A NEW APPROACH FOR CALCULATING TRANSMISSION RELIABILITY MARGIN

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Dedicated to my beloved parents

ABSTRACT

The basic function of an electric power system is to satisfy the system load requirements as economically as possible and with a reasonable assurance of continuity and quality. Therefore, it is essential to maintain the reliability of the electric grid under all situations. Reliability is a time varying function. It is the probability of a system performing its purpose adequately for the period intended under the operating conditions encountered. Under specified system conditions, how reliably power can be transferred from one network zone to another through all the network transmission lines which interconnect the electric systems is known as transfer capability. During any occurrence of uncertainties such as: change in load, line impedances, voltage magnitudes, customer demands etc. in the network, power transfer can't be ceased, so to transfer power productively during these unpredictable condition one needs to enumerate transmission reliability margin (TRM). Available transfer capability (ATC) is the additional amount of power that may flow across the interface. It can also become a useful indicator for the operator to indicate the amount by which the inter area power transfers can be increased without jeopardizing system security. To ensure effective power transfer over the transmission lines during the occurrence of uncertainties an accurate estimation of TRM is required. In this work, a new technique has been proposed for calculating TRM by using AC, DC, and DCQ load flow method considering sensitivity to load, line admittances and voltage parameter. The TRM estimation is incorporated with the ATC since when the amount of power transfer is increased in the transmission network it needs to estimate that the system would be secured under a reasonable range of uncertainty. The proposed technique is used for IEEE 6 bus test system and is done for Normal distribution. The results are compared with previous results for validation.

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LIST OF SYMBOLS

Symbols	Description
B_{ij}	Susceptance of a line *i-j*
G_{ij}	Conductance of a line *i-j*
P_{ij}	Real power flow through a transmission line *i-j*
Q_{ij}	Reactive power flow through a transmission line *i-j*
S_{ij}	Apparent power flow through a transmission line *i-j*
U	A certain number which is calculated from probability by consulting tables of the cumulative distribution function of a normal random variable
v_i; v_j	Voltage magnitude for bus *i* and for bus *j* respectively
υ^2	Variance the uncertainty of a parameter
Y_{bus}	Bus Admittance Matrix
δ_i;δ_j	Voltage angle for *i* bus and for *j* bus respectively
ΔP_{ij}	Real power change in a transmission line quantity
ΔQ_{ij}	Reactive Power Real power change in a transmission line quantity
ΔP_{mn}	Real power transaction between a seller and buyer bus
ΔQ_{mn}	Reactive power transaction between a seller and buyer bus

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LIST OF ABBREVIATIONS

Abbreviations	**Description**
ATC	Available Transfer Capability
ATCV	Available Transfer Capability for Voltage
ATCY	Available Transfer Capability for line admittances
ATCQ	Available Transfer Capability for Reactive power
ACPTDFs	AC Power transfer distribution factors
DCPTDFs	DC Power transfer distribution factors
DCQTDFs	DC Reactive power transfer distribution factors
PTDFs	Power transfer distribution factors
QACPTDFs	AC Reactive power transfer distribution factors
S.D.	Standard Deviation
S.D. S.	Standard Deviation of Sensitivity
TRM	Transmission Reliability Margin

CHAPTER 1

INTRODUCTION

1.1 Introduction

The electric power system consists of complex interconnected network which are prone to different problems that militates against the reliability of the power system [1]. Lines are operated at high voltage and can transmit large quantities of electrical power over long distances. As consumer demands increase the whole electric energy transmission system becomes complex. Inadequate reliability in the power system causes problems such as high failure rate of power system installations and consumer equipment, transient and intransient faults, symmetrical faults etc. To run this complex system securely under a reasonable range of uncertainty, determination of transmission reliability margin (TRM) should incorporate with the available transfer capability (ATC). The transmission reliability margin (TRM) take care of the uncertain parameters which are connected with the transmission system. The definition of TRM is: "The amount of transmission capability which is essential to make sure that the cascaded transmission web is secure under a reasonable range of unpredictability in system conditions." In this work a new approach uses to compute TRM considering uncertainty system parameters such as transmission line impedances, bus voltage magnitudes and load.

1.2 Thesis Motivations

Reliability is a time-variant function, which means it is always varying with time. The prove of a reliable system is that the system should able to perform decently under the desired conditions over specified period [1-3]. Transmission Reliability Margin (TRM) is not notably used for the shipment of energy; it is retained as a reliability margin to echo the unpredictability of the operation of an electric system. Therefore, to ensure effective power transfer over the transmission lines during the occurrence of uncertainties an accurate estimation of transmission reliability margin (TRM) is required. The bootstrap technique has used for estimating TRM for the uncertainties of line outages and system parameters. Besides, for computing TRM some methods incorporate available transfer capability (ATC) with it [4-8]. A time saving method, Stochastic Response Surface Method (SRSM) is used to determine TRM besides, it used polynomial chaos expansion (PCE) with standard random variables (SRVs) and then create the probability distributions of the system response. TRM can calculate by statistical methods [9-10].

For better transmission systems, one of the crucial points is to gauge the transfer capability for multi-transaction in a deregulated power system environment, which is known as ATC. ATC is a measure of the transfer capability remaining in the physical transmission network for further commercial activity over and above the base case flows. ATC is estimated by considering the outages of critical transmission line and critical generator unit and the TRM. For computation ATC, ACPTDF based approach has been proposed for multi-transaction cases using power transfer sensitivity and Jacobian calculated with three different methods as well as for contingency analysis and in combined with economic emission dispatch (CEED) environment [11-16]. Several methods for ATC determination are discussed for single as well as for multi-transactions [17-24].

In previous work, TRM determination corporate with the transfer capability, in some work it also accommodates with ATC but every method is complex, time consuming and using for a particular confidence interval. In this work, three methods are discussed for calculating TRM incorporating ATC and its very flexible. Those three methods can apply for any bus system as well as for any standard and practical data. Besides, ATC determination for AC load flow is only done for real power using ACPTDFs but in this research work both real and reactive power is considered using SPTDFs.

Uncertainty in each transfer capability known as sensitivity and can compute for a wide range of parameters for DC/AC load flow; described a novel approach of application of sensitivity analysis with ATC determination. Illustrates the use of loading margin sensitivities for the avoidance of voltage collapse. Many system models have been described for online computation of voltage collapse sensitivity indices. Margin sensitivity is useful in determining the effectiveness of different parameters for enhancing system loading margin [25-30]. Other methods for calculating sensitivity considered distinct parameters are also explained [31-33].

Most of the previous methods only transfer capability is considered to determine sensitivity but during ATC, sensitivity is also crucial to compute. Besides, sensitivity calculation for line impedances did not explain explicitly. In this work, sensitivity is calculated for ATC considered three distinct parameters such as: system load, voltage magnitudes and transmission line impedances.

ATC is determined by DC load flow for active power only considered DCPTDFs. DC power flow method considered for active power flow rather than reactive power but in a transmission network voltage level needs to keep stable otherwise over-voltage or voltage collapse will happen easily; for this reason, VAR is essential to control the system in a tolerable margin of security and authenticity. A DCQF model is developed with a proposed iterative QF model for compensating of pure VAR market, ATC also calculated for reactive power [34-38]. Shapley approach of cooperative game theory is used for transmission usage cost allocation [39]. To maximize total transfer capability in Central-East-Europe power system, investigates the use of specific FACTS devices and WAMS systems [40]. A configuration is investigated to control the voltage drop across the line by controlling the reactive power flow in the radial line [41]. An integrated approach of geographically production, demand and modelling of the grid for large-area power systems [42]. Improvement in losses estimation and ATC calculation, considering dynamic transmission lines rating, instead of static rating need to improve which is discussed in this paper [43]. Developed a model a physical power flows and the congestion management techniques that control them [44]. In paper [45-46], a bi-level optimization framework is formulated for the evaluation of ATC as well as a review on ATC calculation. presents a probabilistic-based approach for available transfer capability (ATC) assessment. An algorithm is developed to determine ATC for generating group of future wind generation scenarios [47]. Design a probabilistic available transfer capability (PATC) model considered uncertainties and static security constraints [48].

In previous work, DC load flow method is considered to determine ATC is determined by DC load flow considered only real power after that reactive power is also considered for this computation but in this research two modified method is applied for ATC determination one is: modified DC load flow and the other one is DCQ load flow (this one is for reactive power). It’s called modified because through this process sensitivity of ATC w.r.t each system parameter is calculated and finally incorporate the sensitivity and ATC value to determine TRM; for DC load flow system load and transmission line impedance and for DCQ load flow bus voltage magnitudes are considered as system parameter to compute the sensitivity.

1.3 Literature Review

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. As a measure bridging the technical characteristics of how interconnected transmission networks perform to the commercial requirements associated with transmission service requests, ATC must satisfy certain principles balancing both technical and commercial issues. Couple of principles identify the requirements for the calculation and application of ATCs.

Transmission corridor remains the same for transferring the power, but competition arises both in generation and distribution. Due to increase in the number of transactions cause congestion in transmission network. To avoid congestion, one needs to know the value of ATC before every transaction and for that need to know the methods to calculate it [3,11,20].

ATC calculation is based on sensitivity factors, using AC power transfer distribution factors (ACPTDFs) and DC power transfer distribution factors (DCPTDFs). Power transfer distribution factor (PTDF) method is used by many utilities for determination of ATC. In these methods, AC or DC load flow is used to calculate the change in power flow for the respective change in a transaction. In [36] the ATC is calculated using DCPTDFs for multiple line contingencies and an extra generator addition are considered and their effect on the value of ATC. The methodology is applied on IEEE 30-bus test system. DC power flow method is based on DC power transfer distribution factors [16]. This method considers only the real power flow. In a transmission line real and reactive power both flows that's why we need AC power flow method; it gives an accurate estimate of ATC values [19].

Reference [12], explain concepts and calculations of transfer capability and describe applications of transfer capability.

In [13,21], ACPTDF based approach has been proposed for multi-transaction cases using power transfer sensitivity and Jacobian calculated with three different methods. In [15], the ACPTDFs proposed for the calculation of ATC were used to find various transmission system quantities for a change in MW transaction at different operating conditions. Various deterministic methods applied in [22], to reduced Indian Northern Region Power Grid 246-bus power system to compute Available Transfer Capability

(ATC) calculation. DCPTDF, optimal power flow methods are used as well as another method known as repeated AC power flow is used for computation ATC.

Assessment of ATC using ACPTDFs in combined economic emission dispatch (CEED) environment is described in [16]. The ACPTDFs are derived using sensitivity-based approach for the system intact case and utilized to check the line flow limits during ATC determination. In [23] simultaneous bilateral and multilateral wheeling transactions have been carried out on IEEE 6, 30 and 118 bus systems for the assessment of ATC. Reference [24] presents comprehensive study and calculation of ATC on Bangladesh Power System Network. The method being proposed in [26] claims to have two important advantages over the conventional method of ATC determination which uses AC load flow methods. Reference [37] presents a DCQF model which can be built into a DCQF model for market clearing and settlement of pure Q market.

The computation of Available Transfer Capability (ATC) has been performed using an active power linear model, which totally neglects the voltage-reactive power phenomena, as well as other operational issues and security constraints. This drawback in current ATC computations has motivated the definition of the Transmission Reliability Margin (TRM), as a way to take into consideration all uncertainties about the network and all possible computational errors due to model simplifications or wrong data. Reference [38] presents some initial concepts on including reactive power in linear methods for computing ATC. It proposes a new approach that first determines the reactive power flows using the exact circle equation for the transmission line complex flow, and then determines ATC using active power distribution factors.

Transfer capability indicates how much a bulk power transfer can be changed without compromising system security under a specific set of assumptions. In [25], a computationally efficient formula for the first order sensitivity of the transfer capability with respect to the variation of any parameters is presented. Reference [27], showed how efficiently compute security margins defined by limiting events and instabilities and the sensitivity of those margin with respect to system parameter. References [28], proposes the use of trajectory sensitivities to complement time domain analysis of power system dynamics and showed how to compute linear and quadratic estimates to the variation of the loading margin with respect to any power system parameter or control respectively.

Model parameters exerting the most influence on model results are identified through a sensitivity analysis. A comprehensive review [31] is presented of more than a dozen sensitivity analysis methods.

In [32], a continuation method to compute transfer capability and the quick estimates are derived from transfer capability sensitivity formulas is used. The case study illustrates the use of these sensitivities to estimate the effect on the transfer capability of changes in parameters. An application of the Global sensitivity analysis (GSA) method in evaluating performance of impedance measurement [33]. Besides, a straight forward method has described in [26]. The determination of ATC must accommodate a reasonable range of transmission reliability margin (TRM) so that the transmission network is secure from uncertainty of transfer capability that may occur during a power transfer. In [7], presents a computationally accurate method in determining the TRM with large amount of transfer capability uncertainty using the parametric bootstrap technique.

