Same-Time Information System (OASIS) for market participants to arrange transmission transactions.

In a restructured environment, all generation companies (GENCOs) and distribution companies (DISCOs)/retailers bid for the most profitable transactions. This may, therefore, result in a different generation and load dispatch schedule. Some parts of the transmission system may get congested as it must provide fair access to all the market participants. For the sake of system security and reliability, it is necessary to assess the transmission system capabilities along different corridors beforehand. In this context, North American Electric Reliability Council (NERC) has defined 'Available Transfer Capability (ATC)' as a measure of power transfer capability remaining in the physical transmission network for further commercial activity over and above the already committed uses [5].

In other words, it is the additional amount of power that can be transferred over the network with margins for a range of uncertainties and contingencies when power is injected and extracted at the specified seller and buyer buses, respectively.

ATC DEFINITIONS

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).

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.

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.

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.

3.2 TRANSFER CAPABILITY

Transfer capability is the measure of the ability of interconnected electric systems to reliably move or transfer power from one area to another over all transmission lines (or paths) between those areas under specified system conditions [5]. The units of transfer capability are in terms of electric power, generally expressed in megawatts (MW). In this context, "area" may be an individual electric system, power pool, control area, sub region, or NERC Region, or a portion of any of these. Transfer capability is also directional in nature. That is, the transfer capability from Area A to Area B is not generally equal to the transfer capability from Area B to Area A.

3.2.1 FACTOR AFFECTING DETERMINATION OF TRANSFER CAPABILITY

1. Projected Customer Demands — Base case demand levels should be appropriate to the system conditions and customer demand levels under study and may be representative of peak, off-peak or shoulder, or light demand conditions.

2. Generation Dispatch — Utility and non-utility generators should be realistically dispatched for the system conditions being simulated.

3. System Configuration — The base case configuration of the interconnected systems should be representative of the conditions being simulated, including any generation and transmission outages that are expected. The activation of any operating procedures normally expected to be in effect.

4. Base Scheduled Transfers — The scheduled electric power transfers that should be modeled are those that are generally considered to be representative of the base system conditions being analyzed and which are agreed upon by the parties involved.

5. System Contingencies — A significant number of generation and transmission system contingencies should be screened, consistent with individual electric system, power pool, sub regional, and Regional planning criteria or guides, to ensure that the facility outage most restrictive to the transfer being studied is identified and analyzed. The contingencies evaluated may in some instances include multiple contingencies where deemed to be appropriate.

The conditions on the interconnected network continuously vary in real time. Therefore, the transfer capability of the network will also vary from one instant to the next. For this reason, transfer capability calculations may need to be updated periodically for application in the operation of the network. In addition, depending on actual network conditions, transfer capabilities can often be higher or lower than those determined in the off-line studies. The farther into the future those simulations are projected, the greater is the uncertainty in assumed conditions. However, transfer capabilities determined from simulation studies are generally viewed as reasonable indicators of actual network capability.

3.2.2 TOTAL TRANSFER CAPABILITY

TTC is the amount of electric power that can be transferred over the interconnected transmission network in a reliable manner based on all of the following conditions:

1. 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.

2. 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.

3. After the dynamic power swings subside following a disturbance that results in the loss of any single electric system element as described in 2 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.

4. With reference to condition 1 above, in the case where pre-contingency facility loadings reach normal thermal ratings at a transfer level below that at which any first contingency transfer limits are reached, the transfer capability is defined as that transfer level at which such normal ratings are reached.

5. In some cases, individual system, power pool, sub regional, or Regional planning criteria or guides may require consideration of specified multiple contingencies, such as the outage of transmission circuits using common towers or rights-of-way, in the determination of transfer capability limits.

If the resulting transfer limits for these multiple contingencies are more restrictive than the single contingency considerations described above, the more restrictive reliability criteria or guides must be observed.

TTC = Minimum of {Thermal Limit, Voltage Limit, Stability Limit}   (3.1)
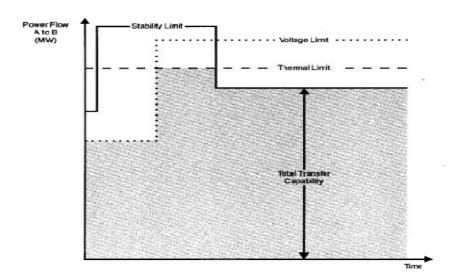
Figure 3.1 Limits of Total Transfer Capability

Individual systems, power pools, sub regions, and Regions should identify their TRM and CBM procedures used to establish such transmission transfer capability margins as necessary. TRM and CBM should be developed and applied as separate and independent components of transfer capability margin. The specific methodologies for determining and identifying necessary margins may vary among Regions, sub regions, power pools, individual systems, and load serving entities. However, these methodologies must be well documented and consistently applied.

3.2.3 TRANSFER RELIABILITY MARGIN

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.

TRM provides a reserve of transfer capability that ensures the reliability of the interconnected transmission network. All transmission system users benefit from the assurance that transmission services will be reliable under a broad range of potential system conditions. TRM accounts for the inherent uncertainty in system conditions and their associated effects on TTC and ATC calculations, and the need for operating flexibility to ensure reliable system operation as system conditions change.

3.2.4 EXISTING TRANSACTION COMMITMENT

The existing transaction commitment (ETC) is known precisely only for the real time applications. For any other time interval in future, this has to be approximated by forecasting techniques. The ETC determines the base case operating point for the specified time interval. It includes the generation schedule, load dispatch, system configuration, state of all the circuit-breakers and contingencies, if any. The margins TRM and CBM are decided as per the relevant policies of the system operator and the market participants. In general, the ATC is defined by,

$$\text{ATC} = \text{TTC} - \text{ETC} \tag{3.2}$$

TRM and CBM are to be accounted for separately when such definition is used for ATC determination. It shows the direct relationship between ATC and TTC. Hence all the constraints applicable to TTC are applicable to ATC and vice-versa.

3.2.5 CAPACITY BENEFIT MARGIN

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. Reservation of CBM by a load serving entity allows that entity to reduce its installed generating capacity below that which may otherwise have been necessary without interconnections to meet its generation reliability requirements.

The CBM is a more locally applied margin than TRM, which is more of a network margin. As such, to the extent a load serving entity maintains policies and procedures to reserve transfer capability for generation reliability purposes, the CBM should be included in the reserved or committed system uses in the calculation of ATC. These CBMs should continue to be a consideration in transmission system development. It is anticipated that individual load serving entities and regional planning groups will continue to address CBMs and that the NERC and Regional reviews of generation adequacy will continue to consider this capability. It is also anticipated that load serving entities will develop additional procedures for reserving transfer capability for generation capacity purposes and include these procedures in Regional planning reviews and regulatory filings as appropriate.

3.2.6 AVAILABLE TRANSFER CAPABILITY

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). ATC can be expressed as:

ATC = TTC - TRM - Existing Transmission Commitments (including CBM) (3.3)

The ATC between two areas provides an indication of the amount of additional electric power that can be transferred from one area to another for a specific time frame for a specific set of conditions. ATC can be a very dynamic quantity because it is a function of

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Variable and inter dependent parameters. These parameters are highly dependent upon the conditions of the network. Consequently, ATC calculations may need to be periodically updated. Because of the influence of conditions throughout the network, the accuracy of the ATC calculation is highly dependent on the completeness and accuracy of available network data.
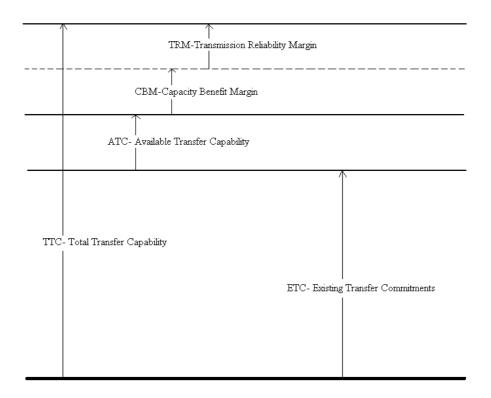
Figure 3.2 Basic Definition of ATC

3.3 FACTORS AFFECTING ATC

The limits to be considered for the calculation of the transfer capability may be broadly classified as:

3.3.1. STATIC CONSTRAINTS

- Line Thermal Limits
- Bus Voltage Limits
- Voltage Stability Limit (Saddle Node Bifurcation)

3.3.2. DYNAMIC CONSTRAINTS

- Small Signal Stability Limit

- Large Signal Stability Limit

3.3.1 STATIC CONSTRAINTS

1. Thermal limits

Thermal limits are described by the current ratings of the line-conductors and the transformer ratings as shown in fig.3.1. It is the maximum amount of electric current that a transmission line, a cable and other electric equipments, like a transformer can conduct for a specified period without getting overheated or damaged.

2. Bus voltage limits

The performance of most of the electric apparatus is dependent on the supply voltage magnitude. These are designed for some nominal voltage as per its ratings. Most of the electric devices fail to operate properly at under-voltage while over-voltages stress the insulation and may be destructive. Therefore, it is common practice to limit the bus voltages within a narrow range around the normal voltage. The system operator (SO) is obliged to supply electricity within the specified voltage range. Therefore, the voltage limits are imposed for ATC calculation.

