

RESEARCH ARTICLE

Available transfer capability calculation methods: A comprehensive review

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Summary

The ceaseless efforts by power system industries to promote sustainable and competitive electric power market structure in the deregulated environment have given rise to enormous research in the area of transfer capability of transmission networks. Due to high demand for electricity, transmission components are stressed to operate close to their operating limits, and this leads to a decrease in transmission efficiency. To address this issue, efficient evaluation of available transfer capability (ATC) is crucial for system planning, operation, and control. Several approaches have been proposed for ATC computation. Surprisingly, a comprehensive literature review on ATC computation is yet to be efficiently presented. Researchers have been able to come up with fast algorithms, but most of these algorithms are not accurate, and the presented accurate techniques are not fast enough for online applications. This paper presents a comprehensive review of the different approaches for ATC determination. It provides the concepts, methods, and the features of the ATC. For each technique, the state of the art of the several contributions made by researchers has been highlighted. This review reveals that there are issues regarding ATC calculation methods that need attention: the development of fast and accurate algorithm incorporating system dynamics and system uncertainties in ATC determination. Additionally, efforts on the incorporation of renewable energy generation in the ATC evaluation need to be intensified. This review will serve as one in all for researchers as well as a guide for the entrants in this field.

KEYWORDS

artificial intelligence, available transfer capability, dc power flow, optimal power flow, repetitive power flow

1 | INTRODUCTION

Power system industry restructuring, known as deregulation, targeted at controlling the existing monopoly structure by introducing competition at different levels of utilities attracts non-governmental participation in the power system investment and control. The deregulated structure consequently improves the power marketing operations,¹ system's efficiency, and efficient customer service deliveries. In return, the power marketing activities have mitigated the

problems associated with generation expansion planning, such as the determination of types, locations, and construction period of new generation facilities required to be added to the existing equipment to meet the growing demand.² The operations of various utilities are included in the generation and distribution, and the decision about generation schedules and load dispatch is based on their contract agreement.³ Therefore, the power flow (PF) schemes in the deregulated environment are presumably different from the previously existing monopoly structure.³ All stakeholders try to take advantage of cheaper derivation and broader profit differences; this consequently leads to transmission network congestion. Transmission congestion could lead to the violation of voltage limits, voltage stability, and thermal limits, thereby threatening the system security. To solve this, available transfer capability (ATC) must be accurately estimated and optimally utilized.

Overestimation of ATC can lead to system instability which could result to cascading collapse⁴⁻⁷ and underestimation of ATC value capable of causing underutilization of the power system resources which can subsequently lead to loss of capital as a result of ineffective marketing operations. For example, the major blackout in the North-eastern United States and Ontario in August 2003 was a result of an overestimation of ATC.^{7,8} Therefore, the results of under/over-estimation of ATC have enormous adverse effects on the utility. The United State Federal Energy Regulatory Commission (FERC) established Open Access Same-Time Information System (OASIS) in which all interconnected companies are required to send their ATC value at a regular interval to serve as a reference value for electricity market activities.^{5,9} This information about the size of ATC is vital to system utilities and the planner as it depicts the general performance of the power system regarding efficiency and economic activities.¹⁰ Independent system operators are required to regularly update their ATC on OASIS for efficient system operation.

The independent system operator (ISO) is a body charged with the responsibility of coordinating the activities of market participants, system security and stability monitoring, balancing between demand and supply, and maintaining system reliability.^{11,12} It is also the responsibility of the ISO to have the knowledge of the system conditions and the ATC for the next business events.¹³ Any contract for power transfer demand should be within the range of ATC of the interconnected systems. Therefore, it is imperative to accurately calculate the ATC value to evaluate the energy production for efficient marketing operations. The flexibility, robustness, and system security are dependent on the amount of ATC which the system can accommodate for power transfer. An accurate value of ATC can be used in forecasting the future upgrading of the transmission network.¹⁴ The precise calculation of ATC should include the system constraints such as voltage limit, thermal limit, voltage stability limit, real and reactive power generation limit, and system uncertainties.⁹

Essentially, ATC is a measure of the extra transmission capability above the base case power transfer for the purpose of power marketing.⁹ ATC value can be derived by considering various parameters relating to transfer capabilities such as total transfer capability (TTC), transmission reliability margin (TRM), and capacity benefit margin (CBM). TTC is the summation of all the network transfers (base case and commercial transfers) including the margins for system security and reliability, and existing transmission commitments (ETC). TRM is the network margin reserved for system uncertainties^{9,15} whereas, CBM is the network margin reserved for the utilities to have access to external generation in case of emergency generation outages.^{9,16} It is measured by using loss of load expectation.

The aim of this paper is to produce a comprehensive review of the deterministic ATC determination methods. The deterministic techniques include linear approximation methods (LAMs), repetitive power flow (RPF), continuation power flow (CPF), optimal power flow (OPF) (conventional and artificial intelligence [AI] techniques), stability-constrained methods.^{17,18} The state-of-the-art of each technique is reviewed while emphasizing the merits and demerits of each of the approaches. The remainder of the paper is arranged as follows. Section 2 presents total transfer capability and transfer capability margins, while Section 3 discusses ATC determination methods. Sections 4 and 5 discuss uncertainties in ATC computation and comparison of all the methods, respectively. Section 6 presents the future directions and suggestions, while Section 7 concludes this study.

2 | TOTAL TRANSFER CAPABILITY AND TRANSFER CAPABILITY MARGINS

TTC represents the maximum amount of power transfer that transmission network can accommodate while meeting the pre-specified and post-specified contingency system conditions. The transfer capability margins are TRM and CBM. The graphical representation of these terms is as shown in Figure 1.¹⁹ It depicts how TTC values vary with the different system limits.

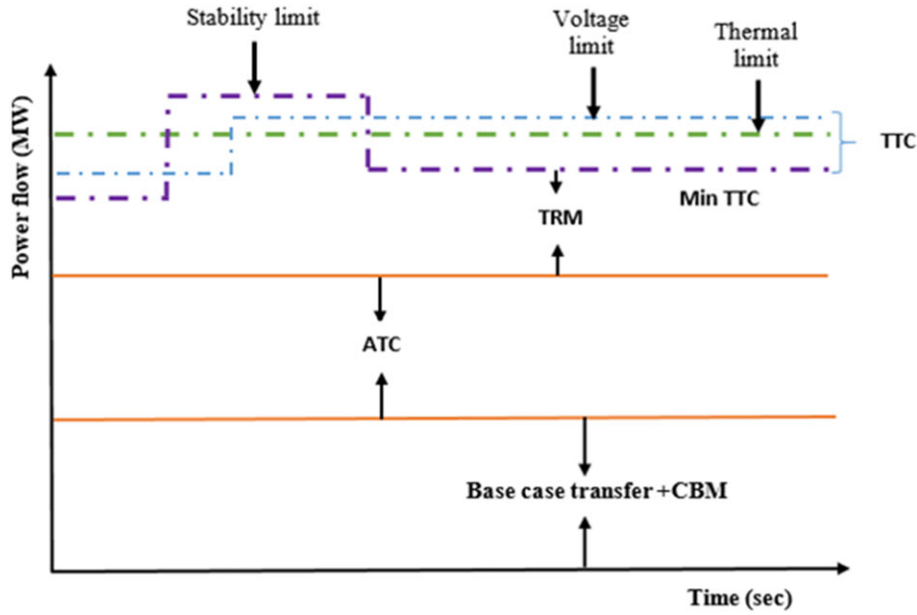


FIGURE 1 ATC limitations and the related parameters

Mathematically, ATC can be expressed as follows⁹:

$$ATC = TTC - TRM - ETC(\text{including CBM}). \quad (1)$$

The computation of transfer capability is commonly based on computer simulations of the interconnected system operation under an assumed set of operating conditions. The simulations are generally performed offline prior the attainment of that operational state by the system. Each simulation depicts a specific operating state of the interconnected systems based on the predictions of many factors. These factors include projected load demand, generation dispatch, system configuration, base case schedule transfer, and system contingencies.⁹ The breaking and dotted lines represent the TTC at different system limits as shown in Figure 1. Moreover, in the power system transfer capability calculation, the simulation is based on the equality and inequality constraints of load flow equations and the system limits (thermal, voltage, and stability), respectively. The results of the simulation give TTC values which vary with the system limits. Next, the ATC values can be obtained by deducting other parameters (TRM, existing transmission commitments, and CBM) from the TTC values. The ATC can be increased/decreased depending on the system operating conditions and the system limits. The purple line is the most restricted TTC value as shown in Figure 1 (Min TTC) and, hence, taken as the systems' TTC.

