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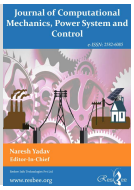

Integrated ATC Enhancement Using Wind Energy Placement and Adaptive Demand Response Framework

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Abstract: Available Transfer Capability (ATC) is vital for the economical, reliable, and secure operation of the power systems. However, renewable energy sources are being integrated into the system at a rapid pace. One drawback of existing approaches is that they fail to recommend the placement of Wind Generation (WG) units at points that could otherwise lower the ATC of the system. Therefore, the model proposes an innovative approach to improve ATC by integrating wind energy placement with the Adaptive Demand Response (ADR) framework. To balance supply-demand flexibility, the integrated framework combines adaptive Flexible Demand Response (FDR) with a sensitivity-based bus selection method for optimal WG placement. For this purpose, a sensitivity-based bus selection technique is employed to identify the best WG locations while reducing computational complexity. Supply and demand are dynamically balanced through a two-stage Flexible Demand Response (FDR) system. Furthermore, the proposed approach integrates the ATCDF-based sensitivity model with a two-stage unit commitment and Demand Response (DR) model to evaluate system sensitivity for optimal WG placement and to improve ATC by ensuring dynamic load balancing and better renewable accommodation. This technique effectively reduces costs and congestion while increasing renewable energy penetration. The ATC value is determined, and the WG is positioned at each bus within the zone formed by the TCDF value. The IEEE-9 and IEEE-14 bus systems are used to test the proposed system model in the MATLAB environment. When the WG is positioned using the suggested approach, the comparison results indicate a clear increase in the ATC value. The proposed approach also helps to identify various locations for WG installation based on the ATCDF value.

Keyword: Wind Generator; Wind Generator; Demand Response; Available Transfer Capability; Adaptive Demand Response; Wind Energy Placement; Flexible Demand Response

Nomenclature

Abbreviation	Description
ATC	Available Transfer Capability
LRA	Low-Rank Approximation
RACPF	Repeated Alternating Current Power Flow
WFs	Wind Farms
PTDF	Power Transfer Distribution Factors
DCPTDFs	DC Power Transfer Distribution Factors
LOPTDFs	Line Outage Power Transfer Distribution Factors
ACPTDFs	AC Power Transfer Distribution Factors
FACTS	Flexible AC Transmission Systems
FDR	Flexible Demand Response
DR	Demand Response
TCDF	Transmission Congestion Distribution Factor
LHS	Latin Hypercube Sampling
ATCDF	Average Transmission Congestion Distribution Factor
TCSC	Thyristor Controlled Series Compensation
PSO	Particle Swarm Optimisation
WG	Wind Generation
BESS	Battery Energy Storage System
FPA	Flower Pollination Algorithm
UC	Unit Commitment
ADR	Adaptive Demand Response
DB	Demand Bidding
WT	Wind Turbine
DDR	Deferrable Demand Response
SDR	Switchable Demand Response
AjDR	Adjustable Demand Response
SCI	System Congestion Index

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1. Introduction

Basically, ATC information of the transmission system must be reported by electrical services for consumers, distributors, and marketers to use this vital information to plan, run, and reserve transmission services [1]. The accurate reporting of ATC ensures efficient energy trading, congestion management, and operational transparency among multiple market participants. The ATC can, however, also offer an exchange restriction that can be raised without threatening the framework's stability and security, which is useful information for the operator to comprehend how far away the restrictions. For calculating ATC, a new probabilistic method utilizing canonical LRA is presented [2]. ATC is the transfer capacity that is maintained in a physical transmission network to facilitate increased commercial activity beyond the designated usage. This indicates that the proper estimation of ATC not only enhances system utilization but also supports fair access to the transmission network in deregulated environments. The fact that many utilities provide transaction services to wholesale customers has made the post-information on ATC of their transmission networks necessary. However, ATC is crucial to power transactions and system stability studies in deregulated power systems. Moreover, highlighted is the state of the art by researchers, which is used for the thorough research of the ATC calculation [3]. Likewise, the RACPF technique can also be used to calculate ATC, has been explained in it. For the IEEE-30 bus system, contingency analysis takes into consideration the generator and inter-area line disruption conditions.