Reference [6] proposes and evaluates several different approaches to the calculation of TRM. The TRM is supposed to account for uncertainty in the operating conditions used in computing Total Transfer Capability (TTC). This uncertainty may be in model parameters (line impedances), load forecast error (P and Q), or other “base case” data. In planning the reliability of the power system, the reliability improvement should be considered [3]. Reference [5], presents a new method that used to estimate the TRM by considering the uncertainties of transmission line outages and system parameters determined by using the bootstrap technique. TRM is determined considering thermal, voltage, stability limits simultaneously [10]. Paper [9] presents a fast assessment method of TRM using stochastic response surface method (SRSM). Wenyuan Li has proposed a method using two-point estimate method for assessing the transmission uncertainties in TTC. Here the standard deviation of TTC is used to estimate TRM [20]. J Zhang has suggested a method for determining the TRM based on sensitivity factors affecting the transfer capabilities and uncertainties probabilistically. The independent time series is derived of each of the uncertainty by determining their probability distributions [19]. All the studies conducted on calculation of TRM, ATC and Sensitivity for a power network system is based on distinct method. Many studies show the estimation method of ATC but only for real power. In transmission line reactive power also flow so real and reactive or if we say apparent power is needed to be considered in the ATC calculation. Besides, sensitivity in a power system must be considered in the calculation; these uncertainties happens on different system parameters such as load, generation dispatch, line impedances, voltage levels etc. We need a clear step by step method to get those results because we know that ATC is the additional amount of power that may flow across the interface without jeopardizing system security. So, how can we flow some extra amount of power with the consideration of uncertainty that's not clearly indicate in any study. In this work a formula is used for sensitivity estimation by using the ATC values considered all those system parameters like: Load, Voltage level and Line impedances. Besides, most of the study have showed the TRM calculation considered the sensitivity factors, discussing the ATC as a term in the paper but an ambiguity is showed that how these three terms are connected. A formula is used to calculate the TRM only for real power, but other factors need to be considered. Finally, an appropriate step by step technique has been shown for TRM calculation by using the ATC and sensitivity values; considering the system parameters discussed above.

Shapley approach of cooperative game theory is used for transmission usage cost allocation [39]. To maximize total transfer capability in Central-East-Europe power system, investigates the use of specific FACTS devices and WAMS systems [40]. A configuration is investigated to control the voltage drop across the line by controlling the reactive power flow in the radial line [41]. An integrated approach of geographically production, demand and modelling of the grid for large-area power systems [42]. Improvement in losses estimation and ATC calculation, considering dynamic transmission lines rating, instead of static rating need to improve which is discussed in this paper [43]. Developed a model a physical power flows and the congestion management techniques that control them [44]. In paper [45-46], a bi-level optimization framework is formulated for the evaluation of ATC as well as a review on ATC calculation. presents a probabilistic-based approach for available transfer capability (ATC) assessment. An algorithm is developed to determine ATC for generating group of future wind generation scenarios [47]. Design a probabilistic available transfer capability (PATC) model considered uncertainties and static security constraints [48].

1.4 Thesis Objectives

Most of the proposed techniques for determining TRM ignored the reactive power. Besides, sensitivity is considered only for loads not for voltage and line impedances. These issues need to be addressed for ATC and TRM computation. For this reason, the objective of this thesis is the development of estimating TRM:

a. To determine ATC by AC and DC load flow.
b. To estimate sensitivity for both load and voltage level changes.
c. To develop a technique for calculating transmission reliability margin of a power system network.

1.5 Thesis Organization

There are five chapters in this thesis and a brief description of all the chapters was presented below.

Chapter 2 presents an elaborate description on thedetermination of ATC by using AC load flow method for considering sensitivity to load, voltage and transmission line impedances. For load and transmission line impedances SPTDFs (Apparent Power Transfer Distribution Factors) and for voltage limits violation Voltage Distribution factors (VDFs) used respectively obtained for two distinct Jacobian approaches (full & Decoupled).

Chapter 3 deals with the estimation of sensitivity of available transfer capability is described elaborately, considered each of the system parameter (load, voltage and line impedances).

Chapter 4 discusses the proposed technique of TRM determination and the validation of the results as well.

C**hapter 5** summarizes the achievement and findings of the research work and gives recommendations for the scope of future research works that can be carried out.

1.6 Chapter Summary

This chapter has identified the necessity of determining TRM as well as the significance of accommodating ATC with the TRM during power transfer. Moreover, the sensitivity is discussed only for transfer capability in previous work; in here sensitivity of ATC is discussed and the calculation is also shown in this book.

CHAPTER 2
TRM CALCULATINION BY AC LOAD FLOW METHOD

2.1 Introduction

In this chapter the determination of TRM is done for AC load flow. Available transfer capability can be stated accurately and effectively by exact determination of TRM (transmission reliability margin) as it comprises of all the uncertainties affecting the system. The different uncertainties considered for estimations of TRM are planned, unplanned outages, variations in load, bus voltage magnitudes variation and transmission line impedances variations. TRM can be defined as the marginal amount of transmission corridor set aside for reliable operation of transmission system. Mathematically, TRM can be given as:

$$TRM = TTC - ATC - (CBM + EC) \tag{2.1}$$

Total transfer capability (TTC), Available Transfer capability (ATC), Capacity Benefit Margin (CBM), Existing Transmission Commitments (EC) need to calculate TRM.

Computation of transfer capability over a one-week period may require analysis for many different load patterns, generation commitments, and source and sink assumptions. Calculations of ATC, CBM, and TRM typically require that the transfer margin computation be repeated for multiple combinations of transfer directions, base case conditions, and contingencies.

To determine transfer capability in proper way some steps need to follow which are also known as basic steps. The basic process involves the following steps:

a. Establish initial assumptions appropriate to time of study
b. Compute transfer capability for base assumptions and Demands
c. Determine or apply systematic changes to assumptions
d. Recomputed transfer capability, Economic dispatch and network topology (outages)
e. Facility ratings. Generator commitment and dispatch and Source, sink, and loss

In this proposed technique standard 6 bus system; the whole process of calculating TRM by AC load flow for IEEE-6 bus system is discussed below:

2.2 Test System Database

According to the objective of this thesis, to be able to determine the reliability of the transmission power system network for IEEE-6 bus system, we need to get a complete network database first. So, collected detailed database from standard IEEE-6 test bus system. According to the database, we have got the following major components:

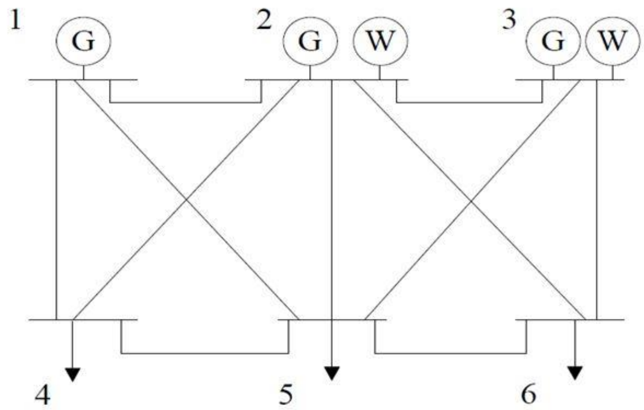

Fig. 2.1: IEEE 6- bus system for AC Load Flow [34]

In Table- 2.1, the bus data is given for the six bus system where the first bus is the slack bus, second and third buses are the generator buses besides, buses 4, 5 and 6 are the load buses. Moreover, real power generation for PV buses are 50 and 60 MW, respectively. For each load bus power is 70 MW. The voltage magnitude for slack bus is 1.05 p.u , PV 2 and PV 3 buses are 1.05 and 1.07, respectively. All PQ buses are 1 p.u.

Table 2.1: Bus Data for AC Load Flow

Bus No.	Bus Type	Voltage magnitude (p.u)	Real power generation (MW)	Real power load (MW)	Reactive power load (MVAR)
1	SB	1.05	0	0	0
2	PV	1.05	50	0	0
3	PV	1.07	60	0	0
4	PQ	1	-	70	70
5	PQ	1	-	70	70
6	PQ	1	-	70	70

In Table-2.2, branch data is represented for 6-bus system for the thirteen lines; resistance, reactance and line charging susceptance values are given for each line as well as the maximum apparent power (MVA) capacity.

Table 2.2: Branch Data for AC Load Flow

Line No.	Bus No. From-To	Resistance (p.u)	Reactance (p.u)	Total line charging susceptance (p.u)	Maximum Apparent power capacity (MVA)
1	1-2	0.1	0.2	0.04	40
2	1-4	0.05	0.2	0.04	60
3	1-5	0.08	0.3	0.06	40
4	1-6	0.17	0.4	0.06	130
5	2-3	0.05	0.25	0.06	40
6	2-4	0.05	0.1	0.02	80
7	2-5	0.1	0.3	0.04	30
8	2-6	0.07	0.2	0.05	90
9	3-4	0.1	0.35	0.05	120
10	3-5	0.12	0.26	0.05	70
11	3-6	0.02	0.1	0.02	90
12	4-5	0.2	0.4	0.08	20
13	5-6	0.1	0.3	0.06	40

In figure 2.1 there are no connection between bus 1 to bus 6 and bus 3 bus 4 so, to transfer power from bus 1 to bus 6, we need to sum line resistance, reactance and MVA flow of bus 1 to bus 2 and bus 2 to bus 6 as well as from bus 3 to bus 4, sum line resistance, reactance and MVA flow of bus 2 to bus 3 and bus 2 to bus 4. TRM has been obtained for different transactions taken as multi-transactions. Table 2.3 shows the transactions considered in this work.

Table 2.3: Transactions Considered for AC Load Flow

SL. No.	Transactions ID	Seller Bus	Buyer Bus
1	T1	1	4
2	T2	1	5
3	T3	1	6
4	T4	2	4
5	T5	2	5
6	T6	2	6
7	T7	3	4
8	T8	3	5
9	T9	3	6

2.3 ATC Determination Using AC Load Flow

AC load flow in any power system deals with the determination of bus voltages magnitudes, phase angles, active and reactive power which is crucial to determine ATC.

2.3.1 ATC determination considering variation load and line impedances

In any power system network power must be injected into the system at a point by generator (seller bus) and must be extracted by a load (buyer bus) at another point which is called a transaction.

From the power transfer point of view, an operation is a specific amount of power that is injected into the system at one bus by a generator and drawn at another bus by a load. The coefficient of linear association between the amount of a transaction and flow on a line is represented by PTDF. It is also called sensitivity because it relates the amount of one change – transaction amount – to another change – line power flow. When PTDFs are calculated using AC load flow, it is called ACPTDFs; when calculated using DC load flow it is called DCPTDFs. For a transaction among the buyer and seller buses, ΔP_{mn}, if the change in the transmission line quantity is ΔP_{ij}, the power transfer distribution factors can be defined as,

$$ACPTDFs = \frac{\Delta P_{ij}}{\Delta P_{mn}} \tag{2.2}$$

$$QACPTDFs = \frac{\Delta Q_{ij}}{\Delta Q_{mn}} \tag{2.3}$$

$$SPTDFs = \sqrt{ACPTDFs^2 + QACPTDFs^2} \tag{2.4}$$

To obtain SPTDFs for calculating ATC for both full and decoupled Jacobian approaches needed to follow the following steps.

Full Jacobian based approach:

The determination of ATC for AC load flow considered Jacobian approach are described step by step below:

a. Run the N-R load flow to get update voltage and angle values for each bus in the system.

b. Calculate the bus admittance matrix (Y_{bus}) using those update voltage and angle magnitudes.

$$Y_{bus} = \begin{bmatrix} Y_{12}+Y_{14}+Y_{15} & -Y_{12} & 0 & -Y_{14} & -Y_{15} & 0 \\ -Y_{12} & Y_{23}+Y_{24}+Y_{25}+Y_{26} & -Y_{23} & -Y_{24} & -Y_{25} & -Y_{26} \\ 0 & -Y_{32} & Y_{32}+Y_{35}+Y_{36} & 0 & -Y_{35} & -Y_{36} \\ -Y_{41} & -Y_{42} & 0 & Y_{41}+Y_{42}+Y_{45} & -Y_{45} & 0 \\ -Y_{51} & -Y_{52} & -Y_{53} & -Y_{54} & Y_{51}+Y_{52}+Y_{53}+Y_{54}+Y_{56} & -Y_{56} \\ 0 & -Y_{62} & -Y_{63} & 0 & -Y_{56} & Y_{62}+Y_{63}+Y_{65} \end{bmatrix} \quad (2.5)$$

c. For SPTDF calculation, the power flow sensitivity and Jacobian of power injection equations is required. The Jacobian can be calculated using N-R load flow-based approach. The power flow equation for both real & reactive power between two buses are:

$$P_{ij} = V_i^2 G_{ij} - V_i V_j (G_{ij} \cos\delta_i + B_{ij} \sin\delta_{ij}) \quad (2.6)$$

$$Q_{ij} = -V_i^2 B_{ij} - V_i V_j (G_{ij} \sin\delta_i - B_{ij} \cos\delta_{ij}) \quad (2.7)$$

$$S_{ij} = \sqrt{P_{ij}^2 + Q_{ij}^2} \quad (2.8)$$

where, V_i and V_j are the bus voltage magnitudes, δ_{ij} is the voltage angle; both voltage magnitudes and angles used from the first step. G_{ij} and B_{ij} are the real and imaginary part of Y_{bus} matrix.

d. Calculate Jacobian matrix using new updated voltage and angle magnitudes from first step.