2.1 | Total transfer capability

The calculation of TTC between the sink and source areas can be performed via interconnected network simulation. To simulate power transfer from source to sink, the complex load at every load bus in the sink area and the active power injected at generator busses in the source area are increased in an incremental step until a system component or system limit (voltage limit, thermal limit, or stability limit) is reached.^{20,21} A contingency power transfer can also be simulated for few lists of contingencies, using an outage of a generator, a transformer, or a transmission line. The least transfer capability is then chosen as the TTC.

TTC computation can be formulated using CPF as a single unknown parameter, λ , which is maximized for each computation of TTC case. The power injections at the participant busses in the source and sink areas are given as linear functions of the scalar parameter λ . The TTC formulations are as follow^{20,21}:

Maximize λ
subject to

$$P_{Gi} - P_{Li} - \sum_{j=1}^N U_i U_j Y_{ij} \cos(\theta_{ij} - \varphi_i + \varphi_j) = 0 \quad (2)$$

$$Q_{Gi} - Q_{Li} - \sum_{j=1}^N U_i U_j Y_{ij} \sin(\theta_{ij} - \varphi_i + \varphi_j) = 0 \quad (3)$$

$$U_i^{\min} \leq U_i \leq U_i^{\max}, \forall_i \in N \quad (4)$$

$$|S_{Li}| \leq S_{Li}^{\max}, \forall_i \in N_L \quad (5)$$

To effect the generation and load changes, the active power generation and the active and reactive loads in the source and sink areas, respectively, need to be modified using the scalar parameter λ .

$$P_{Gi} = P_{Gi}^0(1 + \lambda k_{Gi}) \quad (6)$$

$$P_{Li} = P_{Li}^0(1 + \lambda k_{Li}) \quad (7)$$

$$Q_{Li} = Q_{Li}^0(1 + \lambda k_{Li}) \quad (8)$$

Therefore, the computation of TTC for the power transfer is expressed as in Equation 9:

$$TTC = \sum_{i \in \text{sink}} P_{Li}(\lambda_{\max}) - \sum_{i \in \text{sink}} P_{Li}^0 \quad (9)$$

2.2 | Transmission reliability margin

To mitigate the influence of system uncertainties on the electricity market activities and to minimize hourly schedule curtailments due to unexpected system events, the ISO usually implement TRM. TRM is the amount of transfer capability reserved for the system security, it is reserved for change in system operating condition and the associated system uncertainties in order to ensure reliable system operation.²² The associated uncertainties may be due to the loss of system components such as the loss of a critical unit. Implementation of TRM enables the market to optimize the tie-lines rather than facing the challenges of hourly curtailments. Curtailing the awarded schedules has adverse effects on the electricity market participants and the ISO because of the difficulties in finding the alternatives.²³ Additionally, because the computations of ATC are implemented before the beginning of the operating hour, the OASIS data are continuously displaying positive ATC value while periodic online curtailments have actually affected the market schedules.²⁴ Therefore, electricity market players remain uninformed that the displayed ATC on OASIS are higher than the actual values.

Accurate evaluation of TRM enables reliable power transfer and serves as an index for congestion management. The factors influencing the TRM value are load forecast, transmission line contingencies, generation patterns, and uncertainties associated with system operations and configuration.²² For the purpose of limited space and the intending focus of this paper, readers can refer to the several techniques which have been proposed in literature to evaluate TRM; details about TRM evaluation can be found in the literature.²²⁻²⁸

2.3 | Capacity benefit margin

In order to maintain reliable power supply, utilities usually reserve a particular amount of generation capacity to cater for unexpected generator outage and unexpected increase in demand. However, if these scenarios do not occur, the reserve capacity is termed as surplus facility.²⁹ To minimize this reserve capacity, utilities reserve some margin in the transmission network between interconnected areas, and this margin is tagged as capacity benefit margin (CBM). The CBM indicates the transfer capability margin reserved by the utilities in case of accidental generation outages. Accurate evaluation of CBM value is essential for ATC determination. Over/under-estimation of CBM value can lead to inaccuracy of ATC results, which can, respectively, lead to ineffective utilization of transmission system facilities and sudden generation deficiency.^{7,30}

The CBMs of the interconnected areas are usually evaluated by using the reliability index called loss of load expectation (LOLE). The LOLE is the average number of days or hours in a given period (usually 1 year) in which there is loss of load, ie, the daily peak load or hourly load is expected to exceed the available generating capacity.³¹ The value of LOLE authorized by the Mid-Atlantic Area Council (MAAC) is presently set at 1 day per 10 years (assumed to be 2.4 hours/year) as stipulated in the MAAC Reliability Principles and Standards.³² If the LOLE index of an area in an interconnected system is higher than the specified value (2.4 hours/year), the area needs to improve its generation reliability by importing power from external areas to meet the generation reliability requirement. However, if the area LOLE is less than the specified value, the area is rich in generation, and it could export power to support other areas

facing power deficiency. Therefore, in order to import power to the deficient areas, the load serving entity must reserve a particular amount of CBM depending on the specified value of LOLE. For the purpose of limited space and the intending focus of this paper, readers can refer to the several techniques which have been proposed in literature to evaluate CBM; details about CBM evaluation can be found in the literature.³³⁻⁴⁰

3 | AVAILABLE TRANSFER CAPABILITY DETERMINATION METHODS

Implementation of deregulation in the electric power sector started since 1996, and till present, many techniques are being proposed in literature for efficient ATC determination. The computation of ATC is based on simulating the interconnected transmission network operation for an assumed set of operating conditions. The RPF, CPF, and OPF methods are established on AC PF models. LAMs are based on the determination of transfer capability of interconnected networks using sensitivity indices of the network, and stability-constrained methods are based on the computation of ATC considering dynamic stability limits.²¹ Deterministic methods are used daily for the analysis and assessment of the system planning and operation. It performs the steady-state simulation of power systems, ie, specific values of the system generations and demands of a particular network configuration are used to compute PF and the system states.⁴¹

3.1 | Linear approximation methods

The LAMs are based on the determination of transfer capability of interconnected networks by using sensitivity indices of the network. Power transfer distribution factor (PTDF) is used as an index to evaluate the incremental distribution factors associated with the transfer of power between two control areas/busses/regions. It shows a linear approximation of changes in lines' and interfaces' PF due to power transaction between buyer and seller.⁴² Both the active and reactive PFs are considered in AC PF-based PTDFs, and it gives accurate results in ATC evaluation compared with DC-based PTDFs.⁴³ However, it is complicated and time-consuming because of the incorporation of full AC PF for each generator outage contingency analysis. Therefore, DC PF method is commonly employed in LAMs. Basically, the relationship between active PF and bus angle which was established as part of the decoupled AC PF is employed in DC PF.

3.1.1 | DC power flow

The DC PF formulation is derived by incorporating the following assumptions in AC PF: the system losses and the reactive PF are ignored, all bus voltages are set to one per unit, and all control devices are fixed to a static control setting.⁴⁴

Therefore, the linear equation 10 can be used to represent the entire system:

$$\Delta P_i = \sum_{j=1}^N B_{ij} (\varphi_i - \varphi_j) \quad (10)$$

where; P_i is the real power generations at bus i , B_{ij} is the values of susceptance between the i and j , and φ_{ij} angles between voltages in busses i and j .