The deregulation of power system operations has contributed to the development of a creative and competitive electricity market that encourages the use of alternative energy generation technologies, including solar, wind, and hydropower [4]. In this context, renewable energy integration introduces both opportunities and operational challenges related to uncertainty, variability, and transmission congestion. The clean and natural aspect of wind energy makes it a renewable energy source with the quickest rate of growth. In the context of the power market, power system design and operation should consider both economic performance and dependability, which may be impacted by the incorporation of wind power. Analysis of short- and medium-term reliability with high wind power penetration is done in reference [5]. A method for reliably modeling produces enormous WFs through analysis. Such reliability-based modeling helps to identify the impact of wind variability on ATC and the system's ability to maintain equilibrium under different loading conditions. In order to decrease congestion, the ATC model and calculation have been the subject of extensive research. An optimization technique, ATC computation, and congestion control have all been briefly reviewed in reference [6]. There has never been any research on the ATC model and computation in relation to wind turbines that are connected to the electrical grid. For power systems with wind generation, an efficient ATC calculation method needs to be created.

The power flow sensitivity method is used by many authors to estimate ATC. ATC is calculated quickly by using linear sensitivity factors to estimate variation in line flows. Based on the DC load flow, linear sensitivity factors employ DCPTDFs and LOPTDFs [7]. ATC can be easily calculated with DCPTDFs, which also provide fast computations. Nevertheless, the limitation of DC-based methods lies in their inability to capture voltage and reactive power dynamics, which are vital for realistic system assessment. However, the AC power flow model enables more precise PTDF calculations and gives less accurate DC power flow voltage and reactive power effects [8]. Essentially, the voltages and angles at the terminal buses determine the line power flows. Thus, these voltage and angle sensitivities determine PTDF. In order to calculate ATC, ACPTDFs are also anticipated [9]. ACPTDFs provide more accurate ATC with less computational complexity and are calculated from the base operating point utilizing AC load flow analysis while taking reactive power and voltage restrictions into account [10]. According to this study, improving ATC can effectively improve the generation and load flexibility while maintaining network limitations.

This process is performed with the integration of wind energy placement and an adaptive demand response framework in the power system. The integration ensures that renewable generation variability is counterbalanced by adaptive load-shifting mechanisms, thus maintaining system equilibrium. This paper implemented the ATC enhancement approach in the power system for maintaining system stability and controlling network congestion. The proposed model integrated the WG placement and ADR framework for balancing the dynamic load and improving the ATC of the power system. The organization of the work is given below; Section 1 represents the introduction of the suggested ATC enhancement model. Section 2 shows the related survey and problems of the existing work based on the enhancement of ATC. Section 3 represents the proposed methodology for the optimum improvement of the ATC model. The result and discussion of the proposed model are given in Section 4. Lastly, Section 5 gives the conclusion of the suggested work.

2. Literature Survey

2.1 Related Work

In 2019, Hou et al. [11] suggested a two-phase model for evaluating ATC that incorporates FDR. A demand-side bidding mechanism was created for the first stage, or day-ahead market, where power customers could choose which ways they wanted to participate in DR programs. Three common patterns of FDR were identified in the model: (i) deferrable DR, (ii) switchable DR, and (iii) adjustable DR. The goal was to reduce overall generation and dispatch costs while adhering to FDR limitations, inter-area power trading, small renewable energy accommodation, etc. This approach demonstrated the potential of integrating demand-side flexibility to enhance system responsiveness and stability during high-load conditions. Through load shifting and peak shaving, FDR could be used to improve real-time ATC and support renewable energy sources, according to case studies based on the IEEE 14-bus system and a Chinese provincial power grid.

In 2021, Narain et al. [12] suggested the optimal location of buses for WG using a novel sensitivity-based formula. The zones were created using the TCDF values. The ATCDF was used to determine the system's optimal point. It was evident that the ATC increased when the WG was incorporated into the system, but the primary goal was to determine when the ATC values would be higher. This method provided a computationally efficient way to evaluate multiple wind generator placements without performing exhaustive system simulations. The ATC value was determined, and the WG was positioned at each bus within the zone; thus, the TCDF value was recognized. The IEEE-30 bus system was tested in MATLAB. The comparison result indicated that when the WG was positioned using the suggested approach, the ATC value increased. The finding of several places for WG installation based on ATCDF value was another benefit of the suggested approach.

In 2023, Liu et al. [13] investigated the impact of wind energy on ATC and then explored ways to mitigate transmission congestion from the grid and load side, respectively. By using LHS and backward restriction approaches to create common scenarios, the impact of a stochastic variable was taken into account. The integration of stochastic modeling allowed for a more realistic assessment of wind power fluctuations and their effects on transfer capability. By using DR on the load side and allocating TCSC on the grid side optimally, ATC was enhanced. An enhanced PSO method was used to solve the source-grid-load cooperative optimization scenario for ATC. The findings indicated that the combined use of TCSC and DR could contribute to a more thorough improvement of ATC. By increasing the transmission network's utilization efficiency without altering the network's structure, the model could accomplish the goal of promoting the use of renewable energy.

In 2021, Narain et al. [14] proposed a formula to calculate the WF power output by a that considers the wind direction and wake effect of WT. Incorporating wake effects into the modeling process enhanced the accuracy of wind farm output estimation, which is crucial for ATC prediction. In order to increase the system's ATC value, the BESS was installed, and charging/discharging rules were developed. The TCDF data were used to generate the clusters and zones. In order to choose the best location for WF and BESS, the average TCDF ATCDF value was offered. The suggested method considerably raises ATC. The IEEE-30 bus system was used to replicate the results.

In 2018, Venkatraman et al. [15] proposed the best possible distribution of TCSC to progress the ATC of power transactions between sources and sink areas in the deregulated power system. By reducing the transmission line's effective reactance, the TCSC device improved the network's ATC, and it combines the capacitive voltage with the function of inductive voltage drop in the line. Such a compensation technique effectively enhances power transfer limits and minimizes the impact of line congestion on network performance. However, finding the ideal placement and TCSC device characteristics using FPA could maximize the ATC while reducing power losses and installation costs, which was the aim of the optimization. The effectiveness of the proposed approach may be demonstrated by using an IEEE-30 bus test system to assess the ATC for the selected area-wise transactions, both bilateral and multilateral, under both normal and line outage scenarios.

2.2 Problem Statement

This section shows the advantages and limitations of existing methods of the ATC enhancement model. Paper [11] emphasized improved use of available resources, reduced operating costs, and enhanced grid flexibility and dependability. However, its implementation relies heavily on consumer participation and robust communication infrastructure, which can limit scalability in developing grid systems. There are still issues, though, like the difficulty of organizing consumer involvement, the possibility of communication breakdowns, and the requirement for sophisticated market structures and technologies. Paper [12] gives the advantages of higher ATC, better power transfer efficiency, and possibly reduced

energy costs, a unique sensitivity-based strategy. However, it was limited by the intrinsic complexity of simulating intermittent wind generation inside the power system. Paper [13] used the LHS and backward curtailment approaches, which had the benefits of higher dependability, increased transmission network efficiency, and improved wind energy consumption. Limitations include the intrinsic variability and intermittency of wind power itself, the potential expense of system enhancement devices, and the complexity of stochastic modeling. Although there were improvements in energy distribution and congestion management in Paper [4], there were benefits such as significant enhancements of ATC, effective choice of location, and realistic wind variability consideration. Nonetheless, the success of such models depends on accurate wind forecasting and appropriate BESS sizing, which are both uncertain in practical applications. Similarly, potential errors in wind power production forecasts and the difficulty of real-time wind and surge modeling are among the limitations. Paper [15] suggests the most effective method to distribute TCSC devices to maximize power transfer capability and minimize power losses, but this requires accurate system modeling, and the efficacy of the FPA depends on parameter tuning and computational complexity, which may be a drawback for larger, more complicated systems.

3. Proposed Methodology

3.1 Methodological Architecture

In the power system, ATC is performed because it has the amount of transfer capacity that is present in the physical transmission network for additional commercial activity. Essentially, ATC represents the margin available for further power transfers without violating operational or security limits of the network. Similarly, the integrated process is performed in this proposed power system model to make the power transmission network more commercially viable, stable, and efficient overall. This is accomplished by increasing the capacity of the current transmission lines to safely transport more power. Due to this integration of the ADR framework and WG placement, the ATC is improved in the power system. Thus, the integrated ATC enhancement approach is suggested in this model by optimizing the ADR framework for demand-side response and wind generator allocation for optimizing generator-side flexibility. This dual approach allows the system operator to simultaneously address supply variability and load uncertainty. This integration approach can increase the transmission lines' electric power capacity beyond their pre-planned uses. It is also essential for grid reliability and electricity market operations. This is accomplished through the use of devices such as FACTs to make better use of the current infrastructure, and it can also precisely estimate the ATC to prevent both economic loss of the power system from under-utilization and instability from over-allocation.

There are four hierarchical steps used in the integrated ATC enhancement model with wind energy placement and the ADR framework. It may methodically establish and operate a power system with a high integration of renewable energy. The methodology also allows for scenario-based evaluation, where multiple operational conditions are simulated to ensure robust ATC improvement under uncertainty. The main goal of the paper is to maximize the use of renewable energy sources while maintaining dependability and economic efficiency by expanding the grid's overall transfer capacity.

The overall framework consists of four hierarchical stages:

Stage 1: Base Case Power Flow and Sensitivity Computation

In the stage 1 process, the model can initially perform a Newton-Raphson load flow on the test system (e.g., IEEE 30-bus or IEEE 14-bus) to establish baseline voltage magnitudes, angles, and power flows. This step ensures that the system's normal operating point is accurately determined before any enhancements are applied. Subsequently, compute the ACPTDF to evaluate the sensitivity of each transmission line for the purpose of transmitting the power between the generator and load buses. The sensitivity formulae for the suggested system are given in Eq. (1):

$$ACPTDF_{mn}^{ab} = \frac{\Delta W_{ab}}{\Delta W_{mn}} \tag{1}$$

Where ΔW_{ab} is the power change in line (a,b) due to a unit change in transfer ΔW_{mn} between buses m and n. Identifying these sensitivities is essential for detecting critical lines that may limit ATC.

Then, effectively identify the limiting lines whose power flow approaches thermal limits. These lines form the congestion set, crucial for subsequent ATC estimation. Finally, calculate the ATC for each congested line using Eq. (2):

$$ATC_{mn} = \min \frac{\left(W_{ab}^{\max} - W_{ab}^{0}\right)}{ACPTDF_{ab,mn}} \tag{2}$$

where $(W_{ab}^{\max})$ is the line thermal limit and (W_{ab}^{0}) is the base case flow. This baseline ATC calculation provides a reference point for evaluating the improvements achieved in later stages.

Stage 2: Zonal Sensitivity and Optimal Wind Generator Placement

In the stage 2 process, for each line outage scenario, compute TCDF to quantify the active power change ΔW_{mn} in the line k for unit injection at the bus m is given in Eq. (3):

$$TCDF_m^k = \frac{\Delta W_{mn}}{\Delta W_m} \tag{3}$$

Subsequently, construct zones/clusters based on the magnitude of TCDF values, such as Zone 1, Zone 2, and Zone 3–4. This zoning helps prioritize which areas of the network will benefit most from additional generation or flexibility resources. Similarly, Zone is a high-sensitivity region (high |TCDF|, most congested), Zone 2 is a moderate sensitivity (relevant for expansion planning), and Zone 3–4 is a low-sensitivity zone (ignored for ATC improvement). Then, compute the ATCDF across all congested lines to identify the optimal bus for WG integration, as mentioned in Eq. (4):

$$ATCDF_m = \frac{1}{M}\sum_{k=1}^{N}\left|TCDF_k^m\right| \tag{4}$$

Where M is the number of congested lines.

Therefore, select the bus with the maximum ATCDF (and negative TCDF sign) as the optimal WG installation point. This ensures that the injected renewable power flows in a direction that alleviates congestion, rather than worsening it. This ensures that added renewable generation injects power in a direction that relieves congestion and enhances ATC. Finally, validate by simulating WG integration at different buses, recalculating ATC using ACPTDF. The bus yielding the highest ATC improvement confirms the optimal placement. Example from the IEEE-30 bus test system: Bus 28 was found optimal, yielding superior ATC improvement over other locations.

Stage 3: Two-Stage ADR Integration

In the Stage 3 process, the demand-side flexibility is integrated using a two-stage ATC evaluation model inspired by the FDR-based approach for building upon the generation-side enhancement. This stage addresses load-side contributions to ATC by actively managing flexible demand. The suggested two-stage ADR integration is explained below,

Stage 3.1: Day-Ahead Unit Commitment and Demand Bidding

In stage 3.1, a co-optimization model is developed to use a day-ahead market mechanism for renewable generation, FDR, and schedule thermal units. This allows system operators to pre-plan both generation and flexible demand participation for optimal ATC. Similarly, **Day-Ahead UC and DB are also utilized in market optimization and power system operations**.

❖ **Objective Function**

The **day-ahead UC with demand bidding** problem can be formulated as a **mixed-integer optimization problem is represented in Eq. (5):**

$$\min H_{total} = \sum_g \left(H_g^{gen} + H_g^{SU} + H_g^{SD}\right) + \sum_{j\in FDR} H_j^{DR} - \sum_i \pi_i^{trade} W_i \tag{5}$$

In the above equation, H_g^{gen} is denoted as generation cost, H_g^{SU}, H_g^{SD} signifies the startup and shutdown costs, H_j^{DR} represents the cost of DR participation, π_i^{trade} P_i shows the profit from inter-area trading. The objective function balances cost minimization with reliability and market considerations.

❖ **Decision Variables:**

Decision variables are the variables or quantities that the optimization model calculates to meet all operational and system limitations while minimizing the overall cost of operations. These variables allow flexible and dynamic system operation while maintaining security constraints. Demand participation through demand bidding or demand response programs, producing unit power output and commitment status; similarly, the startup and shutdown activities can be defined by these variables.

- **Generator commitment ($U_{g,t}$)**: The symbol $U_{g,t}$ by itself is typically used to represent the **on/off status of a generator** g **at a time** t in unit commitment problems. As a "mathematical equation," you usually define it as a binary variable: $U_{g,t} \in \{0,1\}$, where, $U_{g,t} = 1 \rightarrow$ generator g is ON at time t, $U_{g,t} = 0 \rightarrow$ generator g is OFF at time t
- **Power output ($W_{g,t}$):** The symbol $W_{g,t}$ usually represents the **power output of the generator** g **at time** t. As an equation in a typical unit commitment or economic dispatch context, you can define it in terms of generator limits and its on/off status $U_{g,t}$: $W_{g,t}^{\min} U_{g,t} \le W_{g,t} \le W_{g,t}^{\max} U_{g,t}$, where $W_{g,t}$ - actual power output of generator g at time t, $W_{g,t}^{\min}$ -minimum generation limit, $W_{g,t}^{\max}$ maximum generation limit, $U_{g,t}$ - binary status (1 if ON, 0 if OFF).

- DR participation levels (DDR, SDR, ADR),
- Interchange power (W_i).These variables together enable co-optimization of generation and demand response for maximum ATC benefit.

❖ **Flexible Demand Categories:**

Flexible demand is the amount of power consumption that can be changed, transferred, or reduced in response to system conditions or market prices. Flexible demand allows the system to dynamically adapt to renewable generation variability. In order to improve system efficiency and save operating costs, this proposed model utilizes variable demand resources through demand bidding programs. The flexible demand can be categorized into several main types based on their characteristics and controllability:

1. DDR: Shiftable loads within a time window.
2. SDR: Multi-mode loads with discrete power patterns.
3. AjDR: Continuously adjustable loads within specified bounds.

❖ **Constraints:**

The constraints of the integrated ATC enhancement using wind energy placement and ADR framework are generation and line limits, demand satisfaction, renewable generation uncertainty, inter-area transmission capacities, and DR bounds and daily energy requirements, respectively. These constraints ensure system security and operational feasibility. This stage yields committed schedules for both generation and flexible demand.

Stage 3.2: Real-Time ATC Maximization

Using the day-ahead commitments as boundary conditions, a real-time optimization is performed to maximize the available interchange capacity is denoted in Eq. (6):

$$Maximize\ ATC_{RT} = \sum_{i \in I} (W_{i,t}^{RT} - W_{i,t}^{commit}) \tag{6}$$

Where ATC_{RT} is a real-time available transfer capability (the quantity to maximize), $W_{i,t}^{RT}$ denoted real-time power of participant i at time t, $W_{i,t}^{commit}$ signifies day-ahead committed power of participant i at time t, $\sum_{i \in I}$ sums this difference across all participants, giving the total real-time adjustment from commitments. Real-time adjustments allow the system to respond to deviations from forecasted renewable generation or load.

Subject to:

- Real-time generation and DR flexibility,
- Transmission capacity limits,
- Renewable power realization,
- System power balance.

In the DR in Real-Time, DDR adjusts actual start times based on real conditions, SDR selects alternative load patterns, and AjDR continuously modulates power within its range. This enables efficient load shifting, peak shaving, and congestion relief, contributing to ATC improvement. This dynamic adjustment enables load shifting and peak shaving, thereby freeing up transmission capacity and increasing ATC by 6–12% as validated in case studies.

Stage 4: Coordinated ATC Enhancement and System Validation

Coordinated ATC enhancement refers to strategies that **maximize ATC across interconnected systems** by optimally managing generation, DR, and inter-area power flows in a coordinated manner. This final stage ensures that both generation-side and demand-side enhancements are integrated to achieve maximal ATC improvement. It is the final stage that combines both the generation-side and demand-side models through an iterative coordination layer:

1. Initialization:

In the initialization process, the model performs sensitivity analysis and identifies optimal WG placement. Then, execute the day-ahead scheduling with initial FDR parameters. This sets the baseline for iterative coordination between generation and demand-side measures.

2. Iteration Loop:

In the iteration loop process, the model recomputes the ATC considering WG output and adjusted loads. Subsequently, update FDR participation to absorb surplus renewable power and reduce congestion. Finally, it applies adaptive learning to refine response parameters (e.g., penalty for excessive curtailment). This iterative approach ensures convergence to an optimal ATC improvement solution.

3. Evaluation Metrics:

The evaluation metrics for the analysis of the suggested integrated ATC enhancement model using wind energy placement and ADR framework are ATC improvement (ΔATC%), renewable energy accommodation rate, SCI, and Cost Reduction (%), respectively. These metrics provide a quantitative measure of system performance and operational efficiency.

4. Implementation Flowchart for the Suggested Model

The integrated ATC enhancement framework combines strategic wind energy placement with ADR to maximize ATC and improve renewable energy integration. The flowchart represents the sequential logic of computations and decision-making steps for the proposed methodology. The flowchart is typically based on the following components and operational logic:

Step 1: Perform base load flow → compute ACPTDF.
Step 2: Identify congested lines → compute TCDF & ATCDF → choose WG bus.
Step 3: Integrate WG → compute revised ATC.
Step 4: Formulate a day-ahead market with FDR bidding.
Step 5: Execute unit commitment with stochastic renewable forecasts.
Step 6: In real-time, apply FDR adjustments → maximize ATC.
Step 7: Iterate coordination until ATC improvement stabilizes.

Fig. 1 shows the flowchart for the suggested integrated ATC enhancement model using wind energy placement and the ADR framework. This visual representation provides clarity for implementation and highlights the interactions between generation-side and demand-side interventions.

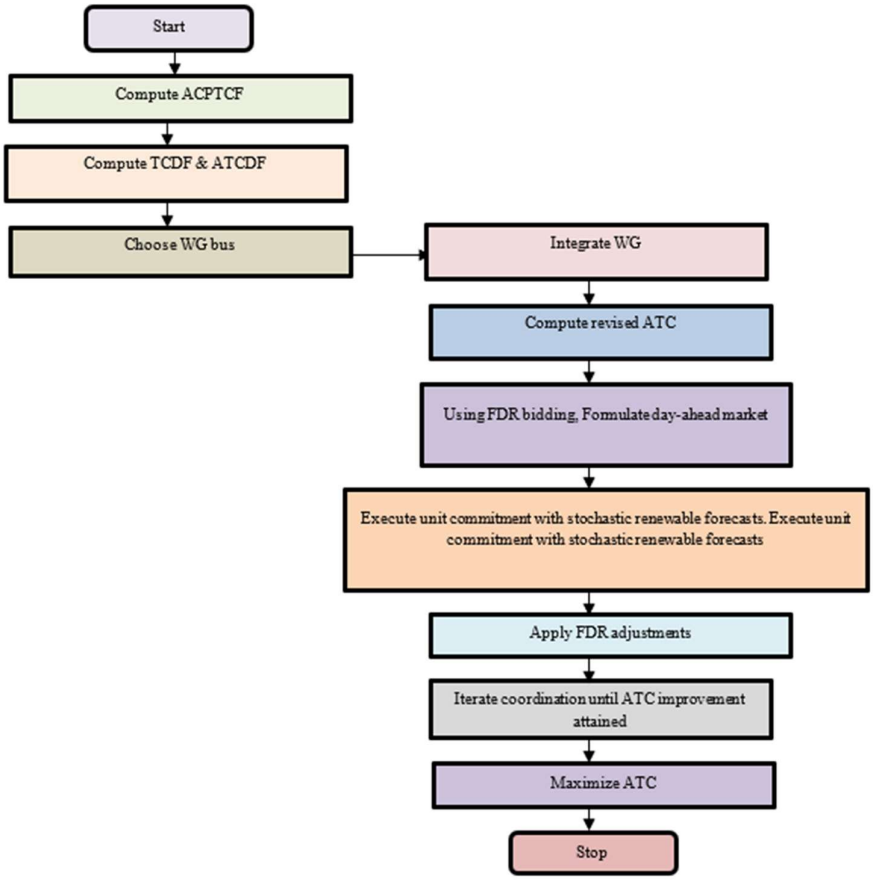

Fig. 1. *Flowchart for the suggested integrated ATC enhancement model*

4. Result and Discussion

This section shows the effectiveness of the novel integrated wind energy placement and ADR Framework for ATC enhancement in the power system by optimally locating wind generators to increase power flow. The evaluation highlights both generation-side and demand-side contributions to the system's transfer capability. MATLAB/CPLEX environment was implemented for numerical optimization. Utilize IEEE-30 or IEEE-14 test systems with integrated wind and solar data that examine the performance of the model. The use of standard test systems ensures the comparability of results with prior studies and validates the proposed methodology under realistic network conditions. Conduct case studies for multiple scenarios (normal load, high renewable, and contingency cases).

Table 1 presents a comparison of ATC for IEEE-9 and IEEE-14 bus systems before and after the integration of wind energy placement and adaptive demand response. The table demonstrates that both network size and renewable integration directly affect ATC improvement. The IEEE-14 bus system witnessed a rise from 180 MW to 207 MW, which likewise represented a 15% improvement, while the IEEE-9 bus system increased from 120 MW to 138 MW. These findings show that the suggested ATC enhancement framework effectively increases the transfer capability of the system, providing improved network resource utilization and more operational flexibility. The results also indicate that integrating ADR with strategically placed wind generators can significantly improve both system reliability and economic performance.

Table 1. *Analysis of the ATC enhancement rate for the IEEE 9 bus and IEEE 14 bus*

Bus System	ATC in MW (Before Enhancement)	ATC in MW (After Enhancement)
IEEE 9	120	138
IEEE 14	180	207

Table 2. *Analysis of System Cost of the 1EEE 9 and IEEE 14 bus for different wind generators used in the model*

Number Wind Generator	IEEE 9 Bus System Cost /MWh	IEEE 14 Bus System Cost /MWh
WG 1	45	48
WG 3	43	46
WG 5	41	44
WG 7	40	42
WG 9	39	41
WG 11	38	40

Table 2 shows the system cost rate of different wind generators that are used in the model for the IEEE 9 bus and the IEEE 14 bus. Cost analysis accounts for both operational savings and the reduced need for conventional generation due to renewable integration. The total system cost per MWh decreases as additional wind generators are integrated, due to the near-zero marginal cost of wind energy. With eleven wind turbines, the cost drops from roughly 45/MWh with one to about 38/MWh with eleven on the IEEE-9 bus system. As wind penetration rises, costs for the IEEE-14 bus system also show a lower tendency, profitable from about 48/MWh to 40/MWh. The results suggest that system operators can achieve both economic and operational benefits simultaneously by coordinating WG placement and demand response. This system's cost reduction and enhanced ATC demonstrate the operational and financial advantages of adaptive demand response and selective wind generator location.

Table 3. *Analysis of the Renewable energy utilization rate of the 1EEE 9 and IEEE 14 bus for different wind generators used in the model*

Number Wind Generator	IEEE 9 Bus Utilization (%)	IEEE 14 Bus Utilization (%)
WG 1	65	60
WG 3	70	66
WG 5	75	72
WG 7	78	75
WG 9	80	77
WG 11	82	79

Table 3 shows the Renewable energy utilization rate of different wind generators that are used in the model for the IEEE 9 bus and the IEEE 14 bus. Renewable energy utilization is an important metric for assessing the effectiveness of the ATC enhancement strategy in accommodating variable generation. More wind generators incorporated into IEEE-9 and IEEE-14 bus systems result in a higher rate of renewable energy utilization. Utilization for the IEEE-9 bus system improves gradually while the wind energy integration increases from around 65% with one wind generator to about 82% with eleven wind generators. Similarly, as wind power increases, the IEEE-14 bus system shows a rise from about 60% to 79%, indicating the network's ability to manage more renewable energy. Higher utilization rates correlate with higher ATC improvements, reflecting better congestion management and load balancing. Since wind energy contributes to greater transfer capability, the ATC enhancement increases as the number of wind generators increases. It begins at 5% for a single generator and reaches 15% with eleven generators.



Fig. 2. *Plot Comparing ATC Enhancement for IEEE-9 and IEEE-14 Bus Systems with Varying Numbers of Wind Generators*

Fig. 2 shows the plot **comparing ATC enhancement** for IEEE-9 and IEEE-14 bus systems with varying numbers of wind generators. Visual representation of ATC improvement helps illustrate trends and incremental benefits from adding renewable resources. The ATC value for the IEEE-9 bus in the Wind Generator (WG-1) analysis is 120 MW, while the ATC value for the IEEE-14 bus is 180 MW. Likewise, for the Wind Generator (WG-9) analysis, the ATC value for IEEE-9 buses yields 138MW, but the ATC value for IEEE-14 buses yields 138MW as well. For both systems, ATC rises as the number of wind producers increases. Because of its greater network capacity, the IEEE-14 bus system has a higher ATC, but both systems show a reduction in incremental improvements with the integration of more generators.

5. Conclusion

The proposed methodology represents a comprehensive ATC enhancement strategy leveraging both sensitivity-based wind placement and FDR. The integration of both generation-side and demand-side flexibility provides a holistic approach to power system optimization under variable renewable penetration. The model implemented a hybrid methodology with the combination of coordinated FDR and optimal WG allocation. The coordinated ADR was functioning on the demand-side responsiveness; however, optimal WG allocation could optimize the generation-side flexibility. This dual approach ensures that both load adjustments and renewable generation are coordinated to maximize system performance. In this approach, the ATCDF-based sensitivity model was used for optimal WG placement, ensuring minimal congestion and maximum transfer capability. However, the two-stage unit commitment and demand response model was safeguarding a dynamic load balance and improving the renewable accommodation. Thus, the ATC was improved in the implemented power system operation. The advantages of the proposed model were that it ensures secure, economical, and sustainable operation of future smart grids by dynamically balancing variable renewable inputs and consumer flexibility. Additionally, the model reduces operational costs by efficiently integrating near-zero marginal cost renewable generation while maintaining grid reliability. The unified framework, validated on IEEE test systems, demonstrates that joint optimization of renewable integration and adaptive demand scheduling can substantially improve ATC, minimize congestion, and foster resilient grid operation.

Compliance with Ethical Standards

Conflicts of interest: Authors declared that they have no conflict of interest.

Human participants: The conducted research follows the ethical standards and the authors ensured that they have not conducted any studies with human participants or animals.

References

[1] S. Singh, and S. P. Jaiswal. "Enhancement of ATC of micro grid by optimal placement of TCSC." Materