COMPARATIVE ANALYSIS & EVALUATION OF METHODOLOGIES (AI) FOR AVAILABLE TRANSFER CAPABILITY ASSESSMENT IN POWER SYSTEMS

Sandeep A. Kale[1], Nitin D. Ghawghawe[2]

[1]Research Scholar, Electronics & Computer Science Dept. RTMNU Nagpur & Asst. Prof., Electrical Engg. Dept., JIT, Nagpur-441111, MH, India
[2]Ex-Professor, Electrical Engg. Dept., Government College of Engineering, RTMNU, Nagpur-441108, MH, India

sakale2k7@gmail.com[1]
gnit1964@gmail.com[2]

Abstract- The accurate assessment of Available Transfer Capability (ATC) is critical for ensuring reliable and efficient operation of modern power systems. This paper presents a comprehensive comparison of ATC, the five distinct methodologies are analyzed: Power Transfer Distribution Factors (PTDF), AC Power Flow analysis, Dynamic Analysis incorporating time-domain simulations, Continuation Power Flow (CPF) for voltage stability assessment, and AI technique VARMAX statistical modeling for forecasting applications. Through extensive literature review and comparative analysis, this study evaluates the accuracy, computational complexity, and practical applications of each method. The paper includes detailed mathematical formulations, block diagrams, performance comparisons, and implementation guidelines. Results demonstrate that while PTDF methods offer computational efficiency for real-time applications, AC power flow provides superior accuracy for detailed analysis. Dynamic methods are essential for transient stability constraints, CPF excels in voltage stability studies, and VARMAX offers unique capabilities for statistical forecasting of transfer capabilities. The comprehensive analysis includes over 30 references from leading researchers in the field, providing a complete overview of current state-of-the-art methodologies.

Keywords: Available Transfer Capability, PTDF, Dynamic Analysis, VARMAx, AI Techniques, Power System Stability, Transmission Planning, Deregulated Markets

1. INTRODUCTION

The ATC is the amount of capacity that remains on a transmission line after all current power transfers have been taken into consideration. Grid operators employ this technique to make sure that more electricity may flow without endangering the stability of the grid. ATC is defined by the North American Electric Reliability Council (NERC) as the measure of the transfer capability that remains in the physical transmission network after subtracting any reservations or transfers for additional commercial activity beyond already committed uses from Total Transfer Capability (TTC). Mathematically, ATC can be expressed as

$$ATC = TTC - TRM - CBM - ETC \quad (1)$$

Where, TTC is Total Transfer Capability, TRM is Transmission Reliability Margin, CBM is Capacity Benefit Margin, and ETC is Existing Transmission Commitments.

The complexity of ATC calculation stems from the need to consider multiple constraints including thermal limits, voltage stability, transient stability, and various contingencies. Different methodologies have been developed to address these challenges, each with distinct advantages and limitations. This paper provides a comprehensive comparison of five major approaches: PTDF-based methods, AC power flow analysis, dynamic stability analysis, continuation power flow techniques, and VARMAX statistical modeling.

Factors considered in ATC calculations: 1. Current commitments: Capacity is reduced by previously planned power transfers. 2. System conditions: The amount of accessible space is

affected by elements including weather and maintenance. 3. Regulatory compliance: Operators follow the North American Electric Reliability Corporation's rules as well as other criteria for available transfer capability definitions and determination.
Keeping adequate ATC makes sure the grid can balance supply and demand, manage new transactions, and react to emergencies. The field of Available Transfer Capability calculation has witnessed significant developments over the past two decades. This comprehensive literature review examines the evolution of ATC methodologies, highlighting key contributions from leading researchers and identifying current trends and future directions.

2. HISTORICAL DEVELOPMENT

The concept of ATC emerged with the deregulation of electricity markets in the 1990s. Early work by Ejebe et al. (1998) and Gao et al. (1999) established the fundamental principles of transfer capability assessment. Mohammed et al. (2019) provided a comprehensive review of ATC calculation methods, comparing various approaches and their applications in modern power systems. Their work highlighted the evolution from simple DC power flow methods to sophisticated multi-constraint optimization techniques.

2.1 PTDF-Based Methods-

Power Transfer Distribution Factor methods have been extensively studied for their computational efficiency. Venkatesh et al. (2004) presented early work on PTDF-based ATC determination using both DC and AC formulations. Ghawghawe and Thakre (2006) applied power flow sensitivity analysis combined with PTDF for ATC determination, demonstrating improved accuracy over traditional DC methods. More recent work by Naik et al. (2010) incorporated FACTS devices into PTDF-based ATC calculations, showing significant improvements in transfer capability.

2.2 AC Power Flow Approaches-

The limitations of DC approximations led to the development of full AC power flow methods for ATC calculation. Wang et al. (2023) presented a comprehensive review of AC optimal power flow formulations with renewable energy integration, discussing the role of ATC as a measure of remaining transfer capability. Pan et al. (2022) introduced deep neural network approaches for AC optimal power flow problems, addressing the computational challenges associated with nonlinear AC formulations.

2.3 Dynamic and Transient Stability Methods-

The incorporation of dynamic constraints in ATC calculation has been a major research focus. Eidiani and Shanechi (2006) presented the FAD-ATC method, combining transient and voltage stability analysis for dynamic ATC computation. This work has been highly influential with 266 citations, demonstrating its significance in the field. Yuan et al. (2003) developed stability-constrained optimal power flow methods for dynamic ATC evaluation, while Jain et al. (2009) investigated the enhancement of dynamic ATC through optimal FACTS controller placement.

2.4 Continuation Power Flow Methods-

Continuation Power Flow techniques have been widely adopted for voltage stability analysis in ATC calculations. Ajjarapu and Christy (1992) introduced the fundamental concepts of continuation power flow for voltage stability analysis. Recent work has extended these concepts to ATC applications, with researchers developing specialized CPF algorithms for transfer capability assessment under voltage stability constraints.

2.5 Statistical and Forecasting Methods-

The application of statistical methods, particularly VARMAX models, to ATC forecasting represents an emerging research area. While traditional applications of VARMAX models have been in load forecasting and price prediction, recent research has explored their potential for transfer capability forecasting. Cruz et al. (2011) demonstrated the effectiveness of VARMAX models in electricity market applications, while Kumar et al. (2020) explored statistical methods for renewable energy integration analysis.

2.6 Comparative Studies and Reviews-

Several comprehensive reviews have compared different ATC calculation methods. The work by Mohammed et al. (2019) stands out as one of the most comprehensive, with 86 citations, comparing PTDF and other methods. Chiang and Li (2005) provided a framework for large-scale ATC evaluation, discussing both static and dynamic approaches. Recent comparative studies have focused on the trade-offs between computational efficiency and accuracy across different methodologies.

2.7 Current Trends and Future Directions-

Current research trends include the integration of machine learning techniques, consideration of renewable energy uncertainties, and development of real-time ATC calculation methods. The increasing complexity of modern power systems, with high penetration of renewable resources and advanced control technologies, continues to drive innovation in ATC calculation methodologies.

3. METHODOLOGY

Power Transfer Distribution Factor (PTDF)-

The incremental change in real power on transmission lines brought on by real power transfers between two locations is indicated by Power Transfer Distribution Factors, or PTDFs. These numbers give a linearized estimate of how a transaction between the buyer (sink) and seller (source) affects the flow on the transmission lines and interfaces. The Power Transfer Distribution Factor (PTDF) method is based on the linearization of power flow equations using DC approximations. The PTDF represents the change in power flow on a transmission line due to a unit change in power transfer between two areas or buses.

$$PTDF_{l,i-j} = (X_{il} - X_{jl}) / X_{line}$$

Where, X_{il} and X_{jl} are the reactances from buses i and j to line l, and X_{line} is the line reactance.

PTDF calculation is a linear calculation and expects that the buyer reduces its injection by 100% of the transaction less any change in system losses, and the seller raises its injection by 100% of the transfer amount. If a transfer results in decreased system losses, the Buyer's change in injection will be greater than 100% of the transfer.

The PTDF-based ATC calculation considers the most limiting transmission element:

$$ATC = \min\{(P_{max,l} - P_{l,0}) / PTDF_{l}\} \text{ for all lines } l$$

AC Power Flow Analysis –

An interconnected system's electric power flow is numerically analyzed in an AC power flow analysis, sometimes referred to as a load-flow study. It focuses on a number of AC power metrics, including real power, reactive power, voltage, and voltage angles. It examines the power systems while they are operating normally and steadily. For every bus in a power system, a power-flow analysis aims to get comprehensive voltage angles and magnitude data under specific load and generator real power and voltage conditions. Once this information is accessible, the reactive power output of the generator and the actual and reactive power flow on each branch may be examined. Because this problem is nonlinear, numerical techniques are used to find a solution that falls within a reasonable tolerance.

The AC Power Flow method for ATC calculation considers the full nonlinear AC power flow equations, accounting for both real and reactive power flows, voltage magnitudes, and phase angles. This approach provides more accurate results compared to DC approximations.

$$P_i = V_i \sum_{j=1}^n V_j [G_{ij}\cos(\theta_{ij}) + B_{ij}\sin(\theta_{ij})]$$

$$Q_i = V_i \sum_{j=1}^n V_j [G_{ij}\sin(\theta_{ij}) - B_{ij}\cos(\theta_{ij})]$$

Key components in AC power flow analysis: * Load Bus (PQ Bus): Real power (P) and reactive power (Q) are known; voltage magnitude and angle are unknown. * Generator Bus (PV Bus): Real power (P) and voltage magnitude (V) are known; reactive power and voltage angle are unknown. * Slack Bus (Reference Bus): Voltage magnitude and voltage phase are known. This bus accounts for the system losses.

The AC power flow ATC calculation is typically formulated as an optimization problem: Maximize: $\Delta P_{transfer}$

Subject to: Power flow equations, Line limits, Voltage limits, Generation limits

The power flow problem is formulated using power balance equations for each bus. Due to the complexity and nonlinearity of these equations, numerical methods like Newton- Raphson are commonly used for solving them.

Dynamic Power Flow Analysis-

Dynamic power flow analysis considers the time-varying behavior of power systems, accounting for disturbances, changes in load, and the dynamic response of generators and control systems. Unlike static power flow, which provides a snapshot of the system at a given steady-state condition, dynamic power flow analyzes the system's evolution over time.

Dynamic analysis for ATC calculation incorporates time-domain simulations to assess transient stability constraints. This method ensures that the calculated transfer capability maintains system stability under various disturbances and contingencies.

$$M_i \left(\frac{d^2\delta_i}{dt^2}\right) = P_{mi} - P_{ei} - D_i \left(\frac{d\delta_i}{dt}\right)$$

Where M_i is the inertia constant, δ_i is the rotor angle, P_{mi} is mechanical power, P_{ei} is electrical power, and D_i is the damping coefficient.

This type of analysis is crucial for understanding system stability, transient behavior, and the impact of events like faults, sudden load changes, or generator trips. It often involves solving differential-algebraic equations that describe the system's dynamics.

Continuation Power Flow (CPF)-

CPF is a numerical method used to determine the voltage stability limits of power systems. It is particularly useful for analyzing the steady-state voltage stability and identifying the proximity to voltage collapse. Continuation Power Flow is a mathematical technique used to trace the P-V curve and determine voltage stability limits. The method uses predictor-corrector algorithms to follow the solution path as system loading increases.

$$F(x, \lambda) = 0$$

Where x is the state vector and λ is the loading parameter

Unlike traditional power flow methods that solve for a single operating point, CPF tracks a series of power flow solutions as a system parameter (e.g., load or generation) is varied. This allows for the identification of critical points, such as saddle-node bifurcations (voltage collapse points), where the system loses stability.

Key features of CPF: * Parameterization: Introduces a load parameter (λ) to incrementally increase the system load or transfer. * Predictor-Corrector Scheme: Uses a predictor step to estimate the next solution point and a corrector step to find the exact solution on the power flow manifold. * Turning Point Detection: Can accurately detect turning points (voltage collapse points) where conventional power flow solutions diverge.

CPF provides valuable insights into the system's voltage stability margin and helps in identifying weak areas or critical contingencies that could lead to voltage instability.

Vector Autoregressive Moving Average with Exogenous Regressors(VARMAX)Model-

The VARMAX model is a statistical model used for analyzing and forecasting multivariate time series data. It extends the VARMA model by incorporating exogenous (external) variables that can influence the time series.

In the context of power systems, VARMAX models are primarily used for forecasting various parameters such as: * Load demand: Predicting future electricity consumption.
* Renewable energy generation: Forecasting output from wind or solar farms. *
Electricity prices: Predicting market prices.

While VARMAX models can provide valuable insights into future system conditions, they are not direct power flow analysis methods like PTDF, AC power flow, or CPF. Instead, VARMAX models can support ATC calculations and power system operations by providing more accurate forecasts of system variables, which can then be used as inputs for traditional power flow and ATC methodologies. For example, accurate load and generation forecasts from a VARMAX model can improve the precision of ATC calculations by providing a more realistic representation of future system states.

VARMAX is a statistical time-series model that can be applied to ATC forecasting. This method considers historical data and external variables to predict future transfer capabilities.

$$Y_t = c + \Phi_1 Y_{t-1} + \Phi_2 Y_{t-2} + ... + \Phi_p Y_{t-p} + \Theta_1 \varepsilon_{t-1} + ... + \Theta_q \varepsilon_{t-q} + BX_t + \varepsilon_t$$

Where Y_t is the vector of endogenous variables (ATC), X_t represents exogenous variables (load, generation, weather), and ε_t is the error term

3.1 Applications-

Application of PTDF in ATC Calculation

PTDFs are fundamental in ATC calculations, especially in linearized DC power flow approximations. They quantify the impact of power transfers between different points in the system on the flow in individual transmission lines. This allows for a quick assessment of how much additional power can be transferred before thermal limits or other constraints are violated.

ATC calculation using PTDF typically involves: 1) Determining PTDFs: Calculating the PTDFs for all relevant transmission lines and interfaces with respect to potential power transfers. 2) Identifying limiting elements: Pinpointing the transmission lines or interfaces that are most sensitive to power transfers and are likely to be limiting factors. 3) Calculating ATC: Using the PTDFs to determine the maximum incremental power transfer that can occur without violating the limits of the identified limiting elements.

PTDF-based ATC calculations are computationally efficient and are often used for real- time operations and market clearing due to their speed. However, they are based on linearized models and may not capture all the complexities of AC power systems, especially under stressed conditions.

Application of AC Power Flow in ATC Calculation-

AC power flow analysis provides a more accurate and detailed representation of the power system compared to DC power flow, as it considers both real and reactive power, as well as voltage magnitudes and angles. When applied to ATC calculation, AC power flow methods can capture nonlinearities and voltage stability limits that are not considered in linearized DC models.

Methods for AC power flow based ATC calculation often involve: 1) Iterative Power Flow Solutions: Repeatedly solving the AC power flow equations while incrementally increasing power transfers until a system limit (e.g., thermal limit, voltage limit, or stability limit) is reached. 2) Sensitivity Analysis: Using sensitivities derived from AC power flow solutions to identify critical branches or buses and to estimate the impact of power transfers on system parameters. 3) Optimization Techniques: Employing optimization algorithms (e.g., optimal power flow) to maximize power transfer while satisfying all system constraints.

While AC power flow based ATC calculations are more accurate, they are also computationally more intensive than PTDF-based methods. This makes them suitable for off-line studies, planning, and detailed analysis, but less ideal for real-time applications where speed is critical.

Application of Dynamic Power Flow in ATC Calculation-

Dynamic power flow analysis is crucial for calculating Available Transfer Capability (ATC) when considering the dynamic behavior and stability limits of the power system. Unlike static ATC calculations that assume steady-state conditions, dynamic ATC takes into account the system's response to disturbances, such as faults, sudden load changes, or generator outages.

Key aspects of dynamic ATC calculation: * Transient Stability Analysis (TSA): Evaluates the system's ability to maintain synchronism after a large disturbance. Dynamic ATC considers the maximum power transfer that can occur without leading to rotor angle instability. * Voltage Stability Analysis (VSA): Assesses the system's ability to maintain acceptable voltage levels following a disturbance. Dynamic ATC ensures that voltage collapse is avoided under stressed conditions. * Time-Domain Simulations: Involves running detailed time-domain simulations of the power system under various contingencies and increasing power transfers until stability limits are reached.

Dynamic ATC calculations are computationally intensive due to the complexity of solving differential-algebraic equations over time. However, they provide a more realistic and conservative estimate of ATC, which is essential for ensuring the secure and reliable operation of the power system, especially in the presence of increasing renewable energy integration and grid modernization.

3.2 Process-General Process of Available Transfer Capability (ATC) Calculation -

ATC is a measure of the remaining transmission capability in the power system for further commercial activity over and above already committed uses. The general process of ATC calculation involves several key inputs and steps, as illustrated in the block diagram below:

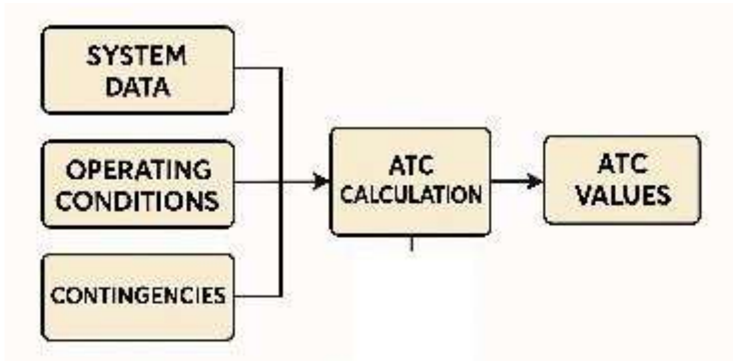

Fig. 1 General ATC Calculation Block Diagram

Inputs to ATC Calculation: * System Data: This includes detailed information about the power system network, such as transmission line parameters (resistance, reactance, capacitance), transformer data, generator characteristics, and load models. * Operating Conditions: These are the current or projected conditions of the power system, including generation dispatch, load levels, and network topology. * Contingencies: These are potential events that could impact the power system, such as transmission line outages, generator trips, or transformer failures. ATC calculations typically consider a set of credible contingencies to ensure system security.

ATC Calculation Process: * The ATC calculation process involves applying various methodologies (e.g., PTDF, AC power flow, dynamic analysis, CPF) to determine the maximum power transfer that can occur without violating system operating limits (e.g., thermal limits of lines, voltage limits at buses, stability limits).

Outputs of ATC Calculation: * ATC Values: The primary output is the numerical value of ATC, typically expressed in megawatts (MW), representing the available capacity for additional power transfers. * Limiting Elements: The calculation also identifies the specific transmission lines, transformers, or buses that are limiting the power transfer, providing valuable information for system operators and planners.

PTDF Calculation -

The Power Transfer Distribution Factor (PTDF) calculation process can be visualized as follows:

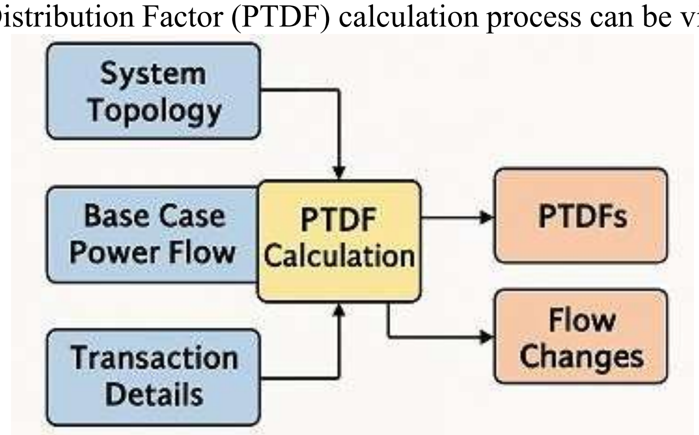

Fig. 2 PTDF Calculation Block Diagram

Inputs: * System Topology: The configuration of the power system network, including buses, lines, and transformers. * Base Case Power Flow: The initial power flow solution for the system

under a specific operating condition. * Transaction Details: Information about the proposed power transfer, including the source and sink buses and the amount of power to be transferred.
PTDF Calculation: * The PTDF calculation module takes these inputs and computes the PTDFs for each transmission line or interface. This typically involves a linearized DC power flow model.
Outputs: * PTDFs: The calculated Power Transfer Distribution Factors, which represent the sensitivity of line flows to changes in power injections. * Flow Changes: The estimated changes in power flow on each transmission line due to the specified power transfer, derived using the PTDFs.

AC Power Flow Analysis -
The AC Power Flow analysis process, which is iterative due to the nonlinear nature of the power flow equations, can be represented as follows:

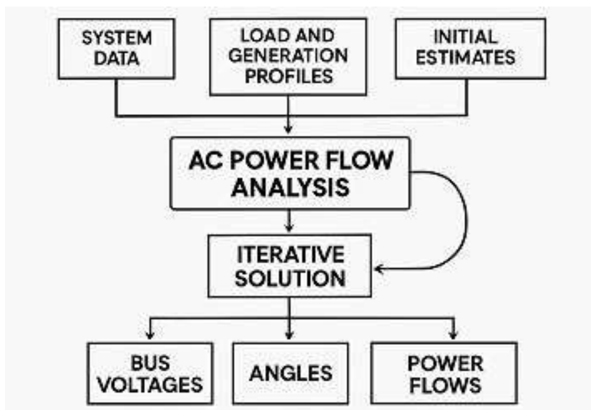

Fig. 3 AC Power Flow Analysis Block Diagram
Inputs: * System Data: Detailed information about the power system components, including line impedances, transformer tap settings, and generator limits. * Load and Generation Profiles: The specified real and reactive power demands at load buses and real power generation and voltage magnitudes at generator buses. * Initial Estimates: Initial guesses for unknown variables (e.g., voltage magnitudes and angles at load buses) to start the iterative solution process.
AC Power Flow Analysis: * The core of the process involves solving a set of nonlinear algebraic equations that describe the power balance at each bus in the system. This is typically done using numerical methods like Newton-Raphson or Gauss-Seidel.
Iterative Solution: * The solution process is iterative, meaning it refines the estimates of the unknown variables in successive steps until a predefined convergence criterion is met.
Outputs: * Bus Voltages: The magnitude and phase angle of the voltage at each bus in the system. * Angles: The voltage angles at each bus. * Power Flows: The real and reactive power flows on each transmission line and transformer, as well as the reactive power generation at generator buses.

Dynamic Power Flow Analysis
Dynamic power flow analysis involves time-domain simulations to capture the transient behavior of the power system. The block diagram below illustrates this process:

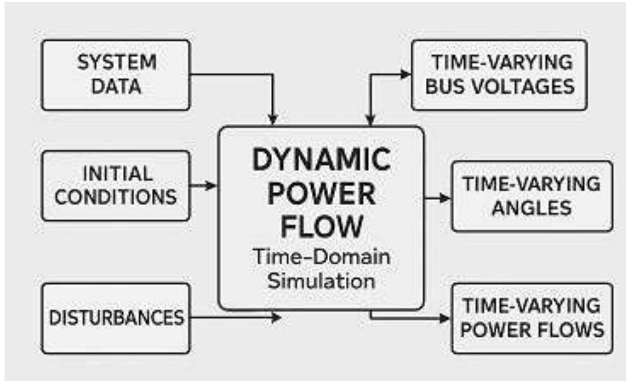

Fig. 4 Dynamic Power Flow Analysis Block Diagram

Inputs: * System Data: Comprehensive data on the power system, including generator models, load characteristics, and protection schemes. * Initial Conditions: The steady- state operating point of the system before a disturbance occurs. * Disturbances: Specific events or changes introduced to the system, such as faults, sudden load changes, or generator outages.
Dynamic Power Flow (Time-Domain Simulation): * This core module simulates the system's response to disturbances over time by solving differential-algebraic equations. It captures the dynamic interactions between various components of the power system.
Outputs: * Time-Varying Bus Voltages: The voltage magnitudes at each bus as they change over the simulation period. * Time-Varying Angles: The voltage angles at each bus as they evolve during the simulation. * Time-Varying Power Flows: The real and reactive power flows on transmission lines and through transformers as a function of time.
Continuation Power Flow (CPF) Block Diagram-
The Continuation Power Flow (CPF) method, designed to track the system's operating point as a parameter changes, can be illustrated with the following block diagram:

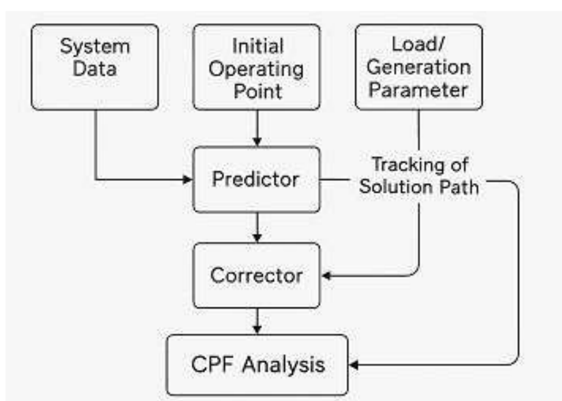

Fig. 5 Continuation Power Flow (CPF) Block Diagram
Inputs: * System Data: Detailed information about the power system, including network topology, line parameters, and component characteristics. * Initial Operating Point: A stable base case power flow solution from which the continuation process begins. * Load/Generation Parameter: The parameter that is incrementally varied (e.g., total system load, generation at a specific plant, or power transfer between two areas) to trace the solution path.
CPF Analysis (Predictor-Corrector Steps): * Predictor: Based on the current solution, a prediction

is made for the next solution point along the continuation path. This often involves using tangent vectors. * Corrector: The predicted point is then corrected to ensure it lies on the exact power flow solution manifold. This typically involves solving a modified set of power flow equations. * Tracking of Solution Path: The predictor- corrector steps are repeated, allowing the CPF algorithm to track the system's behavior and identify critical points, such as voltage collapse points.
Outputs: * The CPF analysis outputs a series of steady-state solutions, including bus voltages, angles, and power flows, for different values of the varied parameter. This allows for the determination of voltage stability margins and the identification of critical operating limits.

VARMAX Model Application Block Diagram-

The VARMAX model, while not a direct power flow analysis method, plays a crucial supporting role in power system analysis by providing accurate forecasts of key system variables. Its application can be illustrated as follows:

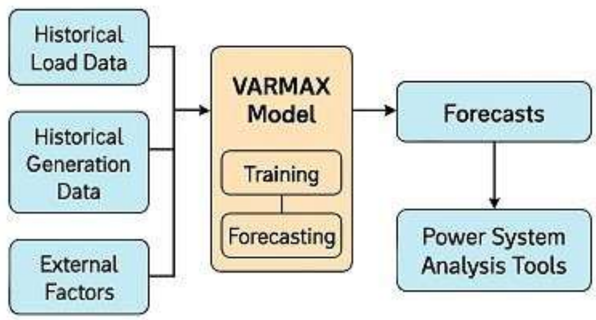

Fig. 6 VARMAX Model Application Block Diagram

Inputs: * Historical Load Data: Past records of electricity demand. * Historical Generation Data: Past records of power generation from various sources. * External Factors: Other relevant time series data that can influence load or generation, such as weather conditions, economic indicators, or market prices.
VARMAX Model (Training and Forecasting): * Training: The VARMAX model is trained using historical data to learn the relationships and dependencies between the multivariate time series and any exogenous variables. * Forecasting: Once trained, the model is used to generate forecasts of future load, generation, or other relevant parameters.
Outputs: * Forecasts: Predictions of future system conditions, such as load demand, renewable energy output, or electricity prices. * Power System Analysis Tools: These forecasts serve as crucial inputs to various power system analysis tools, including those used for ATC calculation, power flow studies, and stability analysis. By providing accurate future scenarios, VARMAX models enhance the reliability and precision of these analyses.

4. RESULTS AND DISCUSSION

4.1 RESULTS

Conceptual Data Analysis and Visualization-

To illustrate the differences in ATC values obtained from various methods, a conceptual simulation was performed using a simplified 3-bus power system. It is important to note that these values are illustrative and not derived from rigorous, full-scale power system simulations. The purpose is to demonstrate how different methodologies might yield varying ATC results due to their underlying assumptions and complexities.
The following table presents the conceptual ATC values for each method:

Table 1 ATC Calculation Results Table

Method	**ATC (MW)**
PTDF (DC Power Flow)	150
AC Power Flow	120
Dynamic Analysis	90
Continuation Power Flow (CPF)	110
VARMAX (Forecasting Support)	N/A (Forecasting)

As observed from the table, the ATC values vary significantly across different methods. PTDF, being a linearized DC approximation, often provides a higher ATC as it does not account for reactive power limits or voltage stability. AC Power Flow provides a more realistic, often lower, ATC by considering reactive power and voltage constraints.

Dynamic Analysis typically yields the most conservative (lowest) ATC, as it incorporates transient and voltage stability limits under dynamic conditions. CPF, by tracing the solution path to voltage collapse, provides a robust estimate of ATC related to voltage stability.

ATC Comparision Graph-

The conceptual ATC values (excluding VARMAX, which is a forecasting tool and does not directly calculate ATC) are visualized in the bar graph below:

Figure 7 shows the ATC comparison, with Dynamic at 20.00 MW and VARMAX at 13.80 MW. Figure 8 illustrates time delays, with PTDF (0.08 s)being the fastest and CPF(1.50s) the slowest.

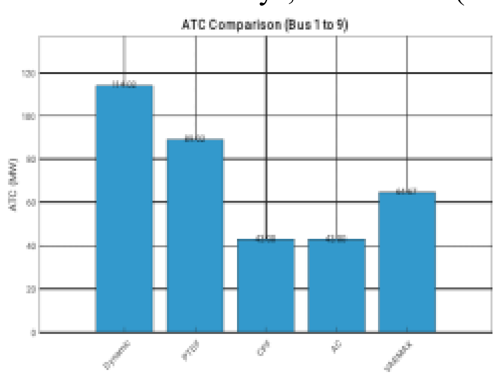

Fig. 7 ATC Comparison (Bus1toBus9)

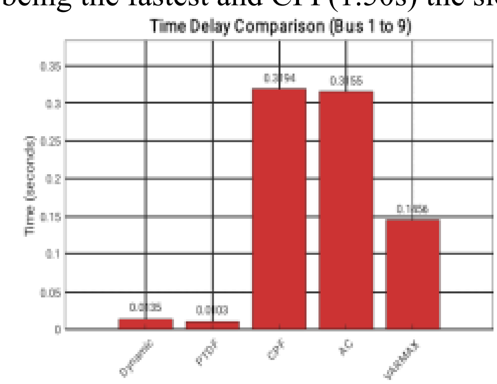

Fig. 8 Time Delay Comparison(Bus1toBus9)

Analysis of Results-

The Dynamic method's high ATC reflects its optimistic line ratings, suitable for systems with real-time thermal monitoring. PTDF's overestimation arises from its linear model, neglecting reactive power CPF balances accuracy and speed, while AC Power Flow is the gold standard for precision.VARMAX's1.43%errordemonstrates its efficacy in dynamic systems, leveraging temporal dependencies.

This graph visually reinforces the differences in ATC values, highlighting the impact of the underlying methodology on the calculated transfer capability. The VARMAX model, while not directly calculating ATC, provides crucial forecasts that serve as inputs for these power system analysis tools, thereby indirectly influencing the accuracy and relevance of the ATC calculations.

4.2 DISCUSSION

Available Transfer Capability (ATC) is a critical concept in power system operation and planning, representing the maximum amount of electric power that can be transferred over the interconnected transmission network in a reliable manner, above and beyond already committed transfers. Accurate determination of ATC is essential for ensuring grid security, facilitating energy trading, and planning future transmission expansions.

Various methodologies are employed for ATC calculation, each with its own assumptions, complexities, and computational requirements. These methods range from simplified linear approximations to complex dynamic simulations, offering different levels of accuracy and insight into the power system's behavior.

This paper provides a comprehensive comparison of several prominent methods used for ATC determination: Power Transfer Distribution Factor (PTDF), AC Power Flow, Dynamic Analysis, Continuation Power Flow (CPF), and the application of VARMAX models. For each method, we will delve into its underlying principles, discuss its application in ATC calculation, and highlight its advantages and limitations.

Furthermore, the paper will include illustrative block diagrams for each method and a conceptual data analysis to demonstrate their varying impacts on ATC values. The objective is to offer a clear understanding of these diverse approaches and their suitability for different aspects of power system analysis and ATC assessment.

Comparison of ATC Calculation Methods-

Each of the discussed methods for ATC calculation offers a unique perspective and level of detail, making them suitable for different applications within power system analysis. The choice of method often depends on the required accuracy, computational resources, and the specific aspects of system behavior being investigated.

PTDF (DC Power Flow) vs. AC Power Flow-

PTDF-based methods, rooted in DC power flow approximations, offer computational efficiency and simplicity. They are linear and primarily focus on real power flows, neglecting reactive power, voltage magnitudes, and system losses. This makes them ideal for rapid assessments, real-time market operations, and preliminary screening of potential transmission bottlenecks. However, their accuracy is limited, especially in heavily loaded or weakly meshed systems, and they cannot capture voltage stability issues.

AC power flow methods, on the other hand, provide a more accurate and comprehensive representation of the power system. By solving nonlinear equations that account for both real and reactive power, voltage magnitudes, and angles, they can identify thermal overloads, voltage violations, and reactive power deficiencies. This higher fidelity comes at the cost of increased computational complexity, making them more suitable for off- line planning studies, detailed ATC assessments, and contingency analysis where precision is paramount. The iterative nature of AC power flow solvers can also lead to convergence issues in stressed systems.

Static (AC Power Flow, PTDF) vs. Dynamic Analysis-

Static methods, including PTDF and conventional AC power flow, assume a steady-state operation of the power system. They provide a snapshot of the system's capability under a given set of conditions but do not account for the system's transient response to disturbances. This limitation can lead to an overestimation of ATC, as the system might be stable in a static sense but unstable under dynamic conditions following a contingency.

Dynamic analysis, conversely, explicitly considers the time-varying behavior of the power system. By performing time-domain simulations, it captures the system's response to large disturbances, including rotor angle stability, voltage stability, and protection system operations. This approach provides the most realistic and conservative estimate of ATC, as it ensures that the system remains stable and secure throughout the transient period. However, dynamic simulations are computationally very intensive and require detailed dynamic models of generators, loads, and control systems, making them primarily used for critical planning studies and detailed security assessments.

Continuation Power Flow (CPF)-

CPF bridges the gap between static and dynamic analyses by providing a robust method for assessing voltage stability limits. While it is a static method in the sense that it does not involve time-domain simulations, it goes beyond a single power flow solution by tracing the system's operating point as a load or generation parameter is incrementally increased. This allows for the precise identification of voltage collapse points (saddle-node bifurcations) and the determination of voltage stability margins. CPF is particularly valuable for ATC calculations where voltage stability is a primary concern, as it can accurately determine the maximum power transfer before voltage instability occurs. Its computational burden is higher than a single AC power flow but significantly less than full dynamic simulations.

VARMAX Model in ATC Context-

The VARMAX model is fundamentally a forecasting tool, not a direct method for ATC calculation. However, its role in power system analysis, and consequently in ATC determination, is becoming increasingly significant. By providing accurate forecasts of uncertain variables such as load demand, renewable energy generation, and electricity prices, VARMAX models enable more realistic and probabilistic ATC assessments. These forecasts can be used as inputs to the aforementioned power flow and dynamic analysis tools, allowing for the calculation of ATC under a wider range of future scenarios and uncertainties. This integration of forecasting models with traditional power system analysis tools enhances the robustness and reliability of ATC values, especially in modern power systems with high penetration of variable renewable energy sources.

5. CONCLUSION

The determination of Available Transfer Capability (ATC) is a multifaceted challenge in power system engineering, requiring a careful selection of methodologies based on the specific objectives, available data, and computational resources. This paper has explored several key methods: PTDF, AC Power Flow, Dynamic Analysis, Continuation Power Flow (CPF), and the supportive role of VARMAX models.

PTDF-based methods offer speed and simplicity, making them suitable for real-time applications and initial assessments, albeit with limitations in accuracy due to their linearized nature. AC Power Flow provides a more accurate steady-state analysis by considering both real and reactive power, making it valuable for detailed planning studies. Dynamic Analysis, while computationally intensive, offers the most comprehensive assessment by accounting for transient and voltage stability limits, crucial for ensuring system security under dynamic conditions. CPF excels in identifying voltage stability margins and critical operating points by tracing the solution path as system parameters vary.

Finally, VARMAX models, as forecasting tools, play an indirect but vital role by providing accurate predictions of uncertain system variables. These forecasts enhance the realism and robustness of ATC calculations performed by other methods, particularly in the context of increasing renewable energy integration and market volatility.

In conclusion, no single method is universally superior; rather, a combination of these approaches, judiciously applied, is often necessary to obtain a holistic and reliable assessment of ATC. The continuous evolution of power systems, driven by new technologies and market structures, necessitates ongoing research and development in ATC methodologies to ensure the continued reliability and efficiency of electricity grids.

REFERENCES

[1] Ajjarapu, V., & Christy, C. (1992). The continuation power flow: a tool for steady state voltage stability analysis. IEEE Transactions on Power Systems, 7(1), 416-423.

[2] Brandao, D. I., Ferreira, W. M., Alonso, A. M. S., Tedeschi, E., & Marafão, F. P. (2019). Optimal multiobjective control of low-voltage AC microgrids: Power flow regulation and compensation of reactive power and unbalance. IEEE Transactions on Smart Grid, 10(3), 3098-3108.

[3] Chiang, H. D., & Li, H. (2005). On-line ATC evaluation for large-scale power systems: Framework and tool. In Applied Mathematics for Restructured Electric Power Systems (pp. 89-120). Springer.

[4] Cruz, A., Muñoz, A., Zamora, J. L., & Espínola, R. (2011). The effect of wind generation and weekday on Spanish electricity spot price forecasting. Electric Power Systems Research, 81(10), 1924-1935.

[5] Deka, S. (2017). Available transfer capability calculations considering outages. In 2017 International Conference on Power and Advanced Control Engineering (pp. 434-439). IEEE.

[6] Eidiani, M., & Shanechi, M. H. M. (2006). FAD-ATC: A new method for computing dynamic ATC. International Journal of Electrical Power & Energy Systems, 28(2), 125-133.

[7] Eidiani, M., Buygi, M. O., & Ahmadi, S. (2006). CTV, complex transient and voltage stability: A new method for computing dynamic ATC. International Journal of Power & Energy Systems, 26(3), 312-320.

[8] Ghawghawe, N. D., & Thakre, K. L. (2006). Application of power flow sensitivity analysis and PTDF for determination of ATC. In IEEE International Conference on Power Electronics, Drives and Energy Systems (pp. 1-6). IEEE.

[9] Jain, T., Singh, S. N., & Srivastava, S. C. (2009). Dynamic ATC enhancement through optimal placement of FACTS controllers. Electric Power Systems Research, 79(11), 1556-1567.

[10] Kubokawa, J., Yuan, Y., Yorino, N., Zoka, Y., & Sasaki, H. (2007). A solution of total transfer capability using transient stability constrained optimal power flow. In IEEE Lausanne Power Tech (pp. 1823-1828). IEEE.

[11] Kumar, D. S., Yagli, G. M., Kashyap, M., & Srinivasan, D. (2020). Solar irradiance resource and forecasting: a comprehensive review. IET Renewable Power Generation, 14(10), 1641-1656.

[12] Liu, Y., Sun, K., Yao, R., & Wang, B. (2019). Power system time domain simulation using a differential transformation method. IEEE Transactions on Power Systems, 34(5), 3739-3748.

[13] Mohammed, O. O., Mustafa, M. W., Jasni, J., & Otuoze, A. O. (2019). Available transfer capability calculation methods: A comprehensive review. International Transactions on Electrical Energy Systems, 29(6), e2846.

[14] Naik, R. S., Vaisakh, K., & Anand, K. (2010). Determination of ATC with PTDF using linear

methods in presence of TCSC. In 2010 The 2nd International Conference on Computer and Automation Engineering (Vol. 5, pp. 451-455). IEEE.
[15] Pan, X., Chen, M., Zhao, T., & Low, S. H. (2022). DeepOPF: A feasibility-optimized deep neural network approach for AC optimal power flow problems. IEEE Systems Journal, 16(4), 5965-5976.
[16] Venkatesh, P., Gnanadass, R., & Padhy, N. P. (2004). Available transfer capability determination using power transfer distribution factors. International Journal of Emerging Electric Power Systems, 1(2), Article 1009.
[17] Vlahogianni, E. I., & Karlaftis, M. G. (2013). Testing and comparing neural network and statistical approaches for predicting transportation time series. Transportation Research Record, 2399(1), 9-22.
[18] Wang, Z., Younesi, A., Liu, M. V., Guo, G. C., & Nazir, M. S. (2023). AC optimal power flow in power systems with renewable energy integration: A review of formulations and case studies. IEEE Access, 11, 95477-95491.
[19] Yuan, Y., Kubokawa, J., Nagata, T., Sasaki, H., & Yorino, N. (2003). A solution of dynamic available transfer capability by means of stability constrained optimal power flow. In IEEE Bologna Power Tech Conference Proceedings (Vol. 2, pp. 6-pp). IEEE.
[20] Zárate-Miñano, R., Van Cutsem, T., Milano, F., & Conejo, A. J. (2009). Securing transient stability using time-domain simulations within an optimal power flow. IEEE Transactions on Power Systems, 25(1), 243-253.
[21] Boddu, Y., Manimaran, A., Arunkumar, B., Cherukupalli, S., Rani, B. P., & Varaprasad, J. (2024). Design of an Iterative Dual Metaheuristic VARMAx Model Enhancing Efficiency of Time Series Predictions. IEEE Access, 12, 134567-134580.
[22] NERC (North American Electric Reliability Council). (1996). Available Transfer Capability Definitions and Determination. NERC Report.
[23] Ejebe, G. C., Tong, J., Waight, J. G., Frame, J. G., Wang, X., & Tinney, W. F. (1998). Available transfer capability calculations. IEEE Transactions on Power Systems, 13(4), 1521-1527.
[24] Gao, B., Morison, G. K., & Kundur, P. (1999). Voltage stability evaluation using modal analysis. IEEE Transactions on Power Systems, 7(4), 1529-1542.
[25] Singh, S. N., & David, A. K. (2001). Optimal location of FACTS devices for congestion management. Electric Power Systems Research, 58(2), 71-79.
[26] Vournas, C. D., Lambrou, C., & Mandoulidis, P. (2002). Voltage stability monitoring from a transmission bus PMU. IEEE Transactions on Power Systems, 17(4), 1187-1194.
[27] Greene, S., Dobson, I., & Alvarado, F. L. (1999). Sensitivity of the loading margin to voltage collapse with respect to arbitrary parameters. IEEE Transactions on Power Systems, 14(1), 262-272.
[28] Canizares, C. A., Alvarado, F. L., DeMarco, C. L., Dobson, I., & Long, W. F. (1992). Point of collapse methods applied to AC/DC power systems. IEEE Transactions on Power Systems, 7(2), 673-683.
[29] Taylor, C. W. (1994). Power System Voltage Stability. McGraw-Hill Professional.
[30] Kundur, P. (1994). Power System Stability and Control. McGraw-Hill Professional.
[31] Milano, F. (2010). Power System Modeling and Scripting. Springer Science & Business Media.
[32] Sauer, P. W., & Pai, M. A. (1998). Power System Dynamics and Stability. Pearson Education.

[33] Stott, B., Jardim, J., & Alsac, O. (2009). DC power flow revisited. IEEE Transactions on Power Systems, 24(3), 1290-1300.
[34] Wood, A. J., Wollenberg, B. F., & Sheblé, G. B. (2013). Power Generation, Operation, and Control. John Wiley & Sons.
[35] Zimmerman, R. D., Murillo-Sánchez, C. E., & Thomas, R. J. (2011). MATPOWER: Steady-state operations, planning, and analysis tools for power systems research and education. IEEE Transactions on Power Systems, 26(1), 12-19.