The only unknown variable is bus angle which can be determined using Equation 11:

$$[\Delta \theta] = [B']^{-1} [\Delta P] \quad (11)$$

where; P , B' , and φ are the vectors of active power injection, susceptance matrix, and bus voltage angle, respectively,

The procedures for the DC PF are as follows:

- Determine the bus injections P_i at each bus i as the algebraic sum of all generator into the bus minus the sum of all loads on the bus.
- Determine the line PF from Equation 10
- Evaluate Equation 11 to get the bus phase angle θ vector.
- Compare the line PF values with the line's MW limit to check for any overloads

3.1.2 | Power transfer distribution factor

From the point of view of PF, power transaction is a prescribed amount of power injected in a particular area by a generator and extracted at another area by a load. PTDFs are used to find the linear effect of a transfer (or change in injected power) on

the power systems' components. The values of PTDFs give a linear approximation of the changes in PF in the system elements (lines and interfaces) due to transactions between specific power marketing participants (buyer and seller).⁴⁵ The coefficient of the linear correlation between the power transaction and the PF on a particular line is called the PTDF. It is also termed as sensitivity because it measures the change in the transaction amount to a change in line flow.⁴⁶ For ATC within an area, the power transaction will be between the source bus and the sink bus. While for inter-area ATC, the transaction will be between generation busses in the source area and load busses in the sink area. Line outage distribution factors (LODFs) and generator outage distribution factors (GODFs) are used to incorporate line outage and generator outage contingencies, respectively. When the contingencies are incorporated, the corresponding values of PTDFs are termed as outage transfer distribution factors (OTDFs).⁴⁷ LODF is the sensitivity of the PF in a specified transmission line to a change in PF in another line in an interconnected transmission network. GODF is the sensitivity of the PF in a monitored branch to a generator outage and the restoration of the injected power by the generator from other generators.^{42,45,47}

Several approaches using linear approximation have been employed in literature.^{42,48-51} Linear ATC (LATC) technique for computing ATC values was proposed in Ejebe et al⁴² and applied to a bulk power system of 2149 bus system consisting of 38 areas. The power transfer was considered to be lossless (ie, the source power equals the sink power), and only the branch thermal limits are considered. Only power transfer from a single source to a single sink is considered in this technique, and the power transfer is assumed to be non-simultaneous. Comparison with CPF results shows that the method is about 30 times faster compared with CPF approach. However, the ATC results for the test system show an average deviation of about 11% compared with the CPF, ie, the ATC is underestimated. The difference is a relatively large percentage and is economically inefficient in a deregulated environment. Cook et al⁴⁸ proposed the application of linear phasor approach to AC PF in ATC determination to mitigate the drawback of conventional DC load flow. The base case contingency results were employed to compute active and reactive power outages distribution factors and subsequently used to change the DC PF to phasor AC analysis. AC-PTDF and participation factor have been used⁴⁹ to evaluate ATC in a combined economic emission dispatch environment, and the line outage contingency is considered in the ATC evaluation. A multi-objective optimization was employed to minimize both the fuel cost and total emission of the generators. Accurate results of less than 1% error (average), compared with the results from the power world simulator, were obtained. However, the method could not be applied to some contingency analysis evaluation. AC-PTDF was proposed⁵⁰ to find the various transmission system parameters due to a change in real power transactions at the base case and other operating conditions close to the base case (+10% and -10%). The results were more accurate than those obtained from DC PTDFs in comparison with AC load flow results.

3.1.3 | Summary and observations

LAMs are desirable as the transmission network sensitivity indices can be easily calculated and the ATC values can be quickly determined. They are commonly employed in the industry.⁵² The DC load flow and AC PF produce nearly the same results except in most severe situations such as low X/R ratio and significant changes in voltage and system losses.^{44,48} The DC load flow is capable of processing a huge number of contingencies to evaluate ATC and in comparison with CPF, the linear ATC computation is 25 times faster for large-scale systems.⁵³ However, DC load flow formulation incorporates some assumptions as stated earlier. These assumptions are not always realistic as each of them has a remarkable impact on the accuracy of the PF computations.⁴⁴ The method only considers thermal limits, but the voltage and reactive power limits are ignored.⁵⁴ Ignoring the voltage and reactive power limits may result in inaccuracy of the ATC values, particularly in a stressed system with limited voltage control and reactive power backup.⁴⁸ Linear phasor to AC PF in ATC and AC-PTDF were used in Cook et al and Manikandan et al,^{48,49} respectively, and a reasonable level of accuracies was achieved compared with conventional DC PF. Nevertheless, the future implementation of LAMs in a competitive power market is not guaranteed due to the poor accuracy of the results.

3.2 | Repetitive power flow and continuation power flow methods

The traditional Newton Raphson (NR) technique has the problem of singularity associated with the Jacobian matrix at the maximum loading point. As the system load increases, this leads to a saddle-node bifurcation point which correlates with the maximum loading point. In this situation, the Jacobian matrix becomes singular; hence, the traditional technique numerical solution becomes difficult.⁵⁵ To avoid this problem, some methods^{56,57} have been suggested via the adjustment of the traditional NR technique. A commonly used technique in power system industry to calculate the nose point which correlates to a specific parameter increase pattern is the RPF calculation to produce P-V and

Q-V curves along the parameter increase direction. In this method, the nose point is declared to be the operating point if it is the first point where the PF solution fails to converge.⁵⁸ RPF repeatedly computes traditional PF equations in a sequence of points along the given transfer directions.³³ However, this method is vulnerable to divergence problem due to singularity problem associated with Jacobian matrix around the saddle-node bifurcation point. To mitigate this problem, CPF was proposed in the literature.^{20,57,59,60}

The mathematical model of RPF is identical to that of CPF, but RPF is more open in terms of modification.^{33,61} That is, the kind of modification pattern to be adopted is not explicitly stated, the power injection direction vector is artificially allocated, and the method of checking the security stability constraints on each PF point is open. This lack of restrictions in RPF makes ATC solutions easier and simple to realize.⁶² CPF is the major calculation method employed in determining ATC. It is established to solve the PF problem by tracing the P-V curve employing predictor-corrector technique.^{63,64} It is the conventional approach for determining the maximum value of a scalar parameter in a linear function of changes in power injections at a specified set of busses in a PF problem. Conceptually, it increases the loading factor in discrete steps, and the result of the each step PF is solved.⁶⁵ It computes a set of augmented PF equations to get the solution curve passing through the nose point without facing the numerical difficulty of ill-conditioning.³³ The PF equations are parameterized, and the parameter increases in discrete steps and the resulting PF is solved. The process is continued until a particular limiting condition is reached.^{66,67} The purpose of the CPF is to find continuous PF solutions for a specific load change case.²⁰ The advantage of CPF is its ability to overcome the singularity problem of the Jacobian matrix. It is introduced to find the maximum loadability and therefore adapted for ATC computation.

Several methods based on RPF and CPF have been employed in literature for the determination of ATC.^{61,68-75} Ejebe et al⁶⁸ formulated ATC problem based on CPF with adaptive localization which improved the speed in solving a large number of contingencies, giving a considerable reduction in computation time. Using this technique, the results may be conservative as the loading factor increases along a particular direction without taking into account the control effects.⁷⁶ Prathiba and Rajan⁶⁹ and Patel and Girgis⁷⁰ proposed RPF and CPF incorporating fuzzy set theory to, respectively, estimate ATC values. Fuzzy logic is employed for the estimation of uncertainties associated with the ATC computation. The uncertainties associated with load parameters and bus injected power are treated as fuzzy variables following a possibility distribution. The results from the former are closer to the value obtained using conventional PF with a considerable reduction in computation time. Linear predictor only continuation method is used in Patel and Girgis,⁷⁰ RPF solution was avoided in this method which makes it faster than the conventional CPF and OPF. The system is assumed to have sufficient stability margin, and the system voltage limit is reached before encountering voltage instability. Voltage limits, thermal limits, and generator limits are the constraints considered in the ATC determination, and the results are more accurate and very close (with an average error less than 0.5%) to the results from AC PF in comparison with DC PTDF and AC PTDF. An improved CPF using a generalized minimum residual method known as CPF-GMRES method and expanded Newton Raphson-Seydel (NRS) were evaluated in Eidiani et al.⁷¹ The evaluation shows that the expanded NRS is reliable and faster compared with the modified CPF and conventional NRS. However, the techniques involve complex computations. Nireekshana et al⁷² proposed CPF and FACTS devices for the ATC determination and enhancement, respectively. The FACTS devices are used to maximize the power transfer during normal and contingency conditions. Cat optimization algorithm is employed to find the optimal location of the FACTS devices and as a tool to tune the FACTS parameters. The ATC results using FACTS and Cat swarm optimization for FACTS parameter settings have higher values compared with the conventional CPF results.

Kim et al⁷⁷ proposed a fuzzy set theory for CPF to incorporate system uncertainty in the TTC determination. The uncertainties related with bus injections and load parameters are represented by fuzzy variables. The number of iterations and the computation time of the proposed approach are less than those of traditional CPF. The proposed approach is 31.7 times faster than the traditional CPF, and the TTC value is closer to that of CPF. An alternative iterative CPF method with multiple load variation and generation economic dispatch patterns was used⁷³ to compute ATC for AC/DC transmission system. Unlike the conventional CPF technique, the piecewise linear model is integrated into the CPF technique which subsequently enables it to deal with nonlinear power injection. The results show that the power injection directions and multi-terminal DC operation model have remarkable effects on ATC. The method outperformed the conventional CPF technique in tracing the AC/DC system operation, although requires substantial computation. Zhou et al⁷⁴ modified the master-slave iterative CPF technique incorporating economic dispatch to calculate ATC. Nodal power injection mode selection was used in the ATC evaluation. In order to determine a more reliable ATC for nodal power injection in the sink area, the modal analysis was applied to search for a load fluctuation mode that commonly affects ATC value. Economic dispatch mode was used instead of the conventional allocation method to dispatch generators output in the source area. The proposed technique was compared with the conventional proportional increase approach, and the ATC results from the traditional method were higher than the results of the

proposed method. However, the conventional CPF technique is known to be conservative; hence, the results might be an underestimation of ATC values which can result in underutilization of transmission network. Incorporation of wind energy in the evaluation of ATC is proposed in Khosravifard and Shaaban⁷⁵; CPF is employed to evaluate the ATC correlating with maximum system loading. The influence of the wind energy is evaluated using a risk-based approach, and cumulative probability was used to measure the associated risk. The results show that there is a remarkable restriction in power transaction due to the risk associated with the intermittent nature of the wind energy; moreover, the related risk outweighs the system components' outages risk.

3.2.1 | Summary and observations

Generally, results of ATC calculations using CPF and RPF techniques are more accurate compared with DC PF. In RPF, the computation of PF solution is more straightforward, and the convergence time is less compared with CPF.⁷⁸ However, several issues have been raised regarding the accuracy of the RPF method.⁵⁸ First, the divergence point of the PF calculations (resulting from numerical failure) does not constitute the nose point (limitation due to physical feature). Hence, the determination of the nose point cannot rely on the limitation of numerical methods. Secondly, depending on the method employed for PF computation, the point at which the PF solution fails to converge may vary. Therefore, due to these issues, the accuracy of the RPF method cannot be completely relied on. In conventional CPF, the nodal power injection commonly adopted in ATC computation is linearly proportional to the base case load demand and base case generation in sink and source areas, respectively.⁷⁴ This approach corresponds to certain system operating condition which does not take into consideration the uncertainties associated with load and generation of the system. Therefore, the reliability and economic viability of the ATC value is weak in practical operation point of view. Although some of the literature cited above presents a modified CPF with the achievement of exciting results compared with the conventional CPF. Another significant disadvantage of CPF algorithm is substantial computation time which can be detrimental to prompt response on a request by the transmission users in real-time scenarios.

In general, the methodology used in RPF and CPF for power transfer is based on the general loading factor for a selected cluster of generators and loads,⁷⁹ and this might result in conservative ATC value because these approaches do not lead to optimal distribution of load increments between the selected busses at sink area and power injection at selected busses at source area. Furthermore, the stochastic features of the system load demands and generation uncertainties are not considered in these methods. Hence, there is a need to develop an algorithm for accurate and efficient determination of ATC incorporating the system uncertainties.

3.3 | Optimal power flow approaches

The reason for the emergence of optimal PF is to solve the optimal settings of a particular system network that optimizes a certain cost function while maintaining system equations, system security, and system components' operating limits.⁸⁰ Optimal power flow (OPF) problem is based on the optimization of steady-state operation of power system performance with respect to various system's constraints (equality and inequality). The mathematical formulation of OPF can be expressed as follows:

$$\text{Minimize } f_c(u, x) \quad (12)$$

Subject to

$$h_i(u, x) = 0 \quad (13)$$

$$g_j(u, x) \leq 0 \quad (14)$$

where u is the set of control variables in the system while x represents the dependent variables in the system. $f_c(u, x)$ is the cost function to be minimized, the equality constraints in Equation 13 are obtained from traditional power system equation in Equations 2 and 3, while the inequality constraints in Equation 14 are limits associated with control variables and the system operating limits.^{80,81} Several methods have been used to solve OPF problem ranging from conventional methods to AI techniques. Recent survey on OPF is presented in Khamees et al and Maskar et al,^{81,82} and some new methods for OPF problems are proposed in Pulluri et al and Sayah and Hamouda.^{83,84}

In the determination of ATC using OPF methods, ATC is formulated as an OPF problem. Unlike the conventional PF techniques, OPF problems are formulated as an optimization problem in which various optimization techniques, ranging from conventional OPF calculations to AI approaches, can be applied to the solution. It also serves as essential support to solve many problems in planning, operation, and control of the system networks.⁸⁵ The objective function is to maximize power transfer from sets of generators of the selected source area to the load busses of the selected sink area, subject to the PF equations and system operation limit constraints. The process of the optimization begins by modifying the power output of the generators in the selected source area and simultaneously increasing loads of the busses in the selected sink area while other areas' power and load are assumed to be unchanged. The equality and inequality constraints are enforced and are verified by the PF convergence and penalty factors, respectively. Therefore, the ATC between areas is determined by the summation of the loads in the sink area and can be expressed as

$$ATC = \sum_{i=1}^{NB} P_{Li} - \sum_{i=1}^{NB} P_{Li}^0 \quad (15)$$

where: $\sum_{i=1}^{NB} P_{Li}^0$ and $\sum_{i=1}^{NB} P_{Li}$ are the summations of loads in the base case condition and power transfer case, respectively.

3.3.1 | Conventional optimal power flow methods

In OPF-based ATC problem, security constrained OPF (SCOPF) methods are frequently employed to maximize power transfer between two control areas under the assumption that all OPF optimized parameters can be centrally dispatched.⁸⁶ This assumption cannot be satisfied in a decentralized environment.³³ The SCOPF is a modified OPF problem which takes into consideration the system operation constraints under an assumed set of contingencies.^{87,88} The SCOPF is a nonlinear, nonconvex, large-scale optimization problem with continuous and discrete variables grouped under the category of mixed integer nonlinear programming optimization problems. The inherent assumption of the conventional SCOPF is that, with or without post-contingency corrective measures, the system will remain stable after the event of a contingency and will attain a stable steady state.⁸⁹ The reliability of this assumption relies on the dynamics of the system which is not incorporated in SCOPF formulation. Therefore, the problem formulation of SCOPF is conservative, and this can result in unpredicted system instability. To subdue the drawback of the traditional SCOPF, a transfer-based SCOPF (TSCOPF) was proposed³³ under the assumption that only all OPF optimized parameters in the selected sink and source areas can be dispatched for use in deregulation power system structure.

Various conventional methods of OPF have been used in literature for the ATC evaluation.⁹⁰⁻⁹⁹ Contingency-constrained OPF (CCOPF) with fuzzy logic is formulated in Hahn et al⁹¹ as a multi-objective problem called fuzzy logic multi-objective CCOPF (FMCCOPF) to minimize both the operating cost at the base case and the post-contingency correction times. The shortcomings in OPF are overcome by parallelizing CCOPF using fuzzy logic approach to evaluate ATC, and the ATC values from FMCCOPF are higher compared with OPF and conventional CCOPF. A bi-level optimization model was proposed⁹⁶ in which the model was first converted to equilibrium constraints mathematical program and later changed to mixed-integer linear programming for evaluation of ATC. The results show that ATC decreases with the system load level due to the reduction in tie-line capacity and the remaining generation capacity. Also, change in the system topology has a different influence on the ATC. Linear programming approach is fast and straightforward, but the accuracy of the results is doubtful because of the over-simplicity of the PF equation. A method using OPF with self-adaptive improved PSO algorithm for ATC determination was proposed in Chen et al¹⁰⁰; the results show that the algorithm is more accurate and faster compared with Bender and basic PSO algorithms. Small signal security-based SCOPF was recommended⁹⁹ to determine TTC under some viable set of contingencies. The results from the approach are more conservative than those of traditional OPF and SCOPF, but it requires more computation time. Moreover, comparison with SCOPF shows that the computational complexity involved outweighs the accuracy.

Evaluation of ATC using Benders decomposition approach has been used.⁹⁷ The problem formulation is divided into master problem and sub-problems which deals with steady-state operating condition and contingency conditions, respectively. Each sub-problem is separately solved, and a Lagrange multiplier is used to generate a linear constraint of the sub-problem which subsequently added to the master problem. The results from the proposed method are compared with the PTDF method, and the proposed method produces higher ATC value than the PTDF method. The percentage error from the results ranges from 20% to 40% when compared with the PTDF technique. However, Bender decomposition algorithm can easily fall into the local optimal solution because it only uses single search mechanism.

To obtain an optimal solution with the above OPF methods, the convexity of the objective function matters.²¹ However, OPF is a nonlinear, non-convex, large-scale optimization problem with continuous and discrete variables. It is grouped under the category of mixed integer nonlinear programming optimization problems. Hence, many local minima can exist particularly for the highly nonlinear system.^{101,102} Furthermore, these methods face challenges in dealing with inequality constraints. Therefore, the optimal solution is not guaranteed due to direct search approaches. There is a possibility of being stocked in local optimal solution or divergence especially in a highly nonlinear system.

3.3.2 | Artificial intelligence approaches

AI approaches are employed to avoid local optimal solution associated with conventional optimization techniques, especially for highly nonlinear systems. Different AI techniques have been used in the determination of ATC such as an artificial neural network (ANN), genetic algorithm (GA), bee algorithm (BA), particle swarm optimization (PSO), and evolutionary programming (EP).

Neural network approach

Remarkable progress has been achieved using ANN in the ATC evaluation due to its robustness, fastness, and its ability to solve complex nonlinear problems which are difficult to solve analytically. The fast algorithms commonly employed for ATC calculation are usually based on approximate methods incorporating several assumptions for simplicity. Accurate techniques are computationally expensive and time-consuming. However, ANN-based ATC evaluation is moderately accurate, and real-time update by the system operators can be achieved quickly as the system condition changes. In ATC determination, training data are generated by using different load patterns. The loads at all busses are perturbed randomly to generate different load patterns and the load flow solution for each pattern at based case and contingencies are obtained using either RPF or OPF technique to compute the ATC.^{103,104}

Generally, the power generation at the source busses and the active and reactive loads at all busses together with the pool demand and line index denoting the line outage of the associated line are employed as the input for the neural network (NN) training.^{104,105} The feature of the input is usually extracted by using techniques such as principal component analysis, random forest^{104,106,107} etc. to select the inputs with a more significant effect on the ATC values. The selection is to reduce the dimensionality of the input and the size of the network. The ideal diagram of the training model for ATC evaluation is as shown in Figure 2, where P_G , P_L , Q_L , P_P , I_L , and $ATC_1 \dots 5$ are active power generation at seller busses, active load demand at buyer busses, reactive load at buyer busses, pool demand, line index, and ATC values, respectively.¹⁰⁴ After the training of the network, the network is validated by analyzing the results and then used to predict ATC value in a real-time application using a set of input data. The relative error can be used to explain the results by comparing the exact outputs from either RPF or OPF with that of NN as expressed in Equation 16.¹⁰³

$$Relative\ error = \left(\frac{A_i - E_i}{E_i} \right) * 100\% \quad (16)$$

where: A_i is the estimated values of ATC using NN while E_i is the exact value using either OPF or RPF.

Different NN techniques have been used in literature for ATC evaluation.^{103,104,107-109} The Levenberg-Marquardt algorithm based NN method is used for the assessment of ATC,^{104,107} and the ATC values were computed for various single line outage contingencies using CPF technique for each loading condition. TRM was incorporated in Pandey et al¹⁰⁷ in evaluating ATC under varying load scenario and single line outage contingency condition using distributed computing. For efficient input variable selection, random forest technique and principal component analysis were proposed in Jain et al and Pandey et al,^{104,107} respectively. The methods are very fast and accurate in comparison to conventional OPF, with maximum percentage-errors ranging from 0.723% to 1.96%.¹⁰⁷ Multilayer feedforward neural network (MFNN) was employed¹⁰³ to estimate the ATC values. The NN was trained by using quick prop algorithm. The method was proved to be fast and accurate; however, the bus-to-bus power transfer, which is fundamental in most of the power transaction, is not incorporated in this method. Jain et al¹⁰⁸ proposed radial basis function NN (RBFNN) method for ATC evaluation in bilateral and multilateral power transactions. The method is very fast compared with OPF, the required computation time for 39-bus and 246-bus systems are, respectively, 0.0071 and 0.0094 seconds, while the corresponding computation time using OPF method are 2.4804 and 82.9769 seconds, respectively.

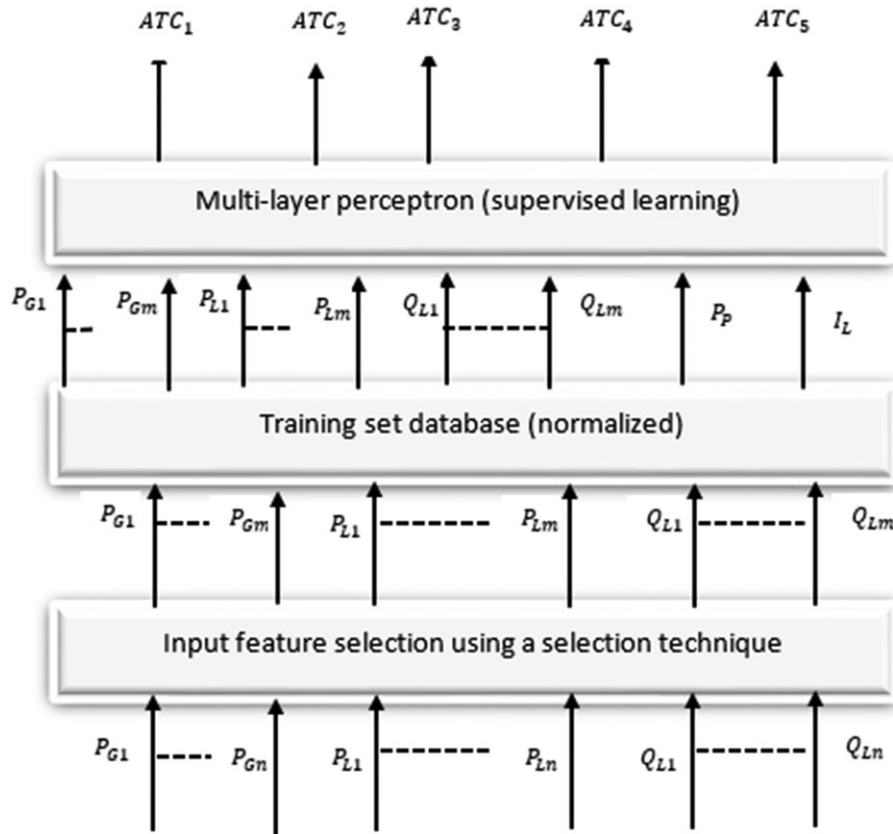


FIGURE 2 The ideal diagram of a training model for ATC determination¹⁰⁴

Other artificial intelligence approaches

Su et al¹¹⁰ formulated an OPF model, under static constraints and chaotic cloud PSO algorithm based on the golden section evaluation criteria, to solve the optimization problem. The objective of the algorithm is to maximize power transfer. In this algorithm, the particle swarm is divided into a standard particle, chaos particle, and cloud particle which employed golden section judge principle based on the fitness level. Different algorithm operations are assigned to every sub-swarm particle which subsequently increases the optimal speed and accuracy, thereby making the algorithm appropriate for the large-scale nonlinear problem. The results are more accurate, and the algorithm is faster compared with cloud PSO and chaos PSO. However, there was an increase in the amount of computation and iterations required. A new algorithm⁷⁹ using evolutionary programming (EP) approach to determine TTC between selected areas. The algorithm was based on complete AC OPF solution considering the effect of active and reactive PFs, voltage limits, and line flow limits. The objective function is to maximize power transfer from a set of generators in the source area to the loads in the sink area subject to PF equations and system operation limits constraints. The results indicated the superiority of the EP algorithm relative to CPF; the results are 23.2% (averagely) higher than the results from CPF.

3.3.3 | Summary and observations

Some excellent improvements have been made in the traditional techniques; however, they are associated with the following disadvantages: inability to solve practical power system problems, most of the mathematical equations have to be simplified, poor handling of system constraints, poor convergence solution and may fall into local optimum solution, only single optimal solution can be obtained in a single simulation run, they are very slow, and computationally expensive for large scale power systems. AI techniques are very fast, evident from the literature, they are excellent in dealing with the system constraints, and multiple optimal solutions can be obtained in a single simulation run. Therefore, they are appropriate in dealing with multi-objective OPF problems. However, neural networks are prone to overfitting, and they are like a black box in which the ability to explicitly distinguish the likely causal relationship is limited.¹¹¹ AI methods have

large dimensionality problem and ability to select appropriate training method. Moreover, substantial ATC data input is required for accurate evaluation of ATC which may consequently result in greater computational resources.

3.4 | Stability-constrained ATC method

Despite the ATC definition that should incorporate stability constraints for a set of postulated contingencies,¹¹² literature survey has shown that most of the methodologies employed in ATC calculations are based on steady-state viability. Few methods evaluate ATC by considering full representation of the power system dynamic behavior within the time frame of the transient stability. However, in many power systems, steady-state limits do not restrict point-to-point power transfer, but it is actually restricted by unwanted dynamic behavior succeeding large disturbances.¹¹³ Assessment of the entire system, when exposed to large and small disturbances, should be considered in ATC determination. The computation of ATC with dynamic stability limits is referred to as dynamic ATC (DATC).¹¹⁴ DATC is based on computing the maximum ATC while retaining the stability and viability of the transient response.¹¹³ In DATC, a number of constraints on the system transient behavior are considered, such as saddle-node bifurcation, loss of instability due to phase angle behavior, and electromechanical swing modes.¹¹⁵ The transient stability constrained ATC calculation can be formulated as a nonlinear programming with mixed-constraints composed of differential equations and algebraic equations as follows¹¹⁶:

$$\text{Minimize } f(x, y) \quad (17)$$

Subject to

$$h(x, y) = 0 \quad (18)$$

$$g(x, y) \leq 0 \quad (19)$$

$$\dot{x}_t^n = F^n(x_t^n, x, y) \quad (20)$$

$$H^n(x_t^n) \leq 0 \quad (21)$$

where $=[\delta^T, \omega^T]^T$, $y = [P_g^T, Q_g^T, V_i^T, V_j^T, \varphi^T]^T$, and $x_t^n = [(\delta^n)^T, (\omega^n)^T]^T$. x is the initial value of x_t^n at $t = 0$. The objective function in Equation 17 can be written as the negative value of the ATC on the specified transmission network, because the objective is to maximize the power transfer between the interconnected systems. Equations 18 and 19 represent load flow equation and steady-state security constraints, respectively, while Equations 20 and 21 represent constraints due to swing equations and transient stability constraints under contingency n , respectively.

There is challenge in solving these nonlinear equations due to the introduction of differential equation as shown in Equation 16 and the time-dependent variable x_t in Equation 17 into the traditional OPF problem. Evidently, the simplest way to solve this optimization problem is to indirectly deal with the differential equation and the time-dependent variable x_t .¹¹⁶ Therefore, the traditional transient stability constraints are converted to equivalents that can be easily handled by conventional optimization techniques; hence, there is degradation in result accuracy.

Several techniques have been employed in literature to determine DATC.^{62,105,114,115,117-129} An algorithm based on improved RPF is proposed⁶² for the determination of DATC in bulk interconnected grid. The effect of power incremental direction and uncertainty factors on ATC is considered and analyzed by using security regions. The security regions are used to reveal whether the system is transient stable or not after disturbances. This algorithm is only applied to bulk power systems. The proposed method was verified using the Central China power grid, and the results indicated that different power incremental directions led to different ATC values. The computation speed was improved by 8.1 times compared with the traditional RPF algorithm. An iterative method was employed in Hiskens et al¹¹⁷ for determining DATC. The algorithm is based on Gauss-Newton solution of a nonlinear least-squares problem. Trajectory sensitivities were used for the full representation of the system model in the form of differential-algebraic-discrete equations. The proposed algorithm was able to evaluate the critical condition which is closely similar to the trajectory produced using repeated simulation technique. However, the approach can only be used to assess a single free parameter which can be employed to produce marginally stable trajectories, and the computational complexity is associated with large systems. Interior point nonlinear

programming was developed¹¹⁸ to evaluate DATC with problem formulation based on OPF incorporating transient stability constraints into the traditional steady-state ATC problem. The results revealed that the steady-state value of TTC is higher than the transient TTC value. However, the system was unstable for the steady-state case after the contingency event. The proposed algorithm has an excellent convergence characteristic, and it is fast enough to converge to the optimal solution. In this approach, it is assumed that bus voltage limits are encountered first before the system can reach nose point and faces voltage stability problem; therefore, voltage stability limits are ignored in order to simplify TTC calculation.

An optimization problem incorporating Hopf bifurcation conditions has been developed¹¹⁹ to determine DATC in bilateral and multilateral transactions. An oscillatory stability-based contingency screening index incorporating the effect of transactions on the severity of contingency was used to identify critical contingencies to be included in the ATC determination. The proposed algorithm was able to determine the oscillatory stability constrained ATC accurately, and the results were observed to decrease slightly in the presence of the dynamic load in the system. Wei et al¹²⁰ employed the saddle-node bifurcation and Hopf bifurcation to determine static and dynamic ATC, respectively. The methodology was applied for static ATC and DATC in AC-DC power grid. The results were accurate compared with those of OPF with percentage errors of about 5% and 4% for static and dynamic ATC, respectively. However, the computational complexity makes the technique impractical. An approach to calculate ATC by incorporating dynamic constraints was suggested by Zhang et al.¹²² This method utilizes equilibrium equations to define pre-disturbance and post-disturbance steady-state constraints and dot product for rotor angle stability criterion. The ATC model was formulated as a differential-algebraic equation optimization problem, and the control variable parameterization method was employed to solve the optimization problem. The results compared with those of SCOPF showed reduced ATC values which indicate that SCOPF overestimates ATC values. The simulation suggests that the system will be unstable if a fault occurs when the SCOPF technique is employed.

However, in a real-time ATC calculation, several point-to-point power transfer and many contingencies are to be considered within a short time frame; using conventional approaches to evaluate DATC is hence impracticable. The feasibility lies in the integration of fast and accurate security assessment algorithms which include energy function methods, single machine equivalent (SIME), second-kick concepts, and trajectory sensitivity-based methods,¹¹³ and application of NN in real time is also feasible. OPF-based algorithms, which incorporate stability constraints, have been used in some literature.¹³⁰⁻¹³² These algorithms can reduce the computational burden with better convergence, but they are somewhat impracticable due to large dimension in problem formulation. Dealing with differential equations, which emerged from transient stability constraints in the optimization procedure also results in another difficulty.^{123,133}

A dynamic method for ATC calculation incorporating transient stability analysis and voltage stability analysis criteria was proposed by Eidiani and Shانهchi.¹²⁴ In this approach, potential energy boundary surface (PEBS) and point of maximum potential energy on post-fault system trajectory were used for transient stability analysis while voltage stability is assessed based on the estimation of the Jacobian matrix determinant. The method is fast and accurate compared with the transient stability analysis constrained maximum allowable transfer (MAT). The accuracy of the technique is 22% higher than the MAT method and 1% less than the exact method of computing ATC. An interesting technique using a support vector machine (SVM) has been suggested¹²⁵ for the estimation of DATC. Differential evolution algorithm was employed to tune the SVM parameters to get the accurate prediction of the DATC values. The New England 39-bus dynamic system is used for estimating DATC values for different cases. The results from the algorithm outperformed the ANN results. However, fixed percentages of TTC were adopted for CBM and TRM as 2% and 5%, respectively; adoption of deterministic values for these margins may result in inaccuracy of the results because the actual values of these margins can only be determined probabilistically. Support vector regression (SVR) approach was applied^{123,134} to determine transient stability-based DATC. The conventional method of PEBS is employed to determine DATC, and the data from PEBS are used to provide input patterns for various load scenarios to the SVR. The approach was used for multiple bilateral/multilateral transactions, and the results were validated using the multilayer perceptron neural network. The method is more accurate and faster than the MLPNN technique in comparison with the PEBS method.

A neural network-based method was proposed by Takahashi and Kumano¹²⁶ using a SVM to evaluate ATC. In this approach, a few different PF scenarios were assumed for a particular power system model, and ATC of each data were computed by the traditional technique using numerical simulations. The obtained data were used as training data for the SVM. The method is faster than the conventional time-domain simulation technique, and it gives approximate values of DATC. However, it is assumed, during the data training condition, that transmission reliability margin (TRM = 0) is zero. This assumption may lead to over-estimation of ATC values. Wada and Kumano¹²⁷ employed relevant vector machine (RVM) to estimate ATC incorporating transient stability constraints. The exact ATC values previously determined using the traditional stability analysis program were used as input patterns for the RVM to reduce the online computation time.

The method is faster and predicts approximate values of DATC with an average of estimated absolute error of 0.18 and the maximum value of the calculated absolute error of 0.50 of the ATC. A structure-preserving energy function model¹²⁸ was employed to calculate DATC for both bilateral and multilateral power transactions. New contingency severity was applied to reduce the credible contingencies to be considered. Contingency screening is essential for the fast assessment of both static and dynamic ATC. However, inaccurate selection of severe contingencies list can result in higher ATC, which is economically advantageous but detrimental to the system security.

3.4.1 | Summary and observations

Generally, it is crucial to investigate many disturbance cases with a critical loading condition being computed for each of the cases. The comparison between those critical conditions with the current operating point provides the desired DATC. The principle is crystal clear, but the implementation is tedious. No efficient technique has been available for practical implementation. Therefore, stability limits are commonly evaluated off-line for limited operating conditions and disturbance cases.¹¹⁷ However, AI techniques possess the capability of dealing with complexity of the DATC formulations.

4 | UNCERTAINTIES IN ATC COMPUTATIONS

The penetration of renewable energy sources in the modern power systems continues to grow following the European Union regulations on the share of renewable energy in the existing power systems by 2020.^{135,136} Modern power systems incorporate renewable energy sources in power generation, and these renewables, especially the wind and solar energies, are associated with uncertainties due to weather conditions.¹³⁷ Furthermore, uncertainties in system loads due to human activities and weather variability, possible outage of generators, and the change of network configurations also contribute to system uncertainties.⁴¹ The conventional deterministic methods determine the steady-state simulation of power systems, which indicate the snapshot of particular operating conditions of the network.¹⁹ Obviously, it is impractical to perform ideal load flow calculations for every feasible and likely combination of generating unit outage and bus loads because of the eventuality of the enormous large computational problems.^{19,138} To address this limitation of the deterministic approaches, probabilistic load flow techniques were proposed.^{19,139-141} Probabilistic load flow is an essential tool for providing detailed information for power system planning, operation, and control.¹⁴² It aimed at assessing node voltages and network flows in response to the system parameters' uncertainties.¹⁴³ The uncertainty analysis of power system performance is crucial, and generally, the uncertainties in any engineering system study can be illustrated probabilistically.¹⁴⁴ Probabilistic techniques are not only accurate but also give more information such as the expected value and variance of ATC.

Several methods have been proposed in literature to deal with the uncertainties in ATC computations. Some researchers employed Monte Carlo Simulation (MCS),^{19,139,145} some employed analytical approaches,^{146,147} while an approximate method which is a combination of numerical and analytic approaches was employed in Wei et al¹⁴⁸ for ATC computation. Few works^{146,149-151} have considered the incorporation of wind energy sources in ATC evaluation. Of all the aforementioned probabilistic approaches, MCS has proven to be more efficient than other techniques¹⁵² due to its ability to incorporate more uncertainty parameters and system constraints. However, MCS cannot settle the relativity among the system components, its accuracy cannot be relied on when handling stability constraint, and substantial computation time is required when dealing with large system due to the large number of load flow to be computed. A recent study¹⁵³ on the influence of demand response on ATC value employed a bi-level optimization technique. The upper level deals with the minimization of demand response compensation cost and power consumption cost, while the lower level deals with the economic dispatch and locational marginal prices.

The deterministic techniques are commonly employed for online application because they are faster and simple to implement in comparison with the probabilistic approaches. However, the results obtained using these methods are not accurate because the system uncertainties are incorporated. It is evident from the existing literature that adequate works have not been done on ATC using probabilistic methods relative to deterministic approaches. The limitations of the probabilistic approaches are the computation time and large amount of ATC data required for the accurate evaluation of ATC. Therefore, effective ATC data management should be established which can serve as an input for most of the probabilistic techniques.

5 | COMPARISON OF THE METHODS FOR ATC DETERMINATION

The comparison between reviewed methods in terms of merits and demerits of each approach is summarized in Table 1. Most of the approaches face computational complexity except through linearization of the load flow equations and incorporation of many assumptions. The accuracy of ATC results lies on the use of entire system dynamics, constraint limits, and system uncertainties which results in a considerable time of computation, while the fastness and simplicity rely on the use of linearized and simplified techniques. However, AI techniques are very effective for ATC evaluation in the face of large data.

TABLE 1 Comparison of different methods with advantages and disadvantages

Methods	Advantages	Disadvantages
Deterministic		
Linear approximation method.	Fast computation of the new ATC after some parameters are changed can be performed. Very simple and fast, 25 times faster for large-scale power systems compared with full AC PF techniques.	The accuracy of the results is degraded as the X/R ratio becomes low, especially in a stress system. When a large change occurs in the system operation, calculation speed may be slowed, and accuracy cannot be guaranteed. Nonlinear constraints such as VAR limits and transient stability limits cannot be included. Many assumptions and over simplicity also contribute to the inaccuracy of the results.
RPF and CPF	Ability to integrate reactive power flow, constant voltage reduction, voltage breakdown, and traditional thermal loading effects. Divergence can be avoided around voltage limit point. Full AC load flow is considered, and results are relatively accurate compared with LAMs.	Require sizeable computational time compared with LAMs. Because it adopts a common factor, conservative results may be obtained when calculating a special transfer limitation without optimization of generation and load distribution.
OPF-conventional	It can incorporate various complex constraints and different objective in the mathematical model. It can adopt the new optimization techniques easily. Maximum power transfer can be achieved; it is simple and fast when linear programming is used.	An optimal solution is not guaranteed due to local search, and it suffers the problem of complexity and convergence when nonlinear programming is used.
Stability-constrained	The entire system dynamic behavior within the time frame of transient stability is represented. Accurate ATC results can be guaranteed.	Very complex and rarely used for online applications.
Probabilistic		
Numerical method	It incorporates system uncertainties, it can easily handle a large amount of uncertainties for large power systems, and accurate ATC result can be obtained.	It cannot explicitly deal with the relativity among the system components, and the accuracy of this method degraded as the system size decreases. Substantial computation time is required due to a large number of load flow equations to be computed.
Analytical method	It considers most system uncertainties, and it is computationally efficient compared with the numerical method.	The accuracy of the results is degraded due to many assumptions and linearization of the complicated mathematical formulations involved.
Approximate method	Accurate ATC results can be obtained without linearization of the load flow equations, and the computational time is faster than numerical method.	Rarely used for real-time application due to large computation time.
Artificial intelligent method	AI techniques are excellent in handling complex nonlinear problems which are difficult to solve analytically, and accuracy of the results can be guaranteed.	Substantial ATC data input is required for accurate ATC evaluation which may consequently result in greater computational resources.

6 | FUTURE DIRECTIONS AND SUGGESTIONS ON ATC EVALUATION

So much have been achieved in ATC evaluation in terms of accuracy and fastness; however, the following points are listed as future directions and suggestions to enhance the determination of ATC in modern power systems.

- The computations of ATC are implemented before the beginning of the operating hour, while the OASIS data are continuously showcasing positive ATC values where periodic online curtailments have actually affected the market schedules.²⁴ Therefore, the electricity market players remain uninformed that the displayed ATC on OASIS are higher than the actual values. Self-adaptive algorithm incorporating the system TRM can be implemented for accurate online ATC display on OASIS.
- In practical scenario, there may be power wheeling on the third-party owned lines to avoid congestions on the direct lines between the market participants. The two critical determining factors of the wheeling rates are the prices associated with the real-time scenario and market-based competition; hence, effective economic analysis of the ATC between the concerned areas should be incorporated in ATC computations.
- Few works^{146,149-151} have considered the incorporation of wind energy sources in ATC evaluation using probabilistic approach. More works should consider the uncertainties associated with other stochastic renewable energy sources in ATC assessment as expansion plans in renewables continue.
- MCS has been proven to be an efficient technique for probabilistic ATC evaluation. However, large computation time and problem in dealing with system stability limit are parts of the drawback of the MCS.¹⁵² AI techniques are competitive with MCS, but large ATC data would be required for accurate evaluation. Therefore, effective ATC data management should be established which can serve as an input for the AI techniques
- Evaluation of transfer capability margins (CBM and TRM) should be integrated in ATC calculation using probabilistic approach.
- Real-time ATC values need to be continuously updated on the OASIS and ATC forecast using an effective statistical analysis should be considered to have the prior knowledge about the system security and economic viability of the network.
- The existing centralized system is gradually shifting to a decentralized system; therefore, the existing control system and energy management roles may not be suitable for the decentralized system. Hence, an approach taking into consideration a decentralized system, in which the control and coordination are decentralized, should be employed for ATC calculation.

7 | CONCLUSION

This paper has presented remarkable efforts made by researchers to evaluate the ATC of interconnected transmission networks. Various deterministic approaches for ATC computation have been presented with the distinguishing attributes of each of the methods. The methods, linear approximation, CPF, RPF, OPF, and stability-constrained, have been reviewed, evaluated, and compared; the merits and demerits of these methods are also highlighted. Uncertainties associated with ATC computations are discussed, and few existing probabilistic approaches are also highlighted. The linear approximation techniques are fast enough to be employed in online scenarios, but the algorithms are not accurate due to many assumptions. The stability constrained techniques capture the systems' dynamics, but the complexity makes their deployment impractical. Moreover, evidence from literature has shown that more efforts are required in the incorporation of renewable energy sources in the ATC evaluation due to the gradual shifting from fossil fuel generating systems to renewable energies. Therefore, it can be concluded that a robust algorithm incorporating sizeable renewable energy sources in real-time ATC evaluation is needed for proper assessment of ATC in modern power systems and fast algorithm incorporating almost all the constraints and systems' uncertainties. The contributions of this paper are as follow: the paper has critically and comprehensively reviewed the existing methods regarding the computation of ATC; issues regarding the accuracy and fastness of the existing techniques are highlighted; the merits and demerits of each technique are stated; and the improvements that are necessary for fast and accurate determination of ATC are also accentuated.

LIST OF SYMBOLS AND ABBREVIATIONS

Symbols

λ	scalar parameter denoting power transfer increment, $\lambda = 0$ for base case transfer
$\lambda = \lambda_{max}$	for maximum power transfer,
P_{Gi}, Q_{Gi}	active and reactive power generations at bus i ,
P_{Li}, Q_{Li}	active and reactive loads at bus i ,
$V_i, V_j, \varphi_i, \varphi_j$	magnitudes and angles of the voltages at bus i and j ,
Y_{ij}, θ_{ij}	magnitude and angle of the bus admittance matrix of the ij th element,
V_i^{min}, V_i^{max}	voltage magnitude limits at bus i ,
S_{Li}^{max}	limits of the i th transformer or line loading,
$ S_{Li} $	transformer or line loading,
N	number of busses,
N_L	number of branches.
P_{Gi}^0	active power generations at bus i in the source area,
P_{Li}, Q_{Li}	active and reactive loads at bus i in the sink area,
k_{Gi}	constant denoting the rate of change in the generation at bus i as λ changes,
k_{Li}	constant indicating the rate of load change at bus i as λ changes.
$\sum_{i \in sink} P_{Li}(\lambda_{max})$	summation of loads in sink area at a maximum value of λ , and
$\sum_{i \in sink} P_{Li}^0$	summation of loads in sink area when $\lambda = 0$.
$f_c(u, x)$	objective function
x	system-dependent variable
u	system control variables
δ	rotor angle of the generators
ω	angular speed of the generators

Abbreviations

ISO	independent system operator
FERC	federal energy regulatory commission
OASIS	open access same-time information system
TTC	total transfer capability
ATC	available transfer capability
TRM	transmission reliability margin
CBM	capacity benefit margin
LAM	linear approximation method
RPF	repetitive power flow
CPF	continuation power flow
OPF	optimal power flow
SCOPF	security constrained optimal power flow
TSCOPF	transfer-based security constrained optimal power flow
CCOPF	contingency constrained optimal power flow
PTDF	power transfer distribution factor
PF	power flow
LODF	line outage distribution factor
GODF	generator outage distribution factor
OTDF	outage transfer distribution factor
NN	neural network
ANN	artificial neural network
DATC	dynamic available transfer capability

PSO	particle swarm optimization
EP	evolutionary programming
NR	Newton-Raphson
NRS	Newton Raphson-Seydel
FACTS	flexible alternating current transmission systems
SVM	support vector machine
SRV	support vector regression
RVM	relevant vector machine
PEBS	potential energy boundary surface
MAT	maximum allowable transfer
RBFNN	radial basis function neural network
MFNN	multilayer feedforward neural network
SIME	single machine equivalent
MCS	Monte Carlo simulation
AI	artificial intelligence

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