3. Voltage stability limits

When the generation and loadings in a power system is gradually increased such that power balance is maintained, a limit is reached at which the load-flow fails to converge. This is known as the voltage stability limit of the transmission system and is the maximum power that the transmission network can transfer in steady state. If the load admittance is further increased in an attempt to increase the load, voltage collapse may occur and the power delivered to the load will decrease. At the voltage stability limit, which is also characterized by non-convergence of the load-flow equations, one of the Eigen values of the load-flow Jacobian becomes zero. This also corresponds to the Saddle Node Bifurcation (SNB) in the system.

3.3.2 DYNAMIC CONSTRAINTS

1. Small signal stability limit

Power System is always operating in a quasi-steady state as there are continuous changes in load demand, generation schedule; transmission parameters etc. for a heavily loaded system, the different control loops are already strained. With modern control systems capable of providing fast response, there is possibility of getting different control loops interacting with each other and subsequent build-up of oscillations when some disturbance appears in the system. The oscillations may grow and lead to instability in case the system is poorly damped. Such a tendency to oscillatory behavior can be studied by Eigen value analysis. For the oscillations to die out all the Eigen values should have negative real part and be located sufficiently far from the imaginary axis in the complex plane. If a pair of complex Eigen values is crossing the imaginary axis, Hopf bifurcation occurs leading to the onset of oscillations.

2. Large signal stability limit

A system, otherwise stable, may experience violent excursions of its states following a large disturbance such as breakdown of a large generator, a contingency on a heavily loaded line etc. large power swings are observed and the machine angles may undergo large oscillations. The inherent system synchronizing and damping torques tend to bring the machines to equilibrium state. In the absence of sufficient synchronizing torque the machines lose synchronism and lack of sufficient system damping will lead to slow decay or build up of oscillations. The problem of angle instability is more severe in heavily loaded systems.

3.4 METHODS FOR ATC DETERMINATION

1. Method based on multiple load flow and continuous power flow
2. Method based on power flow optimization(OPF)
3. Method based on linear sensitivity factors
4. Method based on bifurcation criteria
5. Method based on A.C. Distribution Factors

3.5 DETERMINATION OF AVAILABLE TRANSFER CAPABILITY

The ATC is defined as a measure of the transfer capability remaining in the physical transmission network for further commercial activity over and above already committed uses". This index is often used as a measure of additional power that can be securely transferred by a transmission network. This concept is different from the overall transmission capacity that is theoretically possible in a given system.

The ability of a system to reliably transfer power is constrained by one or more of the following limits: thermal, bus voltage and stability. Thermal limits reflect the current carrying ability of the transmission network before overheating occurs. Bus voltage limits put lower and upper bounds on the bus voltages acceptable in the system before damage to equipment occurs, while stability limits indicate the ability of the system to withstand disturbances. To evaluate the ATC, it is also necessary to consider the effect of contingencies on the limits of the system.

ATC calculation procedures require costly time-domain simulations that are often impractical to implement, especially in light of the fact that multiple system conditions and contingencies must be considered. **Furthermore, these procedures don't readily facilitate sensitivity information that is necessary in the techniques proposed in this thesis. For these reasons, among others, stability limits are approximated by voltage stability limits based on CPF technique [20].**

3.5.1 CONTINGENCY ANALYSIS

In contingency analysis, it is often desirable to consider how a system is affected by a limited number of contingencies at a time. Commonly, the N-1 contingency criterion is used which considers the effect of all reasonable single contingencies occurring. In the analysis, all bus voltage, thermal and voltage stability limits must be respected, and there can be no cascading outages. Similarly, an N-2 analysis considers contingencies taken two at a time under the same conditions. In this thesis, only transmission contingencies are considered.

3.5.2 ATC CALCULATION

Mathematically, the ATC is defined as:

$$ATC = TTC - TRM - ETC$$

Where TRM is the transfer reliability margin; ETC represents the existing transmission commitments and includes the capacity benefit margin (CBM). The TTC is the total transfer capability of the system.

The TRM is designed to provide a reserve of capability to maintain reliability standards. It is defined as:

The amount of transmission transfer capability necessary to ensure that the interconnected transmission network is secure under a reasonable range of uncertainties in system conditions.

The CBM is also a reserve margin for maintaining generation reliability standards, and is defined as:

The amount of transmission transfer capability reserved by load serving entities to ensure access to generation from interconnected systems to meet generation reliability requirements.

Mathematically, the TTC can be expressed as:

$$TTC = min. \{P_{max_{I_{lim}}}, P_{max_{V_{lim}}}, P_{max_{S_{lim}}}\}$$

Where I_{lim}, V_{lim}, and S_{lim} represent the thermal, bus voltage and voltage stability limits respectively.

Typically the N-1 contingency criterion is applied to the TTC calculation in so that the maximum load ability of the system is defined under the single worst possible contingency. Throughout this thesis it is assumed that the N-1 contingency criterion is the basis for the ATC calculation.

Typical computations of the ATC for a sample system are explained graphically in Figures 3.3, 3.4, and 3.5. Two PV curves are shown for a given system.

The outer curve is the system under normal operating conditions, while the inner curve is the system PV curve under the worst single contingency. In Figure 3.3, the bus voltage limits are active and define the TTC of the system under the worst contingency. In Figure 3.4, the bus voltage limits are different and the thermal limits dominate the TTC determination. Finally, if both voltage and thermal limits are changed, as in the case depicted by Figure 3.5, then voltage stability limits dominate.

The following steps are then used to calculate the ATC for a given system:

1. Determine the system conditions that comprise the ETC, and a value for the TRM.

2. Evaluate the direction of load change vector to be used in the CPF calculation. This vector is based on market auction results and/or load forecasts.

3. Define the set of all operating conditions under consideration. This includes all contingencies of interest as well as the normal operating case.

4. Identify the critical contingencies by the N-1 contingency criterion. Sensitivity analysis similar to the techniques proposed in may be used here to identify the critical contingencies.

5. Evaluate the TTC in by finding the maximum load ability of each critical contingency using CPF and the direction of load change from Step 2. A software program such as UWPFLOW [30] can be used in this step.

6. Use the TTC from Step 5 as well as the ETC and TRM from Step 1 to evaluate ATC.
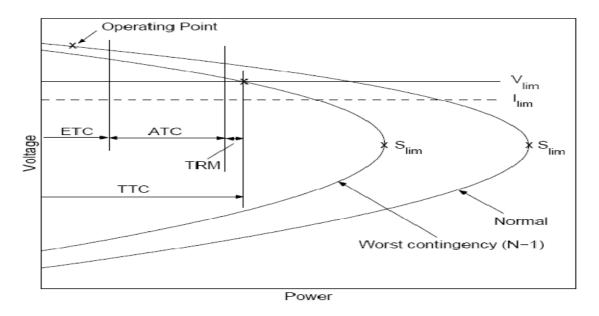
Figure 3.3 ATC evaluation where bus voltage limits dominate
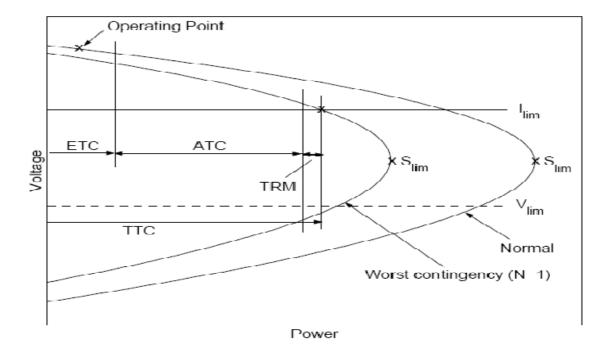
Figure 3.4 ATC evaluation where thermal limits dominate
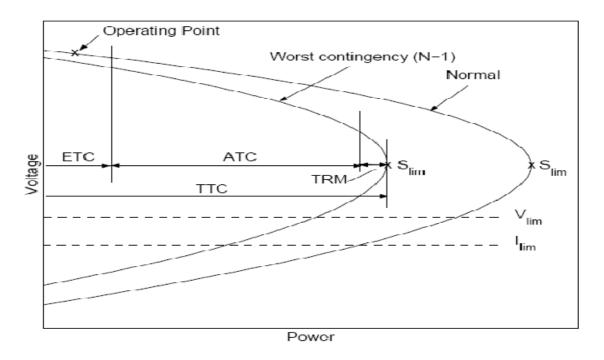
Figure 3.5 ATC evaluation where voltage stability limits dominate

The ATC has traditionally been used to assess security through power corridors". However, it can also be used as a system index since the formal definition does not limit its use to particular transmission corridors.

The continuation power flow [2] has been run to calculate loading margin (the distance between the base case operating point and the nose point) under contingencies and contingencies have been ranked as per post contingency loading margin.

The minimum out of ATC calculated for the intact case and critical contingency cases has been considered as static ATC of the system. Static ATC will be calculated for bilateral as well as multilateral transactions.

3.6 Modeling of bilateral/multilateral contracts

The conceptual model of bilateral dispatch in a competitive electricity market is such that sellers and buyers enter into transactions where the quantities traded and the associated prices are at the discretion of these parties and not a matter for system operators (SOs). If there is no static and dynamic security violation, the SO simply dispatches all requested transactions and charges for the transmission service.

Mathematically, each bilateral transaction between a seller at bus-p and power purchaser at bus-q satisfies the following power balance relationship:

$$P_{Gp} - P_{Dq} = 0$$

The bilateral concept can be generalized to the multilateral case where the seller (for example a generation company) may inject power at several nodes and the buyers also draw load at several nodes. Unlike pool dispatch, there will be a transaction power balance in that the aggregate injection equals the aggregate draw-off for each transaction. The contracted demands of load buses to be provided by generator-m must be shared in a proportion decided by contracted parties. Mathematically, a multilateral contract involving more than one supplier and/or one consumer can be expressed as:

$$\sum_m P_{Gm}^k - \sum_n P_{Dn}^k = 0 \quad k = 1, 2, \dots i_k$$

Where P_{Gm} and P_{Dn} stand for the power injections into the seller bus-m and the power taken out at the buyer bus-n, and t_k is the total number of multilateral contracts.

3.7 CASE STUDIES

Proposed approach of static ATC determination has been tested on IEEE 14-bus system. The single line diagram of the system is shown in figure A.1.

The base case operating point of the system was considered at 90% of the loading value given in system data, to get convergence of solutions under critical contingency cases. The loading margins were calculated for the intact case and line outage cases, using continuation power flow based software package UWPFLOW [30].

 In order to calculate ATC, bilateral transactions were considered between seller bus 2 & buyer bus 13. Multilateral transaction was considered between seller buses 1, 2 and buyer buses 9, 13. Real power demands were calculated at the base case operating point and at the maximum load ability point for the system intact case and critical contingency cases for each of these transactions. The difference between real power demands at the nose point and at the base case operating point were calculated for the system intact case and critical contingency cases, and were considered as ATC for the corresponding cases.

The minimum out of intact case ATC and ATCs for critical contingency cases was considered as static ATC of the system.

Table 3.1 shows ATCs for the system intact case and critical contingency cases for the bilateral transactions between seller bus 2 and buyer bus 13. It is observed from Table 3.1 that static ATC of the system for the bilateral transactions between seller bus 2 and buyer bus 13 is **78.9589 MW** corresponding to outage of line 5-6

Table 3.2 shows ATCs for the system intact case and critical contingency cases for the multilateral transactions between group of seller buses 1, 2 and group of buyer buses 9, 13. It is observed from Table 3.2 that static ATC of the system for the multilateral transactions between group of seller buses 1, 2 and group of buyer buses 9, 13 is **81.59954 MW** corresponding to outage of line 5-6.

Table 3.1 Static ATC for bilateral transactions between seller bus 2 and buyer bus 13 (IEEE 14-bus system)

Outage	ATC (MW)
Intact	224.7204
2-3	201.2324
1-5	199.5984
5-6	**78.95893**
2-4	189.2618
7-9	167.9844
4-5	225.6988
2-5	190.0637
4-7	184.9947
3-4	216.6868

Static ATC of the system = 78.95893 MW
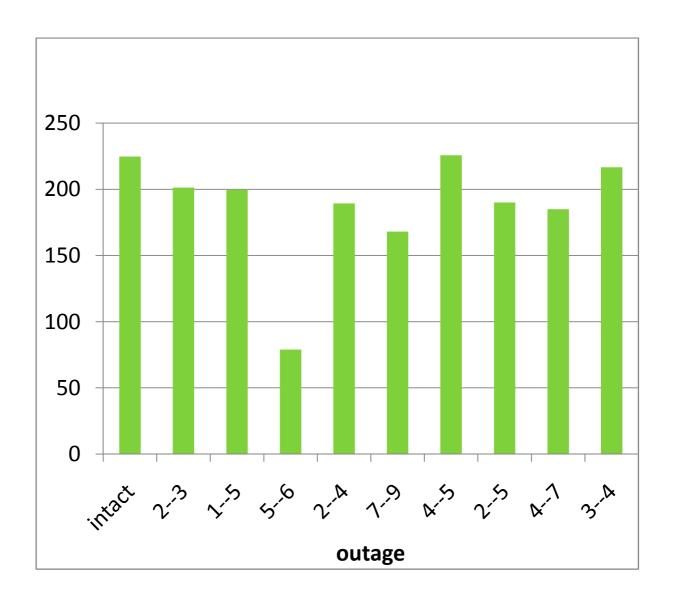
Figure 3.6 Comparison of ATC without UPFC for bilateral transactions between seller bus 2 and buyer bus 13 under different outage conditions (IEEE 14-bus system)

Table 3.2 Static ATC for multilateral transactions between seller buses 1, 2 and buyer buses 9, 13 (IEEE 14-bus system)

Outage	ATC (MW)
Intact	180.6501
2—3	159.9937
1—5	155.5113
5—6	**81.59954**
2—4	145.7421
7—9	95.0813
4—5	182.4744
2—5	150.0369
4—7	110.499
3—4	177.3387

Static ATC of the system = 81.59954 MW
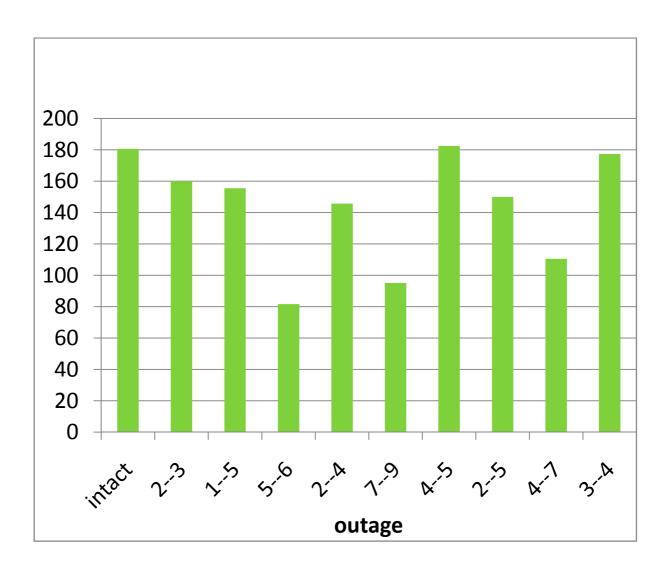
Figure 3.7 Comparison of ATC without UPFC for multilateral transactions between seller buses 1, 2 and buyer buses 9, 13 under different outage conditions (IEEE 14-bus system)

3.8 CONCLUSIONS

In this chapter, computation of static ATC considering difference between system loading at the nose point and at the base case operating point was suggested. The ATCs have been computed for the system intact case and critical contingency cases. The minimum out of ATC for the system intact case and critical contingency cases has been taken as the static ATC for the system. Case studies have been performed on IEEE 14-bus system to obtain static ATC for bilateral and multilateral transactions.

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CHAPTER 4
PLACEMENT OF UPFC FOR
ATC ENHANCEMENT

4.1 GENERAL

With the increasing need for higher exchange of electrical energy through existing transmission lines, grid companies are more interested in raising and controlling the power flow through the main transmission lines without losing system reliability. The electrical load is increasing day by day. To fulfill the demand of additional power, new power plants are being setting up. But the transmission system has a limited capability to transfer power. The transmission lines are getting overloaded nowadays which results in transferring power near to its thermal limit. To meet the demand of additional power through lines, there is a need to increase the power transfer capability of the existing transmission system considering the security and stability constraints.

Power systems over the globe are becoming complex and the requirements for providing stable, secure, controlled, economic, quality power, especially so in the deregulated environment are becoming vitally important. An overwhelming need is being felt for increasing the transmission capacity on transmission lines and controlling power flow in specific corridors, while assuring system reliability during any fault scenarios. In this new deregulated environment, a demand for flexible power flow control is becoming a technical need because of the increase in the level of risk and uncertainty associated with transmission operation and investment. One response to the flexibility in the way that the transmission system is operated is found by applying the Flexible AC Transmission Systems (FACTS) concept. FACTS is a title used to encompass all the newly emerging high-voltage controllers based on leading-edge power electronics technology to enhance the controllability and increase power transfer capacity of a transmission system.

Out of different FACTS controller Unified Power Flow Controller (UPFC) seems to be more promising. In order to assess the impact of the UPFC on the steady-state electric transmission systems operation, it is necessary to develop its mathematical model and include it in a power flow program.

4.2. UPFC MODEL

In the present work, UPFC has been represented by steady-state injection model [17]. The UPFC consists of two switching converters operated from a common DC link, as shown in figure-4.1 [8]. In this figure, Converter 2 performs the main function of the UPFC by injecting an AC voltage with controllable magnitude and phase angle in series with the line.

The basic function of Converter 1 is to supply or absorb the active power demanded by Converter 2 at the common DC link. This is represented by the current, I_p. Converter 1 can also generate or absorb controllable reactive power and provide independent shunt reactive compensation for the line. This is represented by the current, Iq. A UPFC can regulate active and reactive power simultaneously. In principle, a UPFC can perform voltage support, power flow control and dynamic stability improvement in one and the same device.
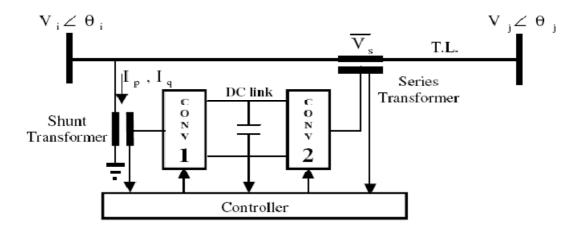
Figure 4.1 UPFC schematic diagram

The UPFC circuit arrangement has been shown in figure-4.2. The series converter is represented by an AC voltage source $\overline{V}_s$ in series with a reactance X_s. The shunt converter has been represented as an independently controllable reactive power Q*conv*1 injected to or absorbed from bus-i. In addition, this converter also supplies or absorbs real power *Pconv*1 to the series converter through the common DC link. *Iij* and *Iji* represent current flowing from bus-i to bus-j and from bus-j to bus-i respectively. V*i'* represents complex voltage of a fictitious bus-i'.
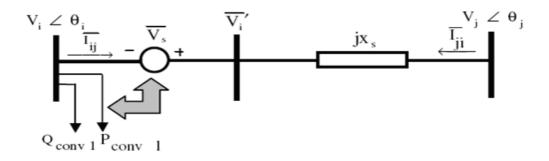
Figure 4.2 UPFC circuit arrangement

4.2.1 SERIES VOLTAGE SOURCE

First it is necessary to consider only the series voltage source. The voltage V′i and the current Iij are defined as

$$\overline{V}'_i = \overline{V}_i + \overline{V}_s$$

$$\overline{I}_{ij} = \frac{\overline{V}_i - \overline{V}_j}{jx_s}$$

The series voltage source $\overline{V}_s$ is controllable in magnitude and phase i.e:

$$\overline{V}_s = r\,\overline{V}_i\,e^{j\gamma} \tag{4.1}$$

where, $0 < r < r_{max}$ and $0 < \gamma < 2\pi$

Variables r and γ control magnitude and phase angle of injected voltage $\overline{V}_s$ r_{max} represents maximum limit of variable r.

In the next step, the series voltage source is transformed to a current source, $I = -jbs\,\overline{V}_s$ in parallel with the line, where bs = 1/Xs, as shown in Fig. 4.3
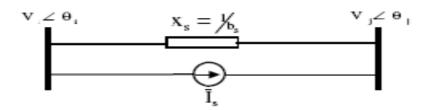
Figure.4.3 Transformed Series Voltage Source

The current source Is corresponds to the injection powers at buses i and j as follows:

$$\overline{S}_{is} = \overline{V}_i(jb_s\overline{V}_s)^*$$
$$= -rb_s V_i^2 \sin\gamma - jrb_s V_i^2 \cos\gamma$$

$$\overline{S}_{js} = \overline{V}_j(-jb_s\overline{V}_s)^*$$
$$= rb_s V_i V_j \sin(\Theta_{ij} + \gamma) + jrb_s V_i V_j \cos(\Theta_{ij} + \gamma)$$
$$\text{where } \Theta_{ij} = \theta_i - \theta_j$$

The series voltage source injection model can be seen as two dependent loads as shown in Fig.4 .4

$$P_{si} - rb_s V_i^2 \sin \gamma \qquad\qquad P_{sj} - -rb_s V_i V_j \sin(\theta_{ji} + \gamma)$$
$$Q_{si} = rb_s V_i^2 \cos\gamma \qquad\qquad Q_{sj} = -rb_s V_i V_j \cos(\theta_{ij} + \gamma)$$
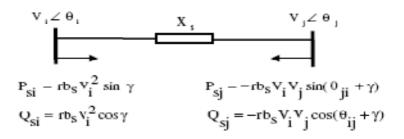
Figure 4.4 Injection Model of Series Voltage Source

4.2.2 UPFC STEADY STATE INJECTION MODEL

The apparent power supplied by the series voltage source converter is calculated from

$$\overline{S}_{ccnv2} = \overline{V}_s \overline{I}_{ij}^* = re^{j\gamma}\overline{V}_i \left(\frac{\overline{V}'_i - \overline{V}_j}{jX_s} \right)^*$$

The active power supplied by converter 1 is

$$P_{conv1} = P_{conv2} = Re(S_{conv2})$$
$$= rb_s V_i V_j \sin(\theta_{ij} + \gamma) - rb_s V_i^2 \sin\gamma$$

The reactive power delivered or absorbed by the converter 1 is independently controllable by UPFC and can be modelled as a separate controllable shunt reactive source, Qconv1 . The UPFC injection model is constructed from the series voltage source (Fig. 4.4) with the addition of a power equivalent to **Pconv1 + j Q conv1** to node i as shown in Fig. 4.5. The model can be incorporated to the power flow equations by including 'bs' into the bus admittance matrix and adding the UPFC injection powers at buses i and j.

The steady-state injection model of UPFC has been derived from figure-4.2 and as shown in figure-4.5.

$$P_{si} = rb_s V_i V_j \sin(\theta_{ij} + \gamma) \qquad P_{sj} = -rb_s V_i V_j \sin(\theta_{ji} + \gamma)$$

$$Q_{si} = rb_s V_i^2 \cos\gamma + Q_{conv1} \qquad Q_{sj} = -rb_s V_i V_j \cos(\theta_{ij} + \gamma)$$
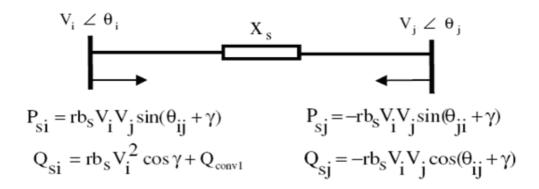
Figure 4.5 UPFC injection model

4.3 OPTIMAL PLACEMENT OF UPFC CONTROLLER

A sensitivity based approach has been suggested in [26] for determination of the optimal location of UPFC to enhance voltage stability margin under contingencies for monopolistic power system. This approach is described below:

The reactive power balance equation at bus-i can be given by:

$$QG_i - (QD_{ib} + \lambda K_{Di} S_{\Delta base} \sin\phi_i)$$
$$= Q_{ik} + \sum_{\substack{j=1 \\ \neq k}}^{n} V_i V_j Y_{ij} \sin(\delta_i - \delta_j - \theta_{ij}) \qquad\qquad (4.2)$$

where,

QG_i = Reactive power generation at bus--i

QD_{ib} = Reactive power demand at bus-i at the base case operating point

Q_{ik} = Reactive power flowing from bus-i to bus-k

λ = Loading factor common to all the buses

K_{Di}= Constant multiplier showing the rate of change of load at the ith bus

$S_{\Delta base}$ =Mega Volt Ampere (MVA) base used for scaling to equivalent MVAR load increase.

Φ_i = power factor angle of the increased load at the ith bus

$V_i \angle \delta_i$ = Complex voltage at bus-–i

$Y_{ij} \angle \theta_{ij}$ = $G_{ij} + jB_{ij}$ = ij^{th} element of the bus-admittance matrix

n= Total number of the buses in the system

Differentiating equation (4.2) with respect to Q_{ik} provides the expression for the sensitivity factor

$$\frac{\partial \lambda}{\partial Q_{ik}} = Y^{-1} [Z^{-1} (1 - X) - 1] \tag{4.3}$$

where,

$$X = \sum_{\substack{j=1 \\ \neq k}}^{n} \left\{ \left[V_i \frac{\partial V_j}{\partial QG_i} + V_j \frac{\partial V_i}{\partial QG_i} \right] Y_{ij} \sin(\delta_i - \delta_j - \theta_{ij}) + V_i V_j Y_{ij} \cos(\delta_i - \delta_j - \theta_{ij}) \left[\frac{\partial \delta_i}{\partial QG_i} - \frac{\partial \delta_j}{\partial QG_i} \right] \right\} \tag{4.4}$$

$$Y = K_{Di} \, S_{\Delta base} \, \sin \phi_i \tag{4.5}$$

$$Z = \frac{\partial Q_{ik}}{\partial Q_{Gi}} = \left[V_i \frac{\partial V_k}{\partial QG_i} + V_k \frac{\partial V_i}{\partial QG_i} \right] Y_{ik} \sin(\delta_i - \delta_j - \theta_{ij})$$
$$+ V_i V_j Y_{ik} \cos(\delta_i - \delta_j - \theta_{ik}) \left[\frac{\partial \delta_i}{\partial QG_i} - \frac{\partial \delta_k}{\partial QG_i} \right] \tag{4.6}$$

The sensitivity factor $\frac{\partial \lambda}{\partial Q_{ik}}$, which relates changes in loading factor with respect to change in reactive power flowing from bus-i to bus-k, can be computed using (4.3) for each of the lines under system intact case and critical contingency cases. Each line is having two such sensitivity values ($\frac{\partial \lambda}{\partial Q_{ik}}$ and $\frac{\partial \lambda}{\partial Q_{ki}}$). Based on maximum absolute value of sensitivity factors computed for the system intact case and critical contingency cases, priority lines for the placement of UPFC can be determined. Depending upon magnitude of $\frac{\partial \lambda}{\partial Q_{ik}}$ and $\frac{\partial \lambda}{\partial Q_{ki}}$

Corresponding to priority lines, bus-i or bus-k can be considered as priority buses. The partial derivatives $\partial V_i/\partial Q_{Gi}, \partial \delta_i/\partial Q_{Gi}, (i = 1...n)$ in (4.4) & (4.6) can be derived for different buses from the inverse Jacobian matrix of the full Newton Raphson Load Flow (NRLF) in polar form.

Based on maximum absolute value of sensitivity factors computed for the system intact case and critical contingency cases for bilateral and multilateral transactions, candidate locations for UPFC placement have been obtained. The static ATC were calculated for bilateral and multilateral transactions after UPFC placement in each of the candidate locations. The optimal location of UPFC has been considered based on percentage increase in ATC for bilateral and multilateral transactions.

4.4 CASE STUDIES

Proposed approach of static ATC enhancement has been tested on IEEE 14-bus system. The single line diagram of the system has been shown in figure A.1.The base case operating point of the system was considered at 90% of the loading value given in system data to get convergence of solutions under critical contingency cases.

The absolute value of sensitivity factor for two most sensitive lines for the bilateral transactions between seller bus-2 and buyer bus-13 have been shown in Table 4.1. It is observed from Table 4.1 that line 8-7 (towards bus-7) and line 4-9 (towards bus-9) are two most sensitive lines for majority of outage cases for the bilateral transactions between seller bus-2 and buyer bus-13. Two most sensitive lines having maximum absolute value of sensitivity factors $\dfrac{\partial \lambda}{\partial Q_{ik}}$ for the multilateral transactions between group of seller buses

1, 2 and group of buyer buses 9, 13 have been shown in Table 4.2.

It is observed from Table 4.2 that line 4-9 (towards bus-9), line 11-10 (towards bus-10) and line 8-7 (towards bus-7) are most sensitive lines for the multilateral transactions between group of seller buses 1,2 and group of buyer buses 9,13. Based on maximum absolute value of sensitivity factor for bilateral and multilateral transactions, line 8-7 (towards bus-7), line 4-9 (towards bus-9) and line 11-10 (towards bus-10) were considered as candidate locations for the placement of UPFC.

Line 12-11 (towards bus-11) has maximum absolute value of sensitivity factor for only one critical contingency case for bilateral transactions. Hence this line was not considered as a candidate location for UPFC placement. ATCs were calculated without UPFC and with UPFC in candidate locations for the system intact case and critical contingency cases.

The ATC for the bilateral transactions have been shown in Table 4.6. It is observed from Table 4.6 that placement of UPFC in line 4-9 (towards bus-9) causes maximum enhancement in ATC for bilateral transactions between seller bus-2 and buyer bus-13. The enhancement in ATC is from **78.9589 MW** to **96.6859 MW**.

The ATC for multilateral transactions between seller buses 1, 2 and buyer buses 9, 13 have been shown in Table 4.10. It is observed from Table 4.10 that placement of UPFC in line 4-9 (towards bus-9) causes maximum enhancement in ATC, from **81.59954 MW** to **104.4645 MW**. Comparing percentage enhancement in static ATC for bilateral and multilateral transactions, optimal location of UPFC was considered as line 4-9 (towards bus-9). Fig 4.8 shows a bar chart showing static ATC without UPFC and with UPFC at optimal location for bilateral and multilateral transactions. It is observed from fig 4.8 that placement of UPFC in line 4-9 (towards bus-9) causes considerable enhancement in static ATC for bilateral and multilateral transactions.

**Table 4.1 Absolute value of $\partial\lambda/\partial Q_{ik}$ for two most sensitive lines for bilateral transactions between seller bus 2 and buyer bus-13
(IEEE-14 bus-system)**

Outage	Line (towards bus)	$\partial\lambda/\partial Q_{ik}$	Line (towards bus)	$\partial\lambda/\partial Q_{ik}$
Intact System	4-9(4)	5.6569	11-10(10)	2.3203
1-2	12-11(11)	3.9030	12-6(6)	3.8737
2-3	8-7(7)	953.4965	4-9(9)	390.7893
1-5	8-7(7)	844.6170	4-9(9)	360.9027
5-6	8-7(7)	483.6107	4-9(9)	188.5700
2-4	8-7(7)	294.6248	4-9(9)	179.7835
7-9	8-7(7)	131.5226	4-9(9)	63.0287
4-5	4-9(4)	14.6632	11-10(10)	11.3839
2-5	8-7(7)	749.8724	4-9(9)	303.6893
4-7	4-9(4)	9.7340	11-10(10)	7.6752
3-4	8-7(7)	392.7642	4-9(9)	284.8620

Table 4.2 Absolute value of $\partial\lambda/\partial Q_{ik}$ for two most sensitive lines for multilateral transactions between group of seller buses 1,2 and group of buyer buses 9,13 (IEEE-14 bus-system)

Outage	Line (towards bus)	$\partial\lambda/\partial Q_{ik}$	Line (towards bus)	$\partial\lambda/\partial Q_{ik}$
Intact System (No outage)	4-9(9)	219.6	4-2(2)	101.0393
1-2	11-10(10)	17.3545	5-2(2)	12.4040
2-3	4-9(9)	144.1886	4-2(2)	58.6407
1-5	4-9(9)	229.6176	4-2(2)	92.9697
5-6	8-7(7)	294.6248	4-9(9)	179.7835
2-4	4-9(9)	98.5635	4-2(2)	41.8725
7-9	8-7(7)	217.8924	4-9(9)	132.9025
4-5	4-9(9)	210.5629	4-2(2)	83.7204
2-5	4-9(9)	173.6732	4-2(2)	64.8923
4-7	4-9(9)	275.3824	4-2(2)	103.7972
3-4	11-10(10)	17.3545	5-2(2)	12.4040

Table 4.3 Static ATC with UPFC in line 14 (8-7) for bilateral transactions between seller bus-2 and buyer bus-13 (IEEE 14-bus system)

Outage	ATC (MW) WITH UPFC IN LINE 14 (8-7)
intact	225.8631
2—3	201.5567
1—5	199.8864
5—6	**79.19939**
2—4	189.5934
7—9	168.4624
4—5	225.9417
2—5	190.3721
4—7	186.7851
3—4	218.3206

Table 4.4 Static ATC with UPFC in line 9 (4-9) for bilateral transactions between seller bus-2 and buyer bus-13 (IEEE 14-bus system)

Outage	ATC (MW) WITH UPFC IN LINE 9 (4-9)
intact	244.1564
2—3	227.9427
1—5	222.0763
5—6	**96.68593**
2—4	215.2525
7—9	211.1933
4—5	245.3801
2—5	213.5361
4—7	211.7837
3—4	218.3206

Table 4.5 Static ATC with UPFC in line 18 (10-11) for bilateral transactions between seller bus-2 and buyer bus-13 (IEEE 14-bus system)

Outage	ATC (MW) WITH UPFC IN LINE 18 (10-11)
intact	233.0346
2—3	212.7592
1—5	209.5007
5—6	**88.8602**
2—4	200.0242
7—9	187.629
4—5	234.7395
2—5	199.679
4—7	197.01
3—4	225.7569

Table 4.6 Enhancement of Static ATC for bilateral transactions between seller bus-2 and buyer bus-13 (IEEE 14-bus system)

Outage	ATC (MW) without UPFC	ATC (MW) with UPFC in line 8-7 (towards bus-7)	Percentage enhancement in real power ATC with UPFC in line 8-7 (towards bus-7)	ATC (MW) with UPFC in line 4-9 (towards bus-9)	Percentage enhancement in real power ATC with UPFC in line 4-9 (towards bus-9)	ATC (MW) with UPFC in line 11-10 (towards bus-10)	Percentage enhancement in real power ATC with UPFC in line 11-10 (towards bus-10)
intact	224.7204	225.8631	0.508508	244.1564	8.648989	233.0346	3.699816
2—3	201.2324	201.5567	0.161162	227.9427	13.27338	212.7592	5.728129
1—5	199.5984	199.8864	0.14428	222.0763	11.26154	209.5007	4.961087
5—6	**78.95893**	**79.19939**	**0.304538**	**96.68593**	**22.45091**	**88.8602**	**12.53977**
2—4	189.2618	189.5934	0.175228	215.2525	13.73269	200.0242	5.686515
7—9	167.9844	168.4624	0.28455	211.1933	25.72196	187.629	11.69425
4—5	225.6988	225.9417	0.107608	245.3801	8.720147	234.7395	4.005634
2—5	190.0637	190.3721	0.16223	213.5361	12.34971	199.679	5.058977
4—7	184.9947	186.7851	0.967801	211.7837	14.48094	197.01	6.494904
3—4	216.6868	218.3206	0.753996	218.3206	0.753996	225.7569	4.18582
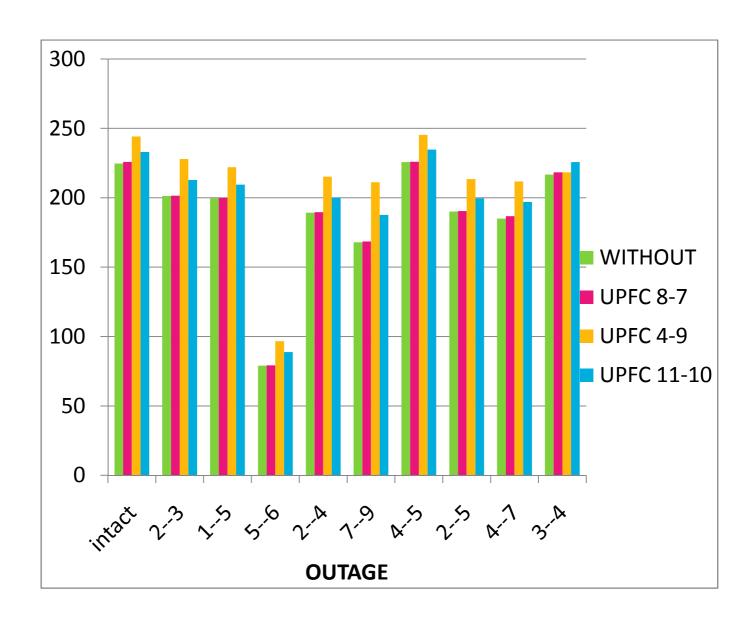
Figure 4.6 Comparison of ATC (MW) without UPFC and with UPFC in line (8-7) (4-9) and (11-10) for bilateral transactions between seller bus 2 and buyer bus 13 under different outage conditions (IEEE 14-bus system)

Table 4.7 Static ATC with UPFC in line 14 (8-7) for Multilateral Transactions between Seller Buses 1, 2 and Buyer Buses 9, 13 (IEEE 14-bus system)

Outage	ATC (MW) WITH UPFC IN LINE 14 (8-7)
intact	182.20929
2—3	160.48663
1—5	165.71457
5—6	**81.89462**
2—4	146.22197
7—9	95.38122
4—5	173.23217
2—5	150.43542
4—7	112.18277
3—4	169.61676

Table 4.8 Static ATC with UPFC in line 9 (4-9) for Multilateral Transactions between Seller Buses 1, 2 and Buyer Buses 9, 13 (IEEE 14-bus system)

Outage	ATC (MW) WITH UPFC IN LINE 9 (4-9)
intact	216.52157
2—3	200.48233
1—5	191.82183
5—6	**104.46457**
2—4	183.4636
7—9	142.43202
4—5	211.92189
2—5	179.35678
4—7	143.33653
3—4	212.33412

Table 4.9 Static ATC with UPFC in line 18(10-11) for Multilateral Transactions between Seller Buses 1, 2 and Buyer Buses 9, 13 (IEEE 14-bus system)

Outage	ATC (MW) WITH UPFC IN LINE 18 (10-11)
intact	193.97176
2—3	175.32126
1—5	142.05874
5—6	**93.39116**
2—4	159.44533
7—9	112.84079
4—5	196.63252
2—5	158.19229
4—7	122.4964
3—4	190.67681

Table 4.10 Enhancement of Static ATC Multilateral Transactions between Seller Buses 1, 2 and Buyer Buses 9, 13 (IEEE 14-bus system)

Outage	ATC (MW) without UPFC	ATC (MW) with UPFC in line 8-7 (towards bus-7)	Percentage enhancement in real power ATC with UPFC in line 8-7 (towards bus-7)	ATC (MW) with UPFC in line 4-9 (towards bus-9)	Percentage enhancement in real power ATC with UPFC in line 4-9 (towards bus-9)	ATC (MW) with UPFC in line 11-10 (towards bus-10)	Percentage enhancement in real power ATC with UPFC in line 11-10 (towards bus-10)
Intact No outage	180.6501	182.20929	0.863094	216.52157	19.85687	193.97176	7.374283
2—3	159.9937	160.48663	0.308093	200.48233	25.30639	175.32126	9.580102
1—5	155.5113	165.71457	6.561084	191.82183	23.34909	142.05874	-8.65056
5—6	**81.59954**	**81.89462**	**0.36162**	**104.46457**	**28.02103**	**93.39116**	**14.4506**
2—4	145.7421	146.22197	0.329239	183.4636	25.88234	159.44533	9.40236
7—9	95.0813	95.38122	0.315435	142.43202	49.80024	112.84079	18.67822
4—5	182.4744	173.23217	-5.06497	211.92189	16.13785	196.63252	7.758939
2—5	150.0369	150.43542	0.265635	179.35678	19.5418	158.19229	5.435611
4—7	110.499	112.18277	1.523769	143.33653	29.71747	122.4964	10.85745
3—4	177.3387	169.61676	-4.35436	212.33412	19.73365	190.67681	7.521251
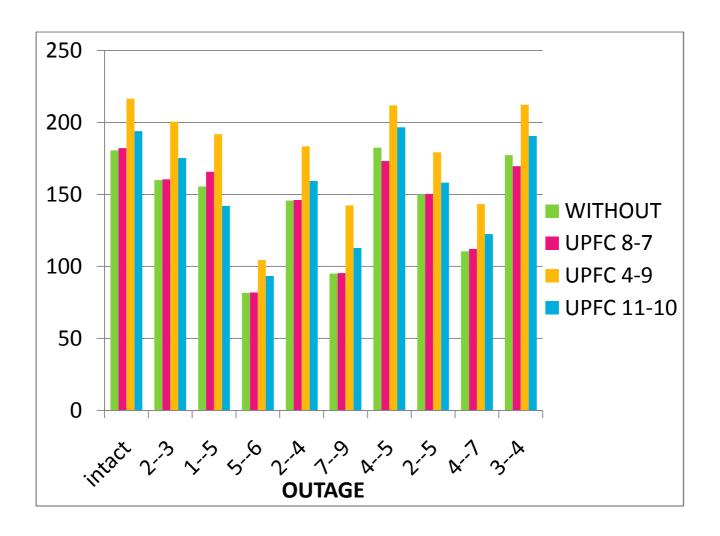
**Figure 4.7 Comparison of ATC (MW) without UPFC and with UPFC in line (8-7), (4-9) and (11-10) for multilateral transactions between seller buses 1, 2 and buyer buses 9, 13 under different outage conditions (IEEE 14-bus system)**
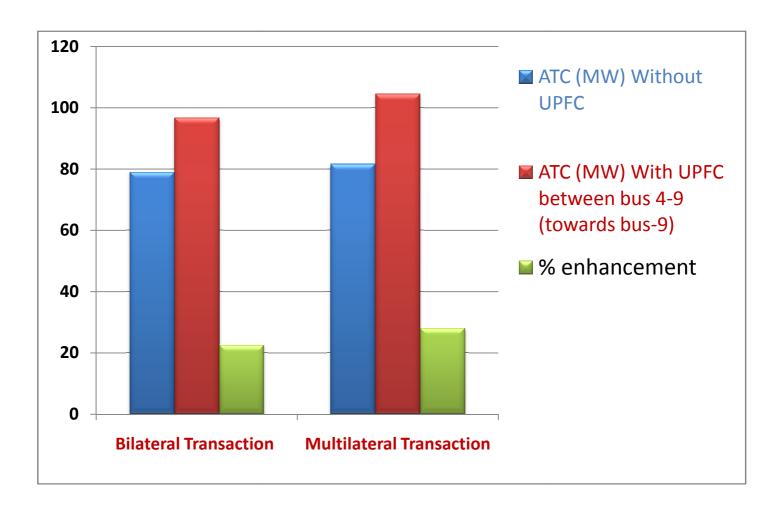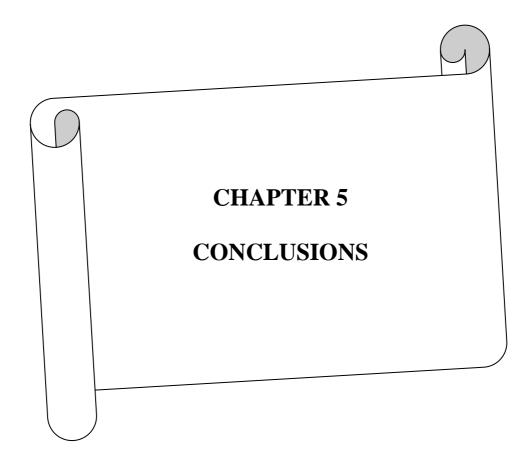
Figure 4.8 Comparison of ATC without UPFC and with UPFC in line 4-9 (towards bus-9) for bilateral transactions between seller bus 2 and buyer bus 13 and multilateral transactions between seller buses 1, 2 and buyer buses 9, 13. (IEEE 14-bus system)

4.5 CONCLUSION

The sensitivity of loading factor with respect to reactive power flow through line derived in [24] has been suggested in this chapter to find optimal location for the placement of UPFC to enhance static ATC of the system. Based on the maximum absolute value of sensitivity factors, candidate locations for UPFC placement have been obtained. The location causing maximum percentage enhancement in ATC for bilateral and multilateral transactions have been considered as the optimal location for the placement of UPFC controller

From the case study performed on IEEE 14-bus-system, it is observed that a considerable enhancement occurred in ATC of the system after UPFC placement at the optimal location decided by sensitivity based approach.

CHAPTER 5

CONCLUSIONS

5.1 GENERAL

Voltage instability has been considered as a major threat to power system networks for researchers and utilities since last two decades. Due to rapid electrification, the electrical power demands from modern power systems are gradually increasing. This results in the operation of the system near voltage stability limit. Voltage stability margin of the system further reduces under occurrence of critical contingencies. Hence, for the survival of the power systems under possible disturbances (contingencies) without interruption of customer service, enhancement of static ATC is required in competitive electricity market.

5.2 SUMMARY OF IMPORTANT FINDINGS

The main findings of this thesis are

The ATC have been computed for the system intact case and critical contingency cases in chapter-3. The minimum out of ATC for the system intact case and critical contingency cases has been taken as the static ATC for the system. Case studies have been performed on IEEE 14-bus system to obtain static ATC for bilateral and multilateral transactions.
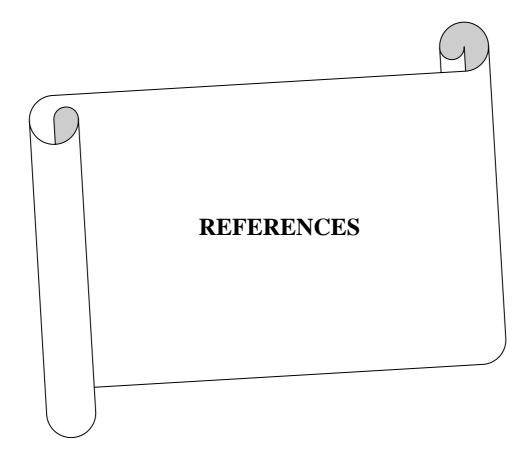
In chapter 4, according to sensitivity based approach, UPFC has been placed at optimal location in power system to enhance ATC under contingencies. From the case studies carried out on IEEE 14-bus system, a considerable increase in ATC has been observed after UPFC placement at the optimal location.

5.3 SCOPE FOR FURTHER RESEARCH

As consequence of investigations carried out in this thesis, the following aspects are being suggested as future research work to be carried out:

- The approach of ATC determination used here requires large computational further research is required to minimize computational time.
- Application of Artificial intelligence for computation of ATC.
- The ATC enhancement has not been calculated for all FACTS controllers, further research can be carried out in considering other FACTS controllers and multiple types of FACTS controllers.
- This thesis has not addressed to the dynamic aspects of voltage stability. It may be interesting to include the dynamic ATC enhancement. The dynamics of the system as a whole, when subjected to small and large disturbances, must be studied and analysed for stability. ATC calculated with dynamic stability limits is referred to as dynamic ATC.

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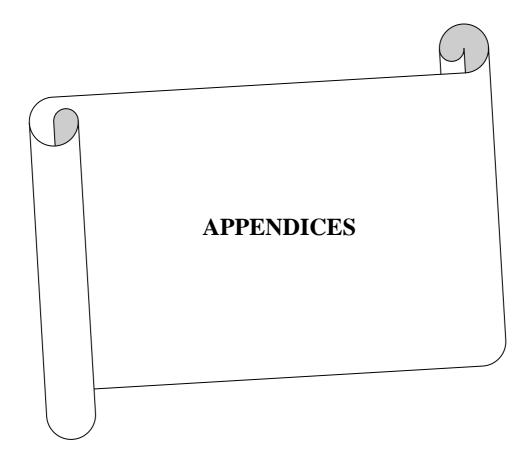
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APPENDICES

Appendix A

Data for IEEE 14-Bus Test System

The IEEE14-bus system data is taken from ref [29]. The relevant data are provided in following tables. Generator Data, Transformer data, Load Bus data and Line data have been shown in Table A.1, Table A.2, Table A.3, and Table A.4 respectively. The single line diagram of the system is shown in Figure-A.1.

Table A.1: Generator data (IEEE 14-bus system)

Bus No	Real Power Generation	Voltage	Load		Real Power Generation Limits		Reactive Power Generation limits	
	P_G(MW)	V_{spec}(p.u)	Real MW	Reactive (MVA)	Maximum (MW)	Minimum (MW)	Maximum (MVAR)	Minimum (MVAR)
1	232.4	1.060	00.00	00.00	200.00	50.00	100.00	-45.00
2	40.00	1.045	21.70	12.70	100.00	20.00	50.0	-40.00
3	--	1.010	94.20	19.00	---	---	40.00	0.00
6	--	1.070	11.2	7.5	---	---	24.00	-06.00
8	--	1.090	00.00	00.00	---	---	24.00	-06.00

Table A.2: Transformer Data (IEEE 14-bus system)

Line No	From Bus	To Bus	Series Impedance		Tap Setting(p.u)
			Resistance(p.u)	Reactance(p.u)	
8	4	7	0.00	0.2091	0.978
9	4	9	0.00	0.5561	0.969
10	5	6	0.00	0.2502	0.932

Table A. 3: Load Bus Data (IEEE 14-bus system)

Bus No	Load		External Shunt Susceptance(p.u)
	Real (MW)	Reactive(MVAR)	
4	47.8	-3.9	0.0
5	7.6	1.6	0.0
7	0.0	0.0	0.0
9	29.5	16.6	0.19
10	9.0	5.8	0.0
11	3.5	1.8	0.0
12	6.1	1.6	0.0
13	13.5	5.8	0.0
14	14.9	5.0	0.0

Table A. 4: Line Data (IEEE14-bus system)

Line No	From No	To Bus	Series Impedance		Shunt Susceptance (p.u)
			Resistance (p.u)	Reactance (p.u)	
1	1	2	0.01938	0.05917	0.0528
2	1	5	0.05403	0.22304	0.0492
3	2	3	0.04699	0.19797	0.0438
4	2	4	0.05811	0.17632	0.0340
5	2	5	0.05695	0.17388	0.0346
6	3	4	0.06701	0.17103	0.0128
7	4	5	0.01335	0.04211	0.0
11	6	11	0.09498	019890	0.0
12	6	12	0.12291	0.25581	0.0
13	6	13	0.06615	0.13027	0.0
14	7	8	0.0	0.17615	0.0
15	7	9	0.0	0.11001	0.0
16	9	10	0.03181	0.08450	0.0
17	9	14	0.12711	0.27038	0.0
18	10	11	0.08205	0.19207	0.0
19	12	13	0.22092	0.19988	0.0
20	13	14	0.17093	0.34802	0.0

IEEE 14 Bus Test Case with 90% loading

BUS DATA FOLLOWS   14 ITEMS

1 Bus 1   HV 1 1 3 1.060 0.0   0.0   0.0   232.4 -16.9 0.0 1.060 0.0   0.0 0.0 0.0

2 Bus 2   HV 1 1 2 1.045 -4.98 19.53 11.43 40.0 42.4 0.0 1.045 50.0 -40.0 0.0 0.0

3 Bus 3   HV 1 1 2 1.010 -12.72 84.78 17.1   0.0   23.4 0.0 1.010 40.0 0.0 0.0 0.0

4 Bus 4   HV 1 1 0 1.019 -10.33 43.02 -3.51 0.0   0.0   0.0 0.0   0.0   0.0 0.0 0.0

5 Bus 5   HV 1 1 0 1.020 -8.78 6.84   1.44 0.0   0.0   0.0 0.0   0.0   0.0 0.0 0.0

6 Bus 6   LV 1 1 2 1.070 -14.22 10.08 6.75   0.0   12.2 0.0 1.070 24.0 -6.0 0.0 0.0

7 Bus 7   ZV 1 1 0 1.062 -13.37 0.0   0.0   0.0   0.0   0.0 0.0   0.0   0.0 0.0 0.0

8 Bus 8   TV 1 1 2 1.090 -13.36 0.0   0.0   0.0   17.4 0.0 1.090 24.0 -6.0 0.0 0.0

9 Bus 9   LV 1 1 0 1.056 -14.94 26.55 14.94 0.0   0.0   0.0 0.0   0.0   0.0 0.0 0.19

10 Bus 10 LV 1 1 0 1.051 -15.10 8.1   5.22 0.0   0.0   0.0 0.0   0.0   0.0 0.0 0.0

11 Bus 11 LV 1 1 0 1.057 -14.79 3.15   1.62 0.0   0.0   0.0 0.0   0.0   0.0 0.0 0.0

12 Bus 12 LV 1 1 0 1.055 -15.07 5.49   1.44 0.0   0.0   0.0 0.0   0.0   0.0 0.0 0.0

13 Bus 13 LV 1 1 0 1.050 -15.16 12.15   5.22 0.0   0.0   0.0 0.0   0.0   0.0 0.0 0.0

14 Bus 14 LV 1 1 0 1.036 -16.04 13.41   4.5   0.0   0.0   0.0 0.0   0.0   0.0 0.0 0.0

-999

BRANCH DATA FOLLOWS   20 ITEMS

 1   2 1 1 1 0 0.01938 0.05917 0.0528 0 0 0 0 0 0.0   0.0 0.0 0.0   0.0 0.0 00.0

 1   5 1 1 1 0 0.05403 0.22304 0.0492 0 0 0 0 0 0.0   0.0 0.0 0.0   0.0 0.0 00.0

 2   3 1 1 1 0 0.04699 0.19797 0.0438 0 0 0 0 0 0.0   0.0 0.0 0.0   0.0 0.0 00.0

 2   4 1 1 1 0 0.05811 0.17632 0.0340 0 0 0 0 0 0.0   0.0 0.0 0.0   0.0 0.0 00.0

 2   5 1 1 1 0 0.05695 0.17388 0.0346 0 0 0 0 0 0.0   0.0 0.0 0.0   0.0 0.0 00.0

 3   4 1 1 1 0 0.06701 0.17103 0.0128 0 0 0 0 0 0.0   0.0 0.0 0.0   0.0 0.0 00.0

 4   5 1 1 1 0 0.01335 0.04211   0.0   0 0 0 0 0 0.0   0.0 0.0 0.0   0.0 0.0 00.0

 4   7 1 1 1 0 0.0   0.20912   0.0   0 0 0 0 0 0.978 0.0 0.0 0.0   0.0 0.0 00.0

 4   9 1 1 1 0 0.0   0.55618   0.0   0 0 0 0 0 0.969 0.0 0.0 0.0   0.0 0.0 00.0

```
  5   6  1 1 1 0  0.0      0.25202  0.0     0   0   0  0 0  0.932  0.0 0.0  0.0   0.0   0.0  0 0.0

  6  11  1 1 1 0  0.09498 0.19890  0.0     0   0   0  0 0  0.0    0.0 0.0  0.0   0.0   0.0  0 0.0

  6  12  1 1 1 0  0.12291 0.25581  0.0     0   0   0  0 0  0.0    0.0 0.0  0.0   0.0   0.0  0 0.0

  6  13  1 1 1 0  0.06615 0.13027  0.0     0   0   0  0 0  0.0    0.0 0.0  0.0   0.0   0.0  0 0.0

  7   8  1 1 1 0  0.0      0.17615  0.0     0   0   0  0 0  0.0    0.0 0.0  0.0   0.0   0.0  0 0.0

  7   9  1 1 1 0  0.0      0.11001  0.0     0   0   0  0 0  0.0    0.0 0.0  0.0   0.0   0.0  0 0.0

  9  10  1 1 1 0  0.03181 0.08450  0.0     0   0   0  0 0  0.0    0.0 0.0  0.0   0.0   0.0  0 0.0

  9  14  1 1 1 0  0.12711 0.27038  0.0     0   0   0  0 0  0.0    0.0 0.0  0.0   0.0   0.0  0 0.0

 10  11  1 1 1 0  0.08205 0.19207  0.0     0   0   0  0 0  0.0    0.0 0.0  0.0   0.0   0.0  0 0.0

 12  13  1 1 1 0  0.2209  0.19988  0.0     0   0   0  0 0  0.0    0.0 0.0  0.0   0.0   0.0  0 0.0

 13  14  1 1 1 0  0.1703  0.34802  0.0     0   0   0  0 0  0.0    0.0 0.0  0.0   0.0   0.0  0 0.0
-999
LOSS ZONES FOLLOWS                   1 ITEMS

 1  IEEE 14 BUS

-99

INTERCHANGE DATA  FOLLOWS          1 ITEMS

 1   2 Bus 2    HV   0.0  999.99 IEEE 14  IEEE 14 Bus  Test  Case

-9

TIE  LINES FOLLOWS                 0 ITEMS

-999

END OF DATA
```
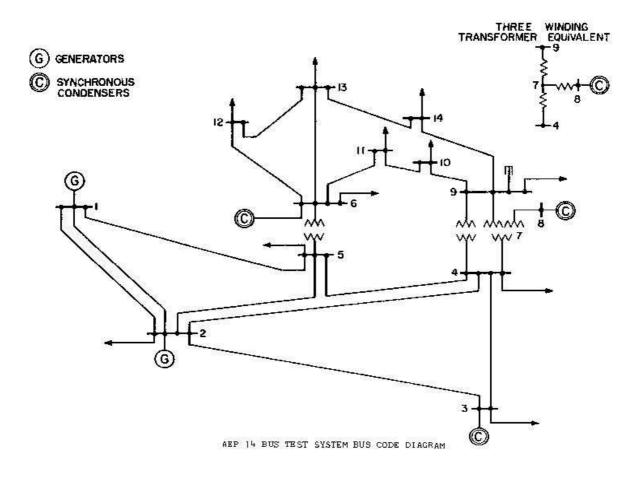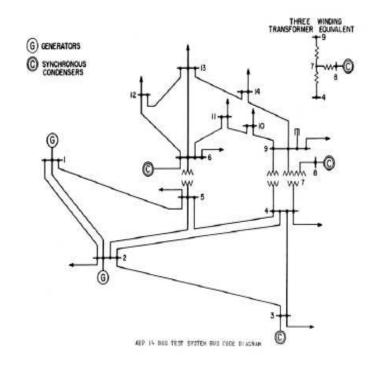
Figure A.1: IEEE 14-bus system diagram

GENERATORS
SYNCHRONOUS CONDENSERS

THREE WINDING TRANSFORMER EQUIVALENT

AEP 14 BUS TEST SYSTEM BUS CODE DIAGRAM

IEEE 14-bus Test System in IEEE Common Data Format [1]

```
08/19/93 UW ARCHIVE          100.0  1962 W IEEE 14 Bus Test Case
BUS DATA FOLLOWS                        14 ITEMS
   1 Bus 1    HV  1 1  3 1.060    0.0      0.0    0.0   232.4  -16.9   0.0  1.060     0.0     0.0  0.0    0.0    0
   2 Bus 2    HV  1 1  2 1.045   -4.98    21.7   12.7    40.0   42.4   0.0  1.045    50.0   -40.0  0.0    0.0    0
   3 BUS 3    HV  1 1  2 1.010  -12.72    94.2   19.0     0.0   23.4   0.0  1.010    40.0     0.0  0.0    0.0    0
   4 Bus 4    HV  1 1  0 1.019  -10.33    47.8   -3.9     0.0    0.0   0.0  0.0       0.0     0.0  0.0    0.0    0
   5 Bus 5    HV  1 1  0 1.020   -8.78     7.6    1.6     0.0    0.0   0.0  0.0       0.0     0.0  0.0    0.0    0
   6 Bus 6    LV  1 1  2 1.070  -14.22    11.2    7.5     0.0   12.2   0.0  1.070    24.0    -6.0  0.0    0.0    0
   7 Bus 7    ZV  1 1  0 1.062  -13.37     0.0    0.0     0.0    0.0   0.0  0.0       0.0     0.0  0.0    0.0    0
   8 Bus 8    TV  1 1  2 1.090  -13.36     0.0    0.0     0.0   17.4   0.0  1.090    24.0    -6.0  0.0    0.0    0
   9 Bus 9    LV  1 1  0 1.056  -14.94    29.5   16.6     0.0    0.0   0.0  0.0       0.0     0.0  0.0    0.19   0
  10 BUS 10   LV  1 1  0 1.051  -15.10     9.0    5.8     0.0    0.0   0.0  0.0       0.0     0.0  0.0    0.0    0
  11 Bus 11   LV  1 1  0 1.057  -14.79     3.5    1.8     0.0    0.0   0.0  0.0       0.0     0.0  0.0    0.0    0
  12 Bus 12   LV  1 1  0 1.055  -15.07     6.1    1.6     0.0    0.0   0.0  0.0       0.0     0.0  0.0    0.0    0
  13 Bus 13   LV  1 1  0 1.050  -15.16    13.5    5.8     0.0    0.0   0.0  0.0       0.0     0.0  0.0    0.0    0
  14 Bus 14   LV  1 1  0 1.036  -16.04    14.9    5.0     0.0    0.0   0.0  0.0       0.0     0.0  0.0    0.0    0
-999
BRANCH DATA FOLLOWS                     20 ITEMS
   1   2 1  1 1 0  0.01938  0.05917  0.0528  0  0  0  0 0  0.0     0.0 0.0    0.0    0.0    0.0    0.0
   1   5 1  1 1 0  0.05403  0.22304  0.0492  0  0  0  0 0  0.0     0.0 0.0    0.0    0.0    0.0    0.0
   2   3 1  1 1 0  0.04699  0.19797  0.0438  0  0  0  0 0  0.0     0.0 0.0    0.0    0.0    0.0    0.0
   2   4 1  1 1 0  0.05811  0.17632  0.0340  0  0  0  0 0  0.0     0.0 0.0    0.0    0.0    0.0    0.0
   2   5 1  1 1 0  0.05695  0.17388  0.0346  0  0  0  0 0  0.0     0.0 0.0    0.0    0.0    0.0    0.0
   3   4 1  1 1 0  0.06701  0.17103  0.0128  0  0  0  0 0  0.0     0.0 0.0    0.0    0.0    0.0    0.0
   4   5 1  1 1 0  0.01335  0.04211  0.0     0  0  0  0 0  0.0     0.0 0.0    0.0    0.0    0.0    0.0
   4   7 1  1 1 0  0.0      0.20912  0.0     0  0  0  0 0  0.978   0.0 0.0    0.0    0.0    0.0    0.0
   4   9 1  1 1 0  0.0      0.55618  0.0     0  0  0  0 0  0.969   0.0 0.0    0.0    0.0    0.0    0.0
   5   6 1  1 1 0  0.0      0.25202  0.0     0  0  0  0 0  0.932   0.0 0.0    0.0    0.0    0.0    0.0
   6  11 1  1 1 0  0.09498  0.19890  0.0     0  0  0  0 0  0.0     0.0 0.0    0.0    0.0    0.0    0.0
   6  12 1  1 1 0  0.12291  0.25581  0.0     0  0  0  0 0  0.0     0.0 0.0    0.0    0.0    0.0    0.0
   6  13 1  1 1 0  0.06615  0.13027  0.0     0  0  0  0 0  0.0     0.0 0.0    0.0    0.0    0.0    0.0
   7   8 1  1 1 0  0.0      0.17615  0.0     0  0  0  0 0  0.0     0.0 0.0    0.0    0.0    0.0    0.0
   7   9 1  1 1 0  0.0      0.11001  0.0     0  0  0  0 0  0.0     0.0 0.0    0.0    0.0    0.0    0.0
   9  10 1  1 1 0  0.03181  0.08450  0.0     0  0  0  0 0  0.0     0.0 0.0    0.0    0.0    0.0    0.0
   9  14 1  1 1 0  0.12711  0.27038  0.0     0  0  0  0 0  0.0     0.0 0.0    0.0    0.0    0.0    0.0
  10  11 1  1 1 0  0.08205  0.19207  0.0     0  0  0  0 0  0.0     0.0 0.0    0.0    0.0    0.0    0.0
  12  13 1  1 1 0  0.22092  0.19988  0.0     0  0  0  0 0  0.0     0.0 0.0    0.0    0.0    0.0    0.0
  13  14 1  1 1 0  0.17093  0.34802  0.0     0  0  0  0 0  0.0     0.0 0.0    0.0    0.0    0.0    0.0
-999
LOSS ZONES FOLLOWS                      1 ITEMS
   1 IEEE 14 BUS
-99
INTERCHANGE DATA FOLLOWS                1 ITEMS
   1   2 Bus 2    HV   0.0  999.99  IEEE14  IEEE 14 Bus Test Case
-9
TIE LINES FOLLOWS                       0 ITEMS
-999
END OF DATA
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