$$J = \begin{bmatrix} J1 & J2 \\ J3 & J4 \end{bmatrix} \quad (2.9)$$

where, $J1 = \frac{\partial P}{\partial \delta}; \quad J2 = \frac{\partial P}{\partial V}; \quad J3 = \frac{\partial Q}{\partial \delta}; \quad J4 = \frac{\partial Q}{\partial V}$

e. The sensitivity of real and reactive power flow equation can be written in a matrix form as shown below:

$$\Delta P_{ij} = [\frac{\partial P_{ij}}{\partial \delta_2},,,,,\frac{\partial P_{ij}}{\partial \delta_n}\frac{\partial P_{ij}}{\partial V_2},,,,,,\frac{\partial P_{ij}}{\partial V_n}] \quad (2.10)$$

$$\Delta Q_{ij} = [\frac{\partial Q_{ij}}{\partial \delta_2},,,,,\frac{\partial Q_{ij}}{\partial \delta_n}\frac{\partial Q_{ij}}{\partial V_2},,,,,,\frac{\partial Q_{ij}}{\partial V_n}] \quad (2.11)$$

where, n = total no. of buses; start from δ_2 and V_2 because assume bus no. one is the reference bus.

$$\frac{\partial P_{ij}}{\partial \delta_i} = V_i V_j Y_{ij} \sin(\theta_{ij} + \delta_j - \delta_i) \tag{2.12}$$

$$\frac{\partial P_{ij}}{\partial \delta_j} = -V_i V_j Y_{ij} \sin(\theta_{ij} + \delta_j - \delta_i) \tag{2.13}$$

$$\frac{\partial P_{ij}}{\partial V_i} = V_j Y_{ij} \cos(\theta_{ij} + \delta_j - \delta_i) - 2V_i Y_{ij} \cos\theta_{ij} \tag{2.14}$$

$$\frac{\partial P_{ij}}{\partial V_j} = V_i Y_{ij} \cos(\theta_{ij} + \delta_j - \delta_i) \tag{2.15}$$

$$\frac{\partial Q_{ij}}{\partial \delta_i} = V_i V_j Y_{ij} \cos(\theta_{ij} + \delta_j - \delta_i) \tag{2.16}$$

$$\frac{\partial Q_{ij}}{\partial \delta_j} = -V_i V_j Y_{ij} \cos(\theta_{ij} + \delta_j - \delta_i) \tag{2.17}$$

$$\frac{\partial Q_{ij}}{\partial V_i} = -V_j Y_{ij} \sin(\theta_{ij} + \delta_j - \delta_i) - 2V_i Y_{ij} \sin\theta_{ij} \tag{2.18}$$

$$\frac{\partial Q_{ij}}{\partial V_j} = -V_i Y_{ij} \sin(\theta_{ij} + \delta_j - \delta_i) \tag{2.19}$$

For a transaction among the buyer and seller buses by ΔP_{mn}, if the change in the transmission line quantity is ΔP_{ij}, the AC power transfer distribution factors can be defined as,

$$ACPTDFs = \frac{\Delta P_{ij}}{\Delta P_{mn}} \tag{2.20}$$

$$QACPTDFs = \frac{\Delta Q_{ij}}{\Delta Q_{mn}} \tag{2.21}$$

Now, Q/ACPTDFs for any transaction between a seller (*k*) and buyer *(l)* bus, for a transmission line between two buses *i* and *j* can be represented as:

$$ACPTDFs_{ij,kl} = \Delta P_{ij}[J^{-1}]\begin{bmatrix} \\ 0 \\ \vdots \\ +P_t \\ 0 \\ \vdots \\ -P_t \\ 0 \end{bmatrix} \quad (2.22)$$

$$QACPTDFs_{ij,kl} = \Delta Q_{ij}[J^{-1}]\begin{bmatrix} \\ 0 \\ \vdots \\ +Q_t \\ 0 \\ \vdots \\ -Q_t \\ 0 \end{bmatrix} \quad (2.23)$$

$P_t =$ Transacted Power = Q_t

$$SPTDFs = \sqrt{ACPTDFs^2 + QACPTDFs^2} \quad (2.24)$$

ATC for a transaction was:

$$ATC_{kl} = ATCY_{kl} = \min\left(\frac{LL_{\max} - S_{ij}}{SPTDFs_{ij,kl}}\right) \quad (2.25)$$

where, LL_{max}= maximum power flow limit through a line *i-j*. Needed to pick minimum value of ATC of each transaction.

Decoupled Jacobian based approach:

For decoupled based approach only J1 and J4 matrices are used in equations (2.22) and (2.23) respectively:

In N-R load flow new update angle and voltage magnitudes has obtained from the following equation:

$$[\Delta\delta] = [J1^{-1}][\Delta P] \quad (2.26)$$

$$[\Delta V] = [J4^{-1}][\Delta Q] \quad (2.27)$$

Using these update values to calculate:

$$J1 = \frac{\partial P}{\partial \delta} \quad (2.28)$$

$$J4 = \frac{\partial Q}{\partial V} \quad (2.29)$$

Then equation (4) to (7) can be written as:

$$\Delta P_{ij} = [\frac{\partial P_{ij}}{\partial \delta_2}, \ldots\ldots., \frac{\partial P_{ij}}{\partial \delta_{12}}] \quad (2.30)$$

$$\Delta Q_{ij} = [\frac{\partial Q_{ij}}{\partial V_2}, \ldots\ldots., \frac{\partial Q_{ij}}{\partial V_{12}}] \quad (2.31)$$

$$ACPTDFs_{ij,kl} = \Delta P_{ij}[J1^{-1}]\begin{bmatrix} \\ 0 \\ \vdots \\ +P_t \\ 0 \\ \vdots \\ -P_t \\ 0 \end{bmatrix} \quad (2.32)$$

$$QACPTDFs_{ij,kl} = \Delta Q_{ij}[J4^{-1}]\begin{bmatrix} \\ 0 \\ \vdots \\ +Q_t \\ 0 \\ \vdots \\ -Q_t \\ 0 \end{bmatrix} \quad (2.33)$$

$$SPTDFs = \sqrt{ACPTDFs^2 + QACPTDFs^2} \quad (2.34)$$

ATC for a transaction is:

$$ATC_{kl} = ATCY_{kl} = \min\left(\frac{LL_{\max} - S_{ij}}{SPTDFs_{ij,kl}}\right) \tag{2.35}$$

where, $LL_{\max}$ = maximum power flow limit through a line *i-j;* for this calculation ***150*** was assumed. Needed to pick minimum value of ATC of each transaction.

2.3.2 ATC determination considering voltage variation (ATCV)

During a transfer capability calculation, many assumptions may arise that would affect the outcome. The main assumptions used in this study are as follows:

a. The base case power flow of the system is feasible and corresponds to a stable operating point.

b. The load and generation are changing very slowly so that the system transient stability is not jeopardized.

c. The system steady state stability is maintained with enough damping.

d. Bus voltage limits are maintained before the system loses voltage stability.

Therefore, at this stage only the thermal limits and voltage limits will be taken into consideration together with generator active and reactive power limits.

To consider voltage limits in ATC determination under the normal cases Voltage Distribution Factors (VDFs) are used. VDFs are defined as the change in the bus voltage magnitude at any bus to the change in a transaction between seller bus and the buyer bus. Only the voltage magnitude is considered.

a. Run N-R load flow to calculate the new voltage magnitude ($V_{m.kl}$)for each bus 'm' and for each transaction (Δkl) between a seller and buyer bus. The VDF is:

$$VDFs_{m,kl} = \frac{\Delta V_m}{\Delta kl} \tag{2.36}$$

where, $\Delta V_m = V_{m,kl} - V_m^0$

V_m^0 = base case voltage magnitudes for each bus '*m*'

$V_{m,kl}$ = new voltage magnitudes for each bus '*m*' for a transaction

b. Estimate ATC considering bus voltage magnitude:

$$ATCV_{kl} = \min\left(\frac{V_{m,kl} - V_{\min}^{m}}{VDFs_{m,kl}}\right) \quad (2.37)$$

where, $V_{\min}^{m}$ = minimum voltage limit at bus '*m*'. Needed to pick minimum value of ATC of each transaction.

2.4 Sensitivity Calculation for AC Load Flow

Sensitivity is defined as the changes in dependent variable with the change in independent variable such as: the ratio of ΔATC/Δ*X* relating slight changes in ΔATC to small changes in Δ*X* of some controllable variable *X*. Here, *X* are the parameters which are considered to calculate the Sensitivity. First one is load variation, second one is bus voltage magnitudes and the third one is line impedances. Sensitivity is calculated for ATC with respect to all these parameters.

Load variation:

Let us assume that *S* is the apparent power consumed at any load bus. Suppose that at the base case, the real power *S* consumed at that load bus is *G* MW and that the available transfer capability *ATC* at this base case is *g* MW. We are interested in how much *ATC* varies from *g* MW when that load bus *S* is changed from *G* MW. We can write Δ*ATC*= A*TC*−*g* and Δ*S* = *S*−*G*, so that we will be interested in how much *ΔATC* varies when Δ*S* is changed. *ATC* is a function of *S*. The sensitivity of *ATC* with respect to *s* is the derivative of *ATC* with respect to *S*: Sensitivity of *ATC* with respect to *S* = *d(ATC)/dS***.** It follows from calculus that if Δ*S* is small, then it is approximately true that and the approximations become exact as Δ*S* becomes vanishingly small. That is, if *S* increases by *G* MW, then *ATC* decreases by *g* MW.

This thesis work increased load by 30 MW for a load bus; the sensitivity of *ATC* (available transfer capability) with respect to *S* (apparent power) ($\frac{dATC}{dS}$) can be written as:

$$(ATC_{new} - ATC_{old}) = \frac{dATC}{dS}(S_{new} - S_{old}) \quad (2.38)$$

where, ATC_{new} and ATC_{old} are calculated from equation (9) for each transaction. ATC_{new} can be calculated after the load changed.

Voltage magnitudes variation:

The limitation on power system performance that we consider in this work is the bus voltage magnitudes. This limit can be handled in an AC load flow power system model. In section- 3.3.2 the whole process of calculating $ATCV$ by varying voltage is described. To calculate sensitivity of ATC with respect to bus voltage magnitude; need to increase the voltage level 5% from its rated value and recalculate $ATCV_{new}$; so the sensitivity of ATC with respect to V, ($\frac{dATC}{dV}$) can be written as:

$$(ATCV_{new} - ATCV_{old}) = \frac{dATC}{dV}(V_{new} - V_{old}) \quad (2.39)$$

Line Impedances variation:

It may be useful to further investigate analytical sensitivities of distribution factors to small changes in reactance’s for computing a TRM to account for model error. In this work we first estimate the $ATCY$ for each transaction as describe in section 2.3.1. We increased impedance of each line by 10% and for each transaction and recalculate the new $ATCY$; the sensitivity of ATC with respect to Y can be written as:

$$(ATCY_{new} - ATCY_{old}) = \frac{dATC}{dY}(Y_{new} - Y_{old}) \quad (2.40)$$

This implies that there is a very close correlation between reduction of line ratings and reduction of ATC.

2.5 TRM Computation Using AC Load Flow Method

TRM determination using the proposed technique is presented below:

a. Determine ATC considering load and line impedances parameter approach for full Jacobian and decoupled Jacobian as discussed in section 2.3.1.
b. Determine ATC considering voltage parameter approach for full Jacobian and decoupled Jacobian as discussed in section 2.3.2.
c. Determine sensitivity of ATC with respect to load, voltage and line impedance parameters is discussed in sections 2.4.
d. Most viable probabilistic approaches to uncertainties in parameters rely on linear approximations and zero-mean Normal Distributions. The computed variance does

however provide an indication of a likely range of values for the deviation. The standard deviation of the sensitivities can be written as follows:

Compute standard deviation of sensitivity of ATC for each parameter:

$$\frac{dATC}{dS} = \frac{(ATC_{new} - ATC_{old})}{(S_{new} - S_{old})} \tag{2.41}$$

$$\frac{dATC}{dV} = \frac{(ATCV_{new} - ATCV_{old})}{(V_{new} - V_{old})} \tag{2.42}$$

$$\frac{dATC}{dY} = \frac{(ATCY_{new} - ATCY_{old})}{(Y_{new} - Y_{old})} \tag{2.43}$$

where, $\frac{dATC}{dS}$ = Sensitivity of ATC with respect to load

$\frac{dATC}{dV}$ = Sensitivity of ATC with respect to voltage magnitude

$\frac{dATC}{dY}$ = Sensitivity of ATC with respect to line impedance

$$S.D.S = \sqrt{[\{(\frac{dATC}{dS})^2 + (\frac{dATC}{dV})^2 + (\frac{dATC}{dY})^2\}\{\sigma^2(g)\}]} \tag{2.44}$$

where, $\sigma(g)$ = variance of each parameter [24];

= 0.1→ for load

= 0.05→ for voltage

= 0.0029→ for line impedance

Equation (2.44) also state as standard deviation of sensitivity. Reference [26], state a formula of TRM which is:

$$TRM = U\sqrt{\sum_{i=1}^{m}(\frac{\partial A}{\partial P_i})^2 v^2(P_i)} \tag{2.45}$$

The formula of above equation needed to define some terms which can be described from the following steps:

a. A choice of uncertainty parameters $P_1, P_2, ..., P_m$;

b. Variance $v^2(P_i)$ of each parameter;

c. Calculation the sensitivity $(\frac{\partial A}{\partial P_i})$ of the transfer capability to each parameter P_i .

We must make the margin large enough so that it can account for the uncertainty in the system, if it can then we can say the system is reliable.

So, the condition is: *probability {uncertainty ≤ TRM} = P;* where *P* is a given high probability. This can be achieved by choosing the TRM to be a certain number *U* of standard deviations of sensitivity. *U* is chosen so that the probability that the normal random variable of mean zero and standard deviation 1 less than *U* is *P*.

$$\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{U} e^{-t^2/2}\,dt = P \tag{2.46}$$

It is straightforward to calculate *U* from *P* by consulting tables of the cumulative distribution function of a normal random variable [49]. For example, if it is decided that the TRM should exceed the uncertainty with probability *P* = 95%, then *U*=1.65.

In this work, we modified equation (16); we used the sensitivity of ATC instead of TC (transfer capability) besides, considered three distinct parameters (load, voltage and line impedance) instead of only load. So, the modified TRM formula becomes:

$$TRM = U\sqrt{[\{(\frac{dATC}{dS})^2 + (\frac{dATC}{dV})^2 + (\frac{dATC}{dY})^2\}\{\sigma^2(g)\}]} \tag{2.47}$$

The standard deviation of sensitivity from equation (2.44) has to multiply with the certain number *U* to determine the *TRM* from equation (2.47). Here, *U*= 1.65, 1.96 and 2.57 for 90%, 95% and 99% probability of uncertainty, respectively. The way of the determination of TRM by AC method presented by flowchart in figure 2.2 (a) and 2.2 (b).

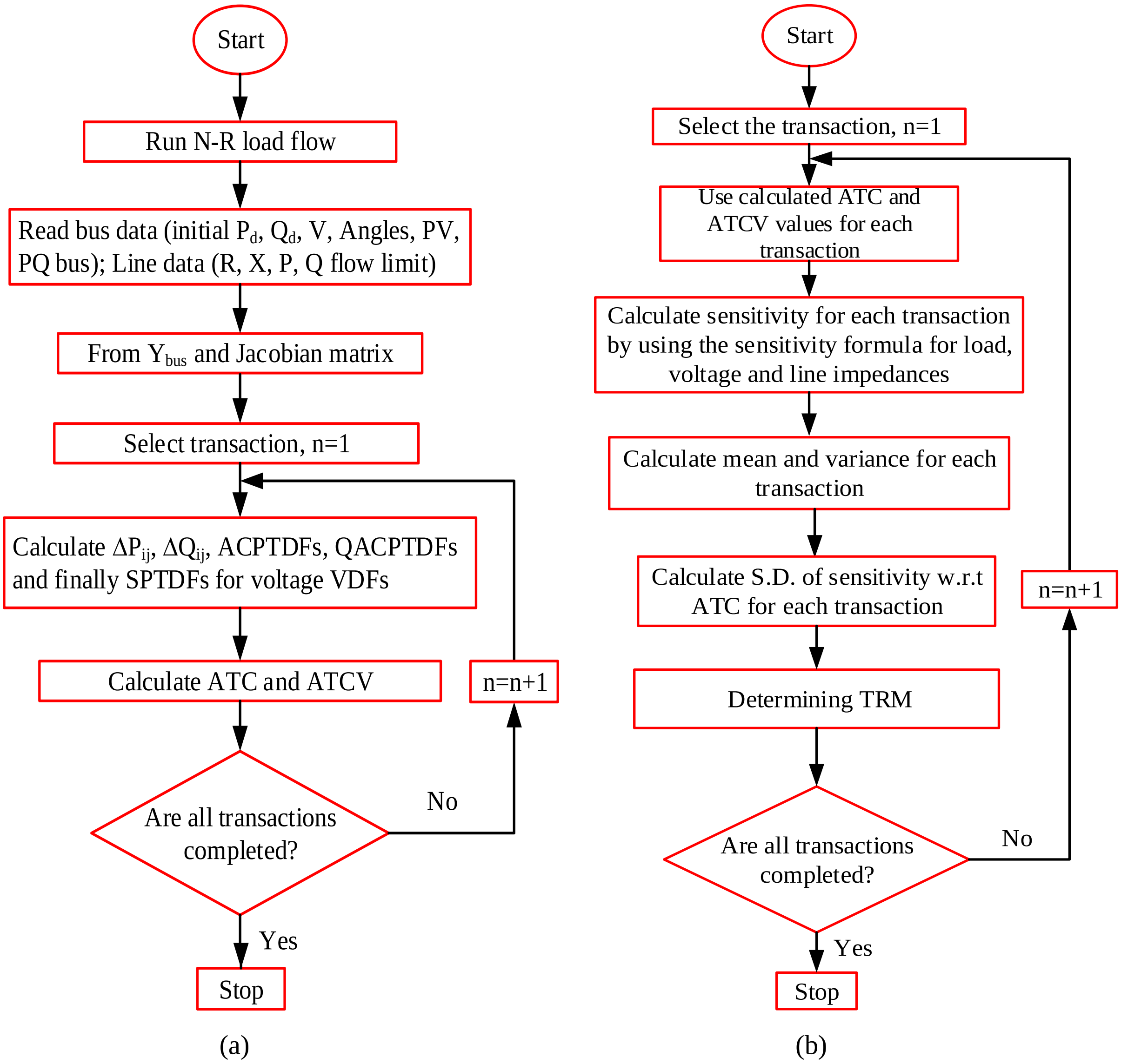

Fig. 2.2(a): Flow chart for ATC determination using AC load flow

Fig. 2.2(b): Flow chart for TRM determination using AC load flow

2.6 Results and Analysis

In this section results of ATC for two distinct Jacobian approaches, sensitivity for three different parameters (load, line impedances and bus voltage magnitudes) and TRM for three discrete probabilities of uncertainty are discussed.

2.6.1 AC load flow method

The comparison in table 2.4, had obtained for AC load flow method by SPTDFs (Apparent power transfer distribution factors) for load and line impedances parameters and Voltage distribution factors (*VDFs*) are used for voltage limit parameter. In this table, *ATC* value decreased after increasing load for both PV and PQ type bus. Even though, *ATCV* value decreased for PV bus type after increasing voltage magnitude but increased for PQ bus because of Ferranti effect. Similarly, for increased in line impedances for each transaction lines *ATCY* value decreased for each transaction. ATC units are in *MW*.

Table 2.4: Comparison ATC Values for Full Jacobian and Decoupled Jacobian

Jacobian Matrix/ Transactions		**ATC for load**	**ATC increase load for bus 2**	**ATC increase load for bus 5**	**ATCV for voltage**	**ATCV increase voltage for bus 2**	**ATCV increase voltage for bus 5**	**ATCY for line impedances**	**ATCY for increase line impedances**
Full J	T14	939.46	693.8	462.15	94.55	94.4	98.4	132	89.3
	T15	575.6	481.1	271.56	100.02	99.95	101.7	170.5	115.9
	T16	412.13	384.7	248.25	95	94	98	148	111.8
	T24	1462	1197.8	676.3	94.94	94.83	98.6	265.3	234.6
	T25	542.95	504.86	184.62	100.2	100	101.8	299.4	284.2
	T26	1005	849.77	454.67	94.93	94.8	98.65	272.2	263.3
	T34	452.8	400.53	170.5	57.69	57.5	58.5	273.3	272.5
	T35	377.1	358.5	152.08	53.34	53.2	54.3	301.96	293.6
	T36	1133.6	1023	615.5	49.95	49.6	50.7	399.6	280.5

Table 2.4: Comparison ATC Values for Full Jacobian and Decoupled Jacobian

Jacobian Matrix/ Transactions		ATC for load	ATC increase load for bus 2	ATC increase load for bus 5	ATCV for voltage	ATCV increase voltage for bus 2	ATCV increase voltage for bus 5	ATCY for line impedances	ATCY for increase line impedances
J1 & J4	T14	968.9	768.96	547.8	90.97	90.93	96.90	188.8	124
	T15	578.2	457.2	275.7	97.56	97.5	100.31	209.13	171.2
	T16	410.5	392.8	278.6	90.9	90.87	96.87	200.1	126.5
	T24	1543.8	1312.4	882.04	91.31	91.27	97.07	311.1	285.4
	T25	549.7	512.4	209.13	97.72	97.67	100.4	336.23	260.99
	T26	1030.4	859.9	514.05	91.25	91.21	97.04	313.6	287.5
	T34	455.7	429.8	221.4	91.45	91.4	97.14	325	311.9
	T35	381.61	360.4	160.01	97.77	97.73	100.4	345.2	270.34
	T36	1141.3	1066.1	757.24	91.391	91.35	97.1	325.1	304.2

Now, in table 2.5, showed sensitivity values after increasing the load, voltage magnitudes and line impedances level for all type of buses in the network system. For this calculation, one PV and one PQ bus were selected. After that, used the formulas of sensitivity determination for each parameter which is described in section 2.4. In this table the sensitivity values for load parameter contains negative values which indicate the effect on the ATC (which is decreased) after increased the load for a particular bus in the system. Similarly, for voltage parameter only PV type bus contains negative values not the PQ bus type; so for PV bus the effect on ATC decreasing at the same time it’s increasing for PQ bus type. Besides, for line impedances it also contains negative values, so the effect on ATC is decreased for each transaction lines. Moreover, the sign of the sensitivity values indicate how the ATC is affected by changing the level of those parameters. Now, TRM results are shown for three distinct probabilities (90%, 95%, 99%). It shows that if any contingencies raised in those lines during power transfer one should maintain that TRM value to compensate or to balance the whole system so that it (the system) can perform normally; and one thing can be notified that TRM values are increased with the increased in probability of uncertainty; the unit of TRM and sensitivity are in MW and $MWMVA^{-1}$.

Table 2.5: Sensitivity of ATC for Load, Voltage and Line Impedances Parameters

Jacobian Matrix / Transactions		Sensitivity for bus 2	Sensitivity for bus 5	Sensitivity voltage of bus 2	Sensitivity voltage of bus 5	Sensitivity line impedances	TRM Values		
							Probability of uncertainty		
							90%	95%	99%
Full J	T14	-2.9	-5.6	-0.022	0.58	-0.303	1.4	2.75	3.61
	T15	-1.11	-3.6	-0.01	0.25	-0.389	0.78	0.92	1.21
	T16	-0.32	-1.9	-0.144	0.45	-1.174	0.37	0.44	0.58
	T24	-3.11	-9.3	-0.016	0.55	-0.157	2.05	2.43	3.2
	T25	-0.45	-4.2	-0.029	0.24	-0.083	0.77	0.91	1.19
	T26	-1.83	-6.5	-0.0188	0.56	-0.097	1.38	1.63	2.14
	T34	-0.62	-3.3	-0.027	0.123	-0.0184	0.65	0.77	1.01
	T35	-0.22	-2.7	-0.02	0.145	-0.0962	0.48	0.57	0.75
	T36	-1.3	-6.1	-0.05	0.114	-0.626	1.22	1.45	1.9
J1 & J4	T14	-2.36	-4.96	-0.006	0.9	-0.4597	1.21	1.44	1.88
	T15	-1.43	-3.6	-0.009	0.42	-0.27	0.83	0.99	1.29
	T16	-0.21	-1.55	-0.004	0.9	-2.39	0.30	0.36	0.47
	T24	-2.73	-7.8	-0.006	0.87	-0.132	1.74	2.07	2.71
	T25	-0.44	-4.01	-0.007	0.41	-0.4089	0.74	0.87	1.14
	T26	-2	-6.1	-0.006	0.88	-0.285	1.33	1.59	2.08
	T34	-0.31	-2.76	-0.007	0.86	-0.3011	0.51	0.61	0.79
	T35	-0.25	-2.6	-0.006	0.4	-0.861	0.47	0.56	0.73
	T36	-0.89	-4.53	-0.007	0.87	-0.1098	0.89	1.07	1.39

2.7 Validation through Published Results

In this section, the TRM values which obtained from the proposed technique were compared to published values of TRM which demonstrated for IEEE 8 and 118 bus system. Compared these results for those transactions. Table 2.6 is presented all TRM values compared for 90%, 95% and 99% probability for AC load flow for each transaction. From those tables we can see that its quiet close to the previous results and it's increasing as the probability of uncertainty is increasing.

Table 2.6: Compared TRM Values between Published and Obtained Results for AC Load Flow

Probability of Uncertainty	90%	95%	99%
Proposed Technique	0.77	0.91	1.19
TRM formula	0.6012	0.7750	1.0944
Monte Carlo	0.6027	0.7846	1.1083

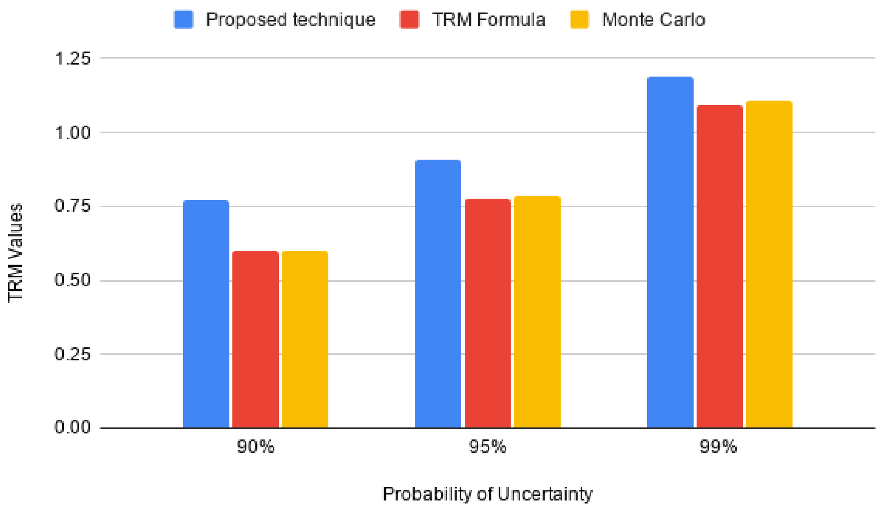

Fig. 2.3: Validation of TRM values for AC load flow method

2.8 Conclusion

In any power system network crucial point is to focus that the whole network is working securely under any disturbances. This technique accommodates ATC with TRM as well as incorporates some parameters among load, voltage magnitudes and line impedances which correlate among the factor Sensitivity. The process of the developed technique compared its results with other techniques for its validation. The validation of the technique through different approaches clearly shows that the results obtained using the proposed technique are close to the published ones. The whole process is done in MATLAB software for an existing standard IEEE 6 bus system and the validation is also done with a standard IEEE bus system.

CHAPTER 3
TRM CALCULATINION FOR DC AND DCQ LOAD FLOW METHOD

3.1 Introduction

In any transmission network, a vital point is to focus on safe power flow through the whole system web considering all possible disruptions. The proposed technique gives safe margin calculation from available power transfer for DC load flow considered system parameters. The process of the developed technique compared its results with other techniques for its validation. Transmission reliability margin (TRM) is the amount of transmission capability which ensures the transmission network security under a reasonable range of uncertainty in system operating condition. This chapter describes a technique for TRM determination by modified DC and DCQ load flow for IEEE-6 bus system. In DC load flow method, transmission line impedances and system loads are considered as sensitivity parameter besides, in DCQ load flow method, bus voltage magnitudes are considered as sensitivity parameter. The technique is applied to the IEEE 6 bus system, and results are compared with previous results for validation. The validation of the technique through different approaches clearly shows that the results obtained using the proposed technique are close to the published ones.

3.2 Test System Database

According to the objective of this thesis, to be able to determine the reliability of the transmission power system network for IEEE-6 bus system, we need to get a complete network database first. So, collected detailed database from standard IEEE-6 test bus system. According to the database, we have got the following major components:

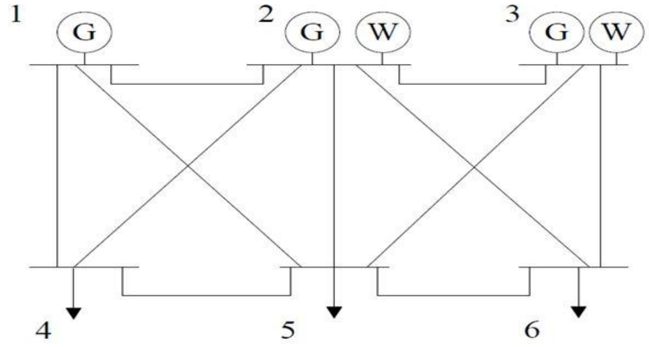

Fig. 3.1: IEEE 6- bus system for DC and DCQ Load Flow [34]

In Table- 3.1, the bus data is given for the six bus system where the first bus is the slack bus, second and third buses are the generator buses besides, buses 4, 5 and 6 are the load buses. Moreover, real power generation for PV buses are 50 and 60 MW, respectively. For each load bus power is 70 MW. The voltage magnitude for slack bus is 1.05 p.u , PV 2 and PV 3 buses are 1.05 and 1.07, respectively. All PQ buses are 1 p.u.

Table 3.1: Bus Data for DC and DCQ Load Flow

Bus No.	**Bus Type**	**Voltage magnitude (p.u)**	**Real power generation (MW)**	**Real power load (MW)**	**Reactive power load (MVAR)**
1	SB	1.05	0	0	0
2	PV	1.05	50	0	0
3	PV	1.07	60	0	0
4	PQ	1	-	70	70
5	PQ	1	-	70	70
6	PQ	1	-	70	70

In Table-3.2, branch data is represented for 6-bus system for the thirteen lines; resistance, reactance and line charging susceptance values are given for each line as well as the maximum apparent power (MVA) capacity.

Table 3.2: Branch Data for DC and DCQ Load Flow

Line No.	**Bus No. From-To**	**Resistance (p.u)**	**Reactance (p.u)**	**Total line charging susceptance (p.u)**	**Maximum Apparent power capacity (MVA)**
1	1-2	0.1	0.2	0.04	40
2	1-4	0.05	0.2	0.04	60
3	1-5	0.08	0.3	0.06	40
4	1-6	0.17	0.4	0.06	130
5	2-3	0.05	0.25	0.06	40
6	2-4	0.05	0.1	0.02	80
7	2-5	0.1	0.3	0.04	30
8	2-6	0.07	0.2	0.05	90
9	3-4	0.1	0.35	0.05	120
10	3-5	0.12	0.26	0.05	70
11	3-6	0.02	0.1	0.02	90
12	4-5	0.2	0.4	0.08	20
13	5-6	0.1	0.3	0.06	40

In figure 3.1 there are no connection between bus 1 to bus 6 and bus 3 bus 4 so, to transfer power from bus 1 to bus 6, we need to sum line resistance, reactance and MVA flow of bus 1 to bus 2 and bus 2 to bus 6 as well as from bus 3 to bus 4, sum line resistance, reactance and MVA flow of bus 2 to bus 3 and bus 2 to bus 4. TRM has been obtained for different transactions taken as multi-transactions. Table 3.3 shows the transactions considered in this work.

Table 3.3: Transactions Considered for DC and DCQ Load Flow

SL. No.	Transactions ID	Seller Bus	Buyer Bus
1	T1	1	4
2	T2	1	5
3	T3	1	6
4	T4	2	4
5	T5	2	5
6	T6	2	6
7	T7	3	4
8	T8	3	5
9	T9	3	6

3.3 ATC Determination Using DC and DCQ Load Flow

Power flow from a seller bus to a buyer bus is called a transaction. A physical connection between zones or power systems is known as flow-gates. The power transfer distribution factors (PTDFs) ensures that the transactions between zones do not jeopardize network operation by an imbalance on a flow-gate. It also represents the relationship between the transaction and the flow through a line. PTDFs calculated using DC load flow is known as DCPTDFs. DC power flows model assumes that bus voltage angles vary only slightly, voltage magnitudes are constant, and transmission lines have no resistance, therefore, no losses. In this section, however, resistances in transmission lines are considered to see the effect of sensitivity. The PTDFs calculation using for DCQ load flow is known as DCQTDFs; for this load flow bus voltage magnitudes considered as sensitivity parameter. ATC and ATCQ for DC and DCQ load flow proceeds as follows respectively:

3.3.1 ATC determination for DC load flow

In this sub-section the complete process of determining ATC by DC load flow is described for two distinct parameters (load and line impedances).

Loads and line impedances variations:

In this model some assumptions are needed; so, the assumptions while DC model is in employment instead of AC model are described below:

a. Voltage magnitudes are constant
b. Only angles of the complex bus voltage vary
c. The variation in angle is small
d. Transmission lines are lossless

These assumptions create a mode that is a reasonable first approximation for the real power system, which is just slightly nonlinear in normal steady state operation. In this method only real power is considered for estimating ATC. With these assumptions, power flow over transmission lines connecting bus i and bus j is given as:

$$P_{ij} = B_{ij}(\theta_i - \theta_j) \tag{3.1}$$

where, $\theta = [B^{-1}][P]$

Power flow from a seller bus to a buyer bus is called a transaction. A physical connection between zones or power systems is known as flow-gates. The power transfer distribution factors (PTDFs) ensures that the transactions between zones do not jeopardize network operation by an imbalance on a flow-gate. It also represents the relationship between the transaction and the flow through a line.

For DC load flow the sensitivity factors considered as DCPTDFs; for a line and a transaction this factor can be expressed as:

$$DCPTDFs = \frac{X_{iM} - X_{jM} - X_{iN} - X_{jN}}{x_{ij}} \tag{3.2}$$

where, x_{ij} = line reactance connecting bus *i* and *j*

X_{iN} = entry of i^{th} row and N^{th} column of the bus reactance matrix *X*.

If $DCPTDFs_{ij,MN} < 0$ then,

$$ATC_{MN} = ATCY_{MN} = \min(\frac{-P_{max} - P_{ij}}{DCPTDFs_{ij,MN}}) \tag{3.3}$$

If $DCPTDFs_{ij,MN} > 0$ then,

$$ATC_{MN} = ATCY_{MN} = \min(\frac{P_{max} - P_{ij}}{DCPTDFs_{ij,MN}}) \tag{3.4}$$

where, P_{max} = maximum power transfer through a line

P_{ij} = power flow through that line

In this thesis, DC load flow has been implemented for ATC and sensitivity determination in multi-transaction environment.

3.3.2 ATCQ determination for DCQ load flow

In this sub section the determination of ATCQ for DCQ load flow method is described; in this technique reactive power is considered and bus voltage magnitude parameter for sensitivity calculation.

Voltage magnitudes variation:

PTDFs calculated using DC load flow is known as DCPTDFs; for reactive power named as DCQTDF. In DCQTDF method active power generations, demands and voltage angles of all buses, resistance of all transmission lines assumed zero. In this thesis, bus voltage magnitudes considered, to see the effect of sensitivity like- increase the magnitudes 5% and then calculate the sensitivity with respect to ATCQ. DC load flow for VAR proceeds as follows:

a. Calculate Y_{bus} matrix from given bus data. Separate the imaginary part of the Y_{bus} matrix. After that, calculate the susceptance matrix B, curtailed 1x1 in the matrix because the first bus is the reference bus.

b. Calculate voltage magnitudes for each bus except reference bus which is considered as 1.05 p.u,

$$Q^{sch} = Q_g - Q_d \tag{3.5}$$

where, Q_g and Q_d are the reactive power of the generator and load buses respectively.

$$V_n = B_x \times V_{sl} + Q^{sh} \tag{3.6}$$

where, B_x is the last column of the bus susceptance matrix B and V_{sl} is the slack bus magnitude.

$$V_{new} = X \times V_n \tag{3.7}$$

where, X is the inverse of the bus susceptance matrix B. Finally, V_{new} gives the voltage magnitudes from bus 2 to bus 6 for 6-bus system.

c. Now, Calculate reactive power flows (Q_o and Q_n) for each transaction (t). Q_o is calculated from the given voltage magnitude for the particular system and Q_n is calculated from the estimated new voltage (V_{new}):

$$Q^t{}_o = (-B_{ij} \times \Delta V_o) \tag{3.8}$$

$$Q_n{}^t = (-B_{ij} \times \Delta V_N) \tag{3.9}$$

where, B_{ij} is the negative value from the susceptance matrix for *i-j* line for a particular transaction (*t*).

$$\Delta V_o = (V_j - V_i) \tag{3.10}$$

$$\Delta V_N = (V_{new}^j - V_{new}^i) \tag{3.11}$$

where, V_j and V_i are the given voltage magnitudes of bus *j* and *i* respectively; V_{new}^j and V_{new}^i are the new bus voltage magnitudes calculated from equation (3.7).

d. Now**,** DC VAR transfer distribution factors **(***DCQTDFs)* are calculated from the following equation for a transaction (zone *M* → zone *N*) which flows through a transmission line (bus *i* → bus *j*).

$$DCQTDF_{ij,MN} = \frac{(Q_n{}^t - Q_o{}^t)}{LL_{\max}} \tag{3.12}$$

where, $LL_{\max}$ is the maximum MVA flow through each line.

e. Calculate ATC for each transaction. There are two conditions to determine *ATCQ* for each transaction.

If $DCQTDF_{ij,MN} < 0$ then,

$$ATCQ_{MN} = \min\left(\frac{-Q_o - LL_{\max}}{DCQTDF_{ij,MN}}\right) \tag{3.13}$$

If $DCQTDF_{ij,MN} > 0$ then,

$$ATCQ_{MN} = \min\left(\frac{Q_o - LL_{\max}}{DCQTDF_{ij,MN}}\right) \tag{3.14}$$

The value of *ATCQ* for each transaction can be calculated from the equation above (3.13) and (3.14), need to calculate the *DCQPTDF* for reactive power again for each transaction.

3.4 Sensitivity Calculation Using DC and DCQ Load Flow

In this section the determination of sensitivity considered load and line impedances parameter for DC load flow and bus voltage magnitudes for DCQ load flow.

3.4.1 Sensitivity calculation using DC load flow

If load increase for any bus, then how it effects the transaction is known as sensitivity. Sensitivity of available transfer capability for load and line impedances parameter are described below:

For DC load flow increased 30 MW (real power) for a load and generator bus and run the whole DC load flow again which will give the new ATC_{new} value; the sensitivity of ATC (available transfer capability) with respect to P (real power) $(\frac{dATC}{dP})$ can be written as:

$$(ATC_{new} - ATC_{old}) = \frac{dATC}{dP}(P_{new} - P_{old}) \qquad (3.15)$$

Section 3.3.1 described the whole process of calculating $ATCY$ for DC load flow*;* we calculate the sensitivity w.r.t line impedance, we change the line impedances by 10%, and recalculate $ATCY_{new}$ in the same process. Finally, the sensitivity of ATC with respect to Y is:

$$(ATCY_{new} - ATCY_{old}) = \frac{dATC}{dY}(Y_{new} - Y_{old}) \qquad (3.16)$$

3.4.2 Sensitivity calculation using DCQ load flow

For sensitivity calculation we increase the bus voltage magnitudes by 5% for each type of bus except for the slack bus. The whole calculation is described below:

As described in section 3.3.2 we can calculate the new VAR flow with change in bus voltage magnitudes. After that, we need to calculate new $ATCQ_{new}$ from equations (30) and (31) for each transaction. So, the sensitivity $ATCQ$ w.r.t voltage is:

$$\frac{\partial ATCQ}{\partial V} = \frac{dATCQ}{dV} \qquad (3.17)$$

where, $dV = (\Delta V_N - \Delta V_o)$

$$\Delta V_o = (V_j - V_i)$$

$$\Delta V_N = (V_{new}^j - V_{new}^i)$$

$$dATCQ = (ATCQ_{new} - ATCQ_{old})$$

3.5 TRM Determination Using DC and DCQ Load Flow

This section is described the determination of TRM by DC and DCQ load flow method. DC load flow considered load and line impedance parameters and DCQ load flow method considered bus voltage magnitude parameter.

3.5.1 TRM determination using DC load flow

For discrete random variables we need to determine the mean, variance and standard deviation for each transaction, respectively; For DC load flow the sensitivity w.r.t load and line impedances for each transaction are considered as discrete random variables. The S.D of sensitivity is described below.

$$Mean, \mu = E(x) = \sum_{l=1}^{k} x_l c_i p_l \tag{3.18}$$

where, x_l is the random variable 1, …. *k;* in this work we considered sensitivity of *ATC* w.r.t each parameter.

p_l is the probability of that random variable; in this work we considered 95% and 99% probability of uncertainty.

c_i is the variance of each parameter distribution; for load and line impedance these values are 0.1 and 0.0029, respectively.

$$Variance, \sigma^2 = E(x^2) - E^2(x) \tag{3.19}$$

where, $E(x^2)$ = square each random variables first and then calculate mean

$E^2(x)$ = square of the mean value

$$S.D.S, \sigma = \sqrt{E(x^2) - E^2(x)} \tag{3.20}$$

$$TRM = U\sigma \tag{3.21}$$

Equation (3.20) also state as standard deviation of sensitivity; where, U = A certain number derived from a given high probability by consulting tables of the cumulative distribution function of a normal random variable. For this work, we used U=1.65 and 2.57 for 95% and 99% probability, respectively. The whole process of the determination of ATC and TRM by DC load flow is shown in the flowchart in figure 3.2(a) and 3.2(b) respectively:

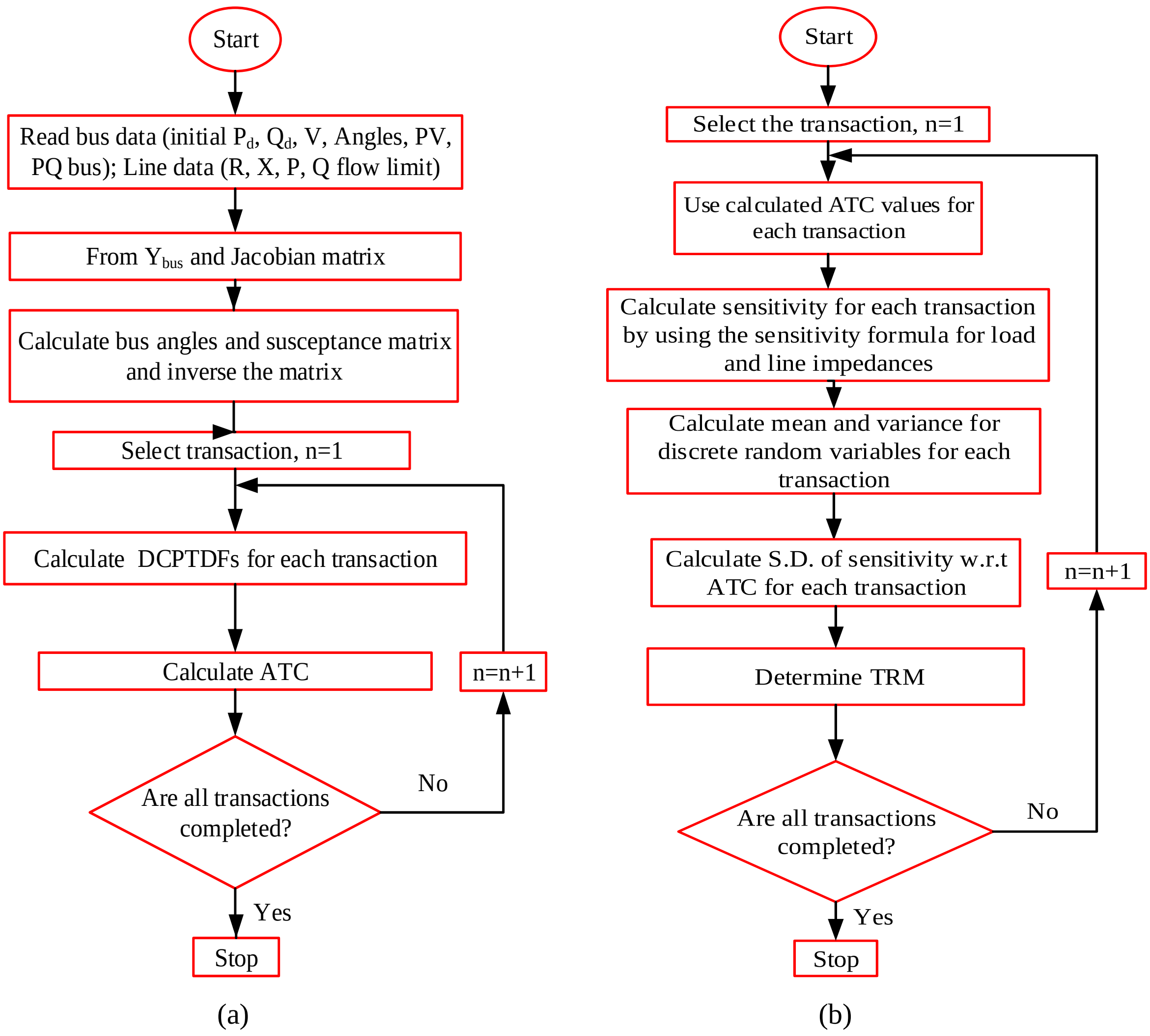

Fig 3.2 (a): Flow chart for ATC determination using DC load flow

Fig 3.2 (b): Flow chart for TRM determination using DC load flow

3.5.2 TRM determination using DCQ load flow

DCQ load flow method considered reactive power for determining TRM. The whole process of calculating TRM by this method is explained below:

a. Determination of ATCQ considering voltage parameter as discussed in section 3.3.2.

b. Determination of Sensitivity considering voltage parameter is discussed in section 3.4.2. Finally, the computation of σ = standard deviation of sensitivity is done by equation (40) which is described below:

$$Mean, \mu = E(x) = \sum_{i=1}^{k} x_i c_i^2 p_i \tag{3.22}$$

x_i is the random variable 1,….,*k*, for this paper it's the sensitivity *;*

p_i is the probability of uncertainty, for this work 95% and 99% are considered;

c_i = 0.05; is the parameter distribution

$$Variance, \sigma^2 = E(x^2) - E^2(x) \tag{3.23}$$

$$S.D.S, \sigma = \sqrt{E(x^2) - E^2(x)} \tag{3.24}$$

c. The TRM formula for the proposed technique is presented below:

$$TRM = U\sigma \tag{3.25}$$

For this work, we used *U*= 1.96 and 2.57 for 95% and 99% probability respectively. The whole process of the determination of ATCQ and TRM by DCQ load flow in the flowchart in figure 3.3(a) and 3.3(b):

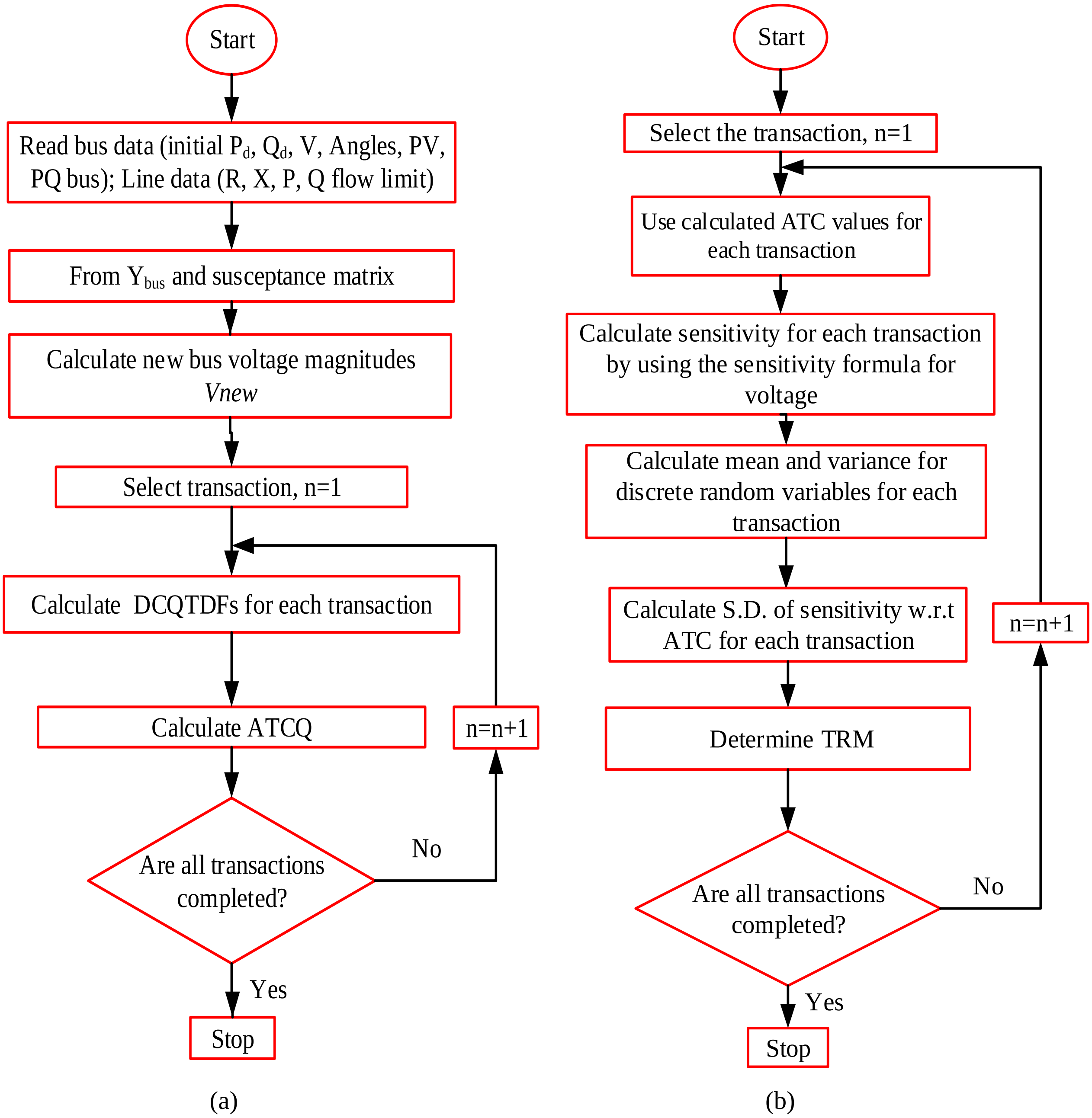

Fig. 3.3 (a): Flow chart for ATC determination using DCQ load flow

Fig. 3.3 (b): Flow chart for TRM determination using DCQ load flow

3.6 Results and Analysis

In this section results of ATC, sensitivity for two different parameters (load, line impedances) by DC load flow and results of ATCQ, sensitivity for bus voltage magnitudes by DCQ load flow are described besides, TRM results are also discussed for these two discrete load flow methods.

3.6.1 DC load flow

In DC method, DCPTDFs and ATC had calculated for different transactions which described in section 3.3. After that, increase load for one PV and one PQ bus to estimate sensitivity of available transfer capability for load and line impedances; which discussed in section 3.4. Finally, TRM was calculated for each transaction by using the TRM formula which included in section 3.5, considered for 95% and 99% probability of uncertainty. Table 3.4 and 3.5 presented the calculated ATC, sensitivity and TRM values using the proposed technique. Sensitivity is calculated for two types of buses (one is PV bus-2 and another is PQ bus-5). The recalculated ATC values get increased with the increased load for some transactions. The sign of the sensitivity values helps to understand whether the ATC values increased (positive sign) or decreased (negative sign). Generally, increase in load will decrease the recomputed ATC values. ATC of PQ bus affected more than the PV bus. Increased load for PV bus-2 increases the recalculated ATC values because of Ferranti effect, this effect happens when there is no load or low load besides there is no load on bus-2 so when we increase it up to 30 MW it is still low compared to other buses; because of that in most of the transactions, ATC values get increased. In PQ bus-5, recalculated ATC increased for three transactions that happened because of the same effect. The effect of increase (10%) in the impedances reduce the ATC.

Table 3.4: ATC Values for DC Load Flow

Transactions	ATC for			
	Base case	**Increased load for bus 2**	**Increased load for bus 5**	**Increased line impedances**
T14	142.45	148.37	52.09	136.98
T15	195.798	181.1	101.53	199.36
T16	398.52	385.8	411.36	371.8
T24	134.85	143.5	134.4	137.59
T25	71.74	53.7	43.92	68.66
T26	244.74	253.98	247.5	251.3
T34	227.4	227.8	225.04	226.82
T35	205.81	208.9	216.34	211.53
T36	164.78	166.8	162.68	166.64

Table 3.5: Sensitivity and TRM Values for DC Load Flow

Transactions	Sensitivity for			TRM	
				Probability of Uncertainty	
	Bus 2	**Bus 5**	**Line impedances**	**95%**	**99%**
T14	0.197	-3.01	-0.038	2.41	3.4
T15	-0.49	-3.14	0.025	2.28	3.23
T16	-0.42	0.43	-0.87	0.89	1.25
T24	0.29	-0.015	0.014	0.23	0.32
T25	-0.60	-0.93	-0.017	0.63	0.89
T26	0.31	0.092	0.072	0.18	0.25
T34	0.013	-0.079	-0.014	0.064	0.09
T35	0.103	0.35	0.066	0.21	0.29
T36	0.067	-0.07	0.0098	0.09	0.13

3.6.2 DCQ load flow

In DCQ method, DCQTDFs and ATCQ had calculated for different transactions in section 3.3.2. After that, increase load for one PV and one PQ bus to estimate sensitivity of *ATCQ* for voltage parameter in section 3.4.2. Finally, TRM was calculated by using the TRM formula which included in this chapter at section 3.5.2, considered 95% and 99% probability of uncertainty. Table 3.6, presented the calculated ATCQ results for base case and for other two cases increase voltage magnitude for bus-2 and bus-5 and recalculate ATCQ. The results affected only (2-4, 2-5 & 2-6) transactions when increased voltage level for bus-2 as well as for bus-5 affected the (1-5, 2-5 and 3-5) transactions. So, it can state that for DCQ load flow method, if any changes happen in one point only those lines will be affected which are connected to that point. Besides, sensitivity is also calculated for those transactions and for two types of buses (one is PV bus-2 and another is PQ bus-5). If voltage level increases for PV bus it increases the power transfer capability and for PQ bus it decreases the transfer. In PQ bus 5 real and reactive power are fixed, so if voltage level increased then the ATCQ values are decreased but for PV bus 2 increased the recalculated ATCQ values because of Ferranti effect. In table 3.7, shows the sensitivity and TRM results using the proposed technique for 95% and 99% probability of uncertainty.

Table 3.6: ATC Values for DCQ Load Flow

Transactions	**ATCQ values**		
	Base	**PV 2**	**PQ5**
T14	95.83	95.83	95.83
T15	105.895	105.895	79.77
T16	420.5	420.5	420.5
T24	137.73	195.6	137.73
T25	133.58	183.22	85.7
T26	365.35	463	365.35
T34	682.52	682.5	682.5
T35	334.06	334.06	256.71
T36	297.22	297.22	297.22

Table 3.7: Sensitivity and TRM Values for DCQ Load Flow

Transactions	**Sensitivity**	**TRM**		**Transactions**	**Sensitivity**	**TRM**	
	PV 2	95%	99%		PQ 5	95%	99%
T24	8.35	0.79	1.07	T15	-3.9	0.37	0.49
T25	7.2	0.69	0.92	T25	-7.3	0.69	0.93
T26	14.1	1.35	1.8	T35	-11.7	1.12	1.49

3.7 Validation Through Published Results

In this section, the TRM values which obtained from the proposed technique were compared to published values of TRM which demonstrated for IEEE 8 and 118 bus system.

3.7.1 DC load flow

Table 3.8 is presented all TRM values compared for 95% and 99% probability of uncertainty for DC load flow for each transaction. From those tables we can see that it quiet close to the previous results and it's increasing as the probability of uncertainty is increasing.

Table 3.8: Compared TRM Values between Published and Obtained Results for DC Load Flow

Probability of Uncertainty	95%	99%
Proposed Technique	0.89	1.25
TRM formula	0.775	1.09
Monte Carlo	0.785	1.108

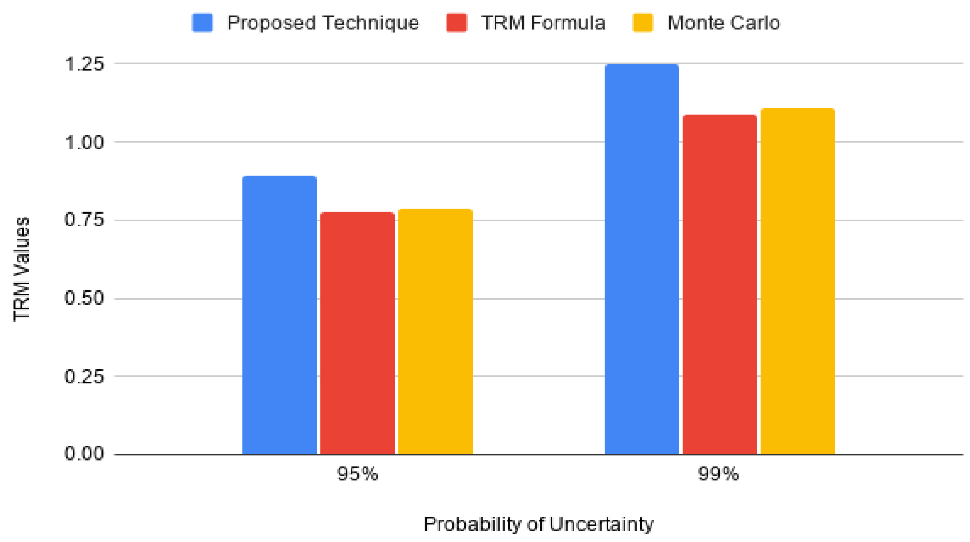

Fig. 3.4: Validation of TRM values for DC load flow method

3.7.2 DCQ load flow

Table 3.9 is represented all TRM values compared for 95% and 99% probability of uncertainty for DCQ load flow for each transaction. From those tables we can see that it quiet close to the previous results and it’s increasing as the probability of uncertainty is increasing.

Table 3.9: Compared TRM Values between Published and Obtained Results for DCQ Load Flow

Probability of Uncertainty	95%	99%
Proposed Technique	0.79	1.07
TRM formula	0.775	1.09
Monte Carlo	0.785	1.108

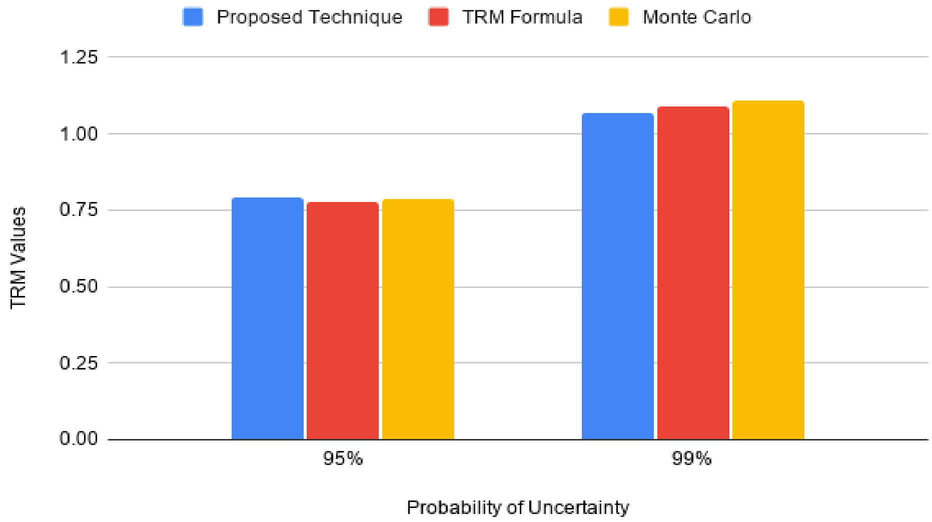

Fig. 3.5: Validation of TRM values for DCQ load flow method

3.8 Conclusion

In any transmission network, a vital point is to focus on safe power flow through the whole system web considering all possible disruptions. The proposed technique gives secure margin calculation from available power transfer as well as system parameter uncertainty for DC load flow. Reactive power plays a vital role for system reliability purpose especially for voltage security margin because in a power system network voltage stability is influenced by VAR support at various locations. The main focus of this chapter is to develop a new technique to determine TRM and ATCQ by DCQ load flow method considered voltage parameter for sensitivity calculation. Most of the previous technique considered reactive power in DC load flow to determine ATC but in this technique the whole process applied to determine TRM. Normally, in DC load flow is considered for real power not reactive power but need to considered reactive power because sometimes voltage and current will not be in phase to explain that imbalance state need DCQ load flow. The proposed technique compared its results with other techniques for its validation. The validation presents that the results of the proposed technique is closed to the previous one.

CHAPTER 4
RELATION BETWEEN TRM AND STANDARD DEVIATION OF UNCERTAINTY

4.1 Introduction

In any power system the major responsibility of a designer is to make the best possible balance between economical and reliable electrical power supply according to the customers' demand as well as acknowledge the uncertainties which will occur in the system. There is a capability of transferring power between two nodes and power transfer between those two nodes must not exceed that transfer capability. To fulfil demand, more power need to be transferred over the existing amount; that's why the estimation of Available Transfer Capability (ATC) is needed which give us the information of further transactions after the base transactions. That additional flow of power in the system network must be done without jeopardizing the system adequacy and security; for that the computation of Transmission Reliability Margin (TRM) is needed. Besides, any uncertainty in a system affects the TRM. In this chapter, the relation between the S.D (Standard Deviation) of sensitivity and TRM explains briefly as well as presents it in graphs. Sensitivity means any kind of unpredictability in system parameters like: voltage limit, thermal limits, load, changes etc. In this chapter, system load is considered for estimating S.D of sensitivity and how that sensitivity affects the TRM; this work is done for the same test database system which is described in previous chapters.

4.2 Sensitivity of Available Transfer Capability

This work described, how ATC affects, if load increases at any bus in the system. From table-4.1 we can observe that ATC values decrease from its base value with increases in load. The decreasing values of ATC of PV bus is larger than PQ bus which states that load increases in PQ bus will affect the power transfer more than the PV bus. That affects the sensitivity too.

Standard deviation of sensitivity (S.DS) is calculated from those sensitivity values of ATC and the variance of load parameter. Distribution of the system loading parameter collected from the distribution tables,$\sigma_i = 0.1$.

Sensitivity of ATC for load change:

$$(ATC_{new} - ATC_{old}) = \frac{dATC}{dS}(P_{new} - P_{old}) \tag{4.1}$$

$$S.D.S = \sqrt{(\frac{dATC}{dP})^2 \sigma^2(P)} \tag{4.2}$$

where, $\frac{dATC}{dP}$ = Sensitivity of *ATC* with respect to load

$\sigma^2(P)$ = Variance of system loading parameter distribution (0.1)

S.D. of sensitivity from equation (4.2) is calculated for each transaction separately.

4.3 Relation between TRM and S.D. of Uncertainty

The significance of considering the TRM in ATC estimation is to ensure a reliable power transfer during the occurrence of transfer capability uncertainty. Table-4.1 showed the ATC values for load parameter and also the new ATC value after increased load 30 MW for full and decoupled Jacobian matrix; new ATC values are decreased with the increased in load. Now, table-4.2 showed the S.D of sensitivity method to determine the value of TRM and presented a relation between them. The value of TRM is increased as the sensitivity of a parameter is increased for normal distribution. To keep the system reliable TRM must be greater than the S.D. of sensitivity.

TRM is determined for every transaction between a seller and buyer bus. The sensitivity of ATC which is used to compute the TRM is given by:

$$TRM = N\sqrt{(\frac{dATC}{dP})^2 \sigma^2(P)} \tag{4.3}$$

If probability for a given time period is f(x)=P(-∞≤x≤∞), where x is a continuous random variable and for this work it's a system parameter, if the average failure time rate is r, then total area of probability density function will be,

$$\int_{-\infty}^{\infty} f(x)dx = 1 \tag{4.4}$$

$$\%PDF = \frac{1}{\sigma\sqrt{2\pi}} \int_{-N\sigma}^{N\sigma} e^{-t^2/2\sigma^2} dt \tag{4.5}$$

For normal distribution *PDF* could be the highest probability, for 95%, N = 1.65and 99%, N = 2.57. After calculating the *PDF*, we can determine the TRM from equation (4.3); here N is a certain number which we can get from equation (4.5); this factor helps to increase the transmission reliability margin (TRM).

4.4 Results and Analysis

In this section results of ATC, sensitivity for load parameter (load, line impedances) by DC load flow and results of ATCQ, sensitivity for bus voltage magnitudes by DCQ load flow are described besides, TRM results are also discussed for these two discrete load flow methods. In table 4.1 presented the ATC values for full and decoupled Jacobian matrix with increasing load for generator bus 3 and for load bus 6.

Table 4.1: ATC Values

Jacobian Matrix/ Transactions		**ATC for load**	**ATC with increase in load at PV 3**	**ATC with increase in load at PQ 6**
Full J	T14	950.8	687.2	434.7
	T15	596.15	505.5	319.9
	T16	436.6	419.2	199.1
	T24	1491.8	1221.4	644.2
	T25	748.2	663.4	249.1
	T26	1015.8	900.12	335.95
	T34	524	400.8	133.4
	T35	668.5	636.9	238.7
	T36	1270.9	1244.6	519.3

Table 4.1: ATC Values

Jacobian Matrix/ Transactions		ATC for load	ATC with increase in load at PV 3	ATC with increase in load at PQ 6
J1 & J4	T14	978.3	768.3	459.7
	T15	598.91	482.2	343.4
	T16	430.4	414.1	289.9
	T24	1628	1355.1	764.06
	T25	772.8	657.4	304.5
	T26	1050.7	910.5	536.15
	T34	548.3	446.2	170.2
	T35	703.99	611.3	302.7
	T36	1300.7	1266.2	906.5

In table 4.2, sensitivity and TRM values are showed for two distinct probability of uncertainties; sensitivity with negative values expressed the reduction of ATC value after increased load.

Table 4.2: TRM and S.D of Uncertainty Values

Jacobian Matrix/ Transactions		Sensitivity for load PV bus 3	Sensitivity for load PQ bus 6	S.D Of uncertainty	TRM Values Prob. Of Uncertainty	
					95%	99%
Full J	T14	-6.22	-12.2	1.37	2.74	4.11
	T15	-2.14	-6.5	0.68	1.37	2.05
	T16	-0.41	-5.6	0.56	1.12	1.68
	T24	-6.37	-20	2.099	4.2	6.3
	T25	-2	-11.8	1.197	2.39	3.59
	T26	-2.7	-16	1.623	3.25	4.87
	T34	-2.9	-9.2	0.965	1.93	2.89
	T35	-0.74	-10.13	1.02	2.03	3.05
	T36	-0.62	-17.7	1.77	3.54	5.3

Table 4.2: TRM and S.D of Uncertainty Values

Jacobian Matrix/ Transactions		**Sensitivity for load PV bus 3**	**Sensitivity for load PQ bus 6**	**S.D Of uncertainty**	**TRM Values Prob. Of Uncertainty**	
					95%	**99%**
J1 & J4	T14	-4.95	-12.2	1.32	2.63	3.9
	T15	-2.75	-6.02	0.66	1.3	1.99
	T16	-0.38	-3.3	0.33	0.66	0.99
	T24	-6.4	-20.3	2.13	4.26	6.39
	T25	-2.7	-11.04	1.14	2.27	3.41
	T26	-3.31	-12.1	1.25	2.51	3.76
	T34	-2.41	-8.9	0.92	1.84	2.77
	T35	-2.2	-9.46	0.97	1.94	2.91
	T36	-0.81	-8.5	0.85	1.71	2.6

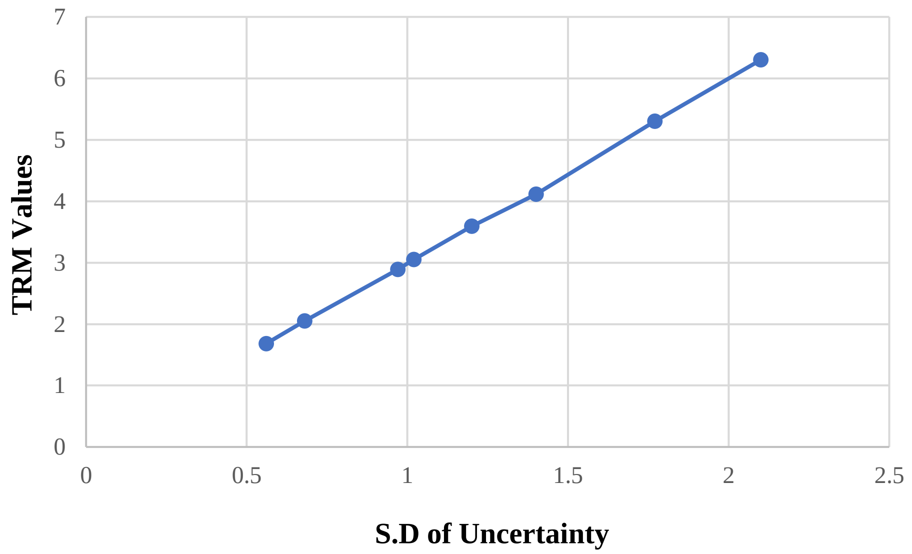

Fig. 4.1: TRM and S.D of Uncertainty relation for 95%

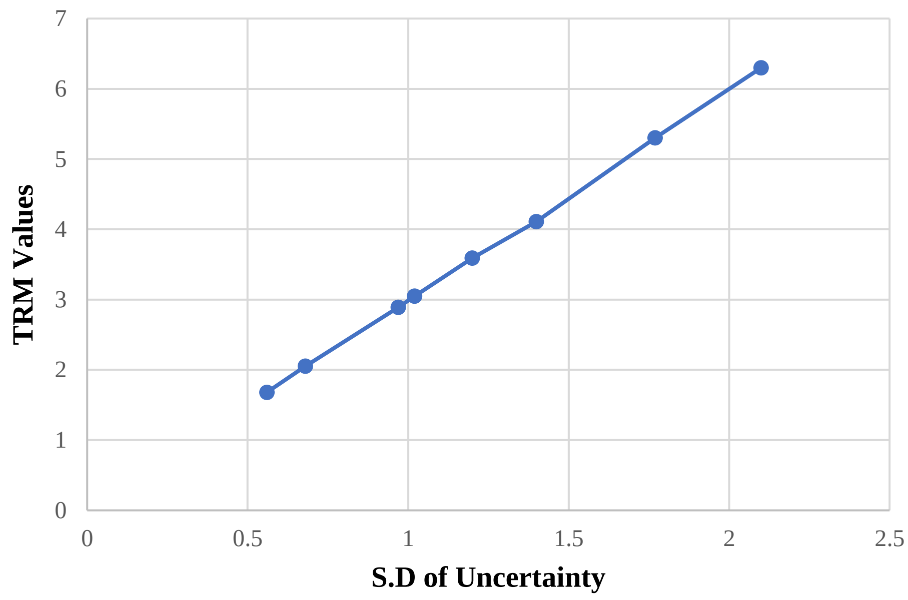

Fig. 4.2: TRM and S.D of Uncertainty relation for 99%

In Fig 4.1 and Fig 4.2, the relation between TRM and S.D. of Sensitivity are shown for 95% and 99% probability respectively. These two figures proved that these two terms are linearly proportional whenever sensitivity grows up at the same time TRM also increases.

4.5 Validation of TRM and S.D of Uncertainty

TRM is the amount of transmission capability ensuring that the transmission network is secure from the sensitivity in system operating condition. The accurate evaluation of TRM is of great importance in the calculation of ATC. This work presented a fast assessment method of TRM using stochastic response surface method (SRSM). The statistics and probability distributions of TRM can be accurately estimated with less computational cost [32].

Table 4.3: Compared TRM and S.D of Uncertainty Values with Previous Published Results

Techniques	**Standard Deviation of Uncertainty**	**TRM**
Proposed	1.197	2.39
SRSM	1.0616	1.89
Monte carlo	1.099	1.93

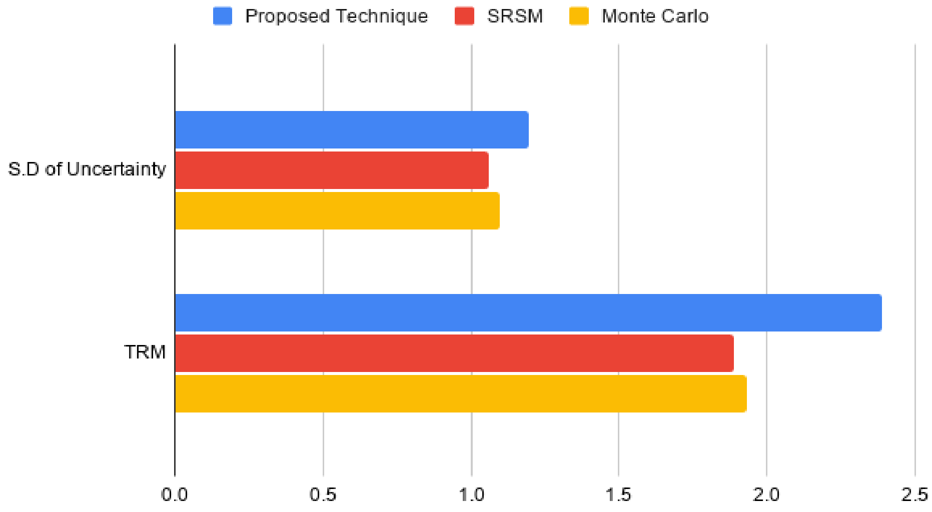

Fig. 4.3: Validation of TRM and S.D of Uncertainty values

The need for electricity grows the necessity of safety which lead to the accurate determination of TRM takes into account the ATC because additional can be transferred by knowing this term. The determination of TRM is needed for ensuring the adequacy and safety under any kind of unreliability. Moreover, the results show the linear relation between the transmission reliability margin and the S.D of Sensitivity which means abnormalities can never cross the reliability margin, if it does then the system will become unreliable. Even though this is an established fact, in this work it proved in a new distinct approach. The modified IEEE 6-bus is used to verify the effectiveness of the proposed method.

4.6 Conclusion

The need for electricity grows the necessity of safety which lead to the accurate determination of TRM takes into account the ATC because additional can be transferred by knowing this term. The determination of TRM is needed for ensuring the adequacy and safety under any kind of unreliability. Moreover, the results show the linear relation between the transmission reliability margin and the S.D of uncertainty which means abnormalities can never cross the reliability margin, if it does then the system will become unreliable. Even though this is an established fact, in this work it proved in a new distinct approach. The modified IEEE 6-bus is used to verify the effectiveness of the proposed method.

CHAPTER 5
CONCLUSION

5.1 Conclusion

In any power system network, the crucial point is to focus on system security; which means if there are any disturbances occur in the system, the whole system must work confidently under that reasonable range of uncertainty. For this reason, the estimation of TRM needs to do properly. Most of the calculation of ATC involves determination of TRM but in this proposed theory, ATC is considered for calculating TRM.

Before transferring available power through the network needs to know the secure margin whether it's safe for transferring that available power or not. So, the new proposed technique gives that secure margin calculation from that available power transfer as well as system parameter uncertainty. This technique incorporates some parameters such as: load, voltage magnitudes and transmission line admittances. For validation, the results from the proposed technique is compared with other existing results.

The validation of the technique through different approaches clearly shows that the results obtained using the proposed technique are close to the published ones. The whole process is done in MATLAB software for an existing standard IEEE 6 bus system and the validation is also done with a standard IEEE bus system.

5.2 Summary of Major Contributions

In various research works related to the determination of transmission reliability margin, focused on load parameter several times rather than other parameters. Some works also mentioned line impedances and voltage magnitudes but the explanation of calculating TRM was quite equivocal. So, the first objective of this thesis was to develop a technique to determine TRM for these three distinct parameters (load, line impedances and bus voltage magnitudes) by AC load flow method. Additionally, ATC calculation was done for real power but in this technique both real and reactive power are considered and sensitivity was done only for load but in this approach load, line impedances and bus voltage magnitudes were considered. Based on this objective, the calculation of TRM was done smoothly and the results are quite satisfactory; the validation of this technique was showed in chapter 2 at section 2.7.

Moreover, previously ATC calculation was done for DC load flow but not TRM; so to achieve this, DC load flow method is used for two distinct parameters such as: load and line impedances to determine TRM as well as results were quite acceptable; the validation of this technique was presented in chapter 3 at section 3.7.1.

In some cases, DC load flow could not apply for voltage magnitudes and reactive power as discussed earlier, voltage assume constant for DC load flow. To solve this, DCQ load flow method was proposed; by this method TRM and ATC both were calculated for bus voltage magnitudes parameter. Moreover, validation of this technique was presented in chapter 3 at section 3.7.2.

Limitation of this work

The TRM computation is done only for Normal distribution but it can be done for other distributions like: Rayleigh distribution, Binomial distribution etc.

5.3 Recommendations for Future Works

Some restrictions are considered in developing the proposed technique of estimating TRM for IEEE 6 bus system. The technique is developed considering three system parameters. For developing more generalized technique, the suggestions for future research are as follows:

a. The procedure considered three parameters but other parameters like- generation dispatch, system topology, customer demand can be added.
b. Determine of TRM for Binomial distribution by DCQ load flow method.
c. Determination of TRM for Rayleigh distribution by AC load flow method.

LIST OF PUBLICATIONS

The contributions of this thesis have been published international conferences as listed below:

International Journal:

1. A. Nadia, A. Hasib Chowdhury, E. Mahfuj, M. Sanwar Hossain, K. Ziaul Islam, and M. Istianatur Rahman, “Determination of transmission reliability margin using AC load flow,” *AIMS Energy*, vol. 8, no. 4, pp. 701–720, 2020.

International Conferences:

1. A. Nadia and A. H. Chowdhury, “Transmission Reliability Margin Calculation by Modified DC Load Flow Method,” *2019 5th International Conference on Advances in Electrical Engineering (ICAEE),* Sep. 2019.

2. A. Nadia and A. H. Chowdhury, “Correlation between Transmission Reliability Margin and Standard Deviation of Uncertainty,” *2019 5th International Conference on Advances in Electrical Engineering (ICAEE),* Sep. 2019.

3. Nadia, A., Rahman, M.I., Rahman, M.S. and Chowdhury, A.H., 2020, “Interrelation Between TRM, Wind Power, and Wind Speed,” *In 2020 IEEE Region 10 Symposium (TENSYMP),* pp. 1743-1746, IEEE, June. 2020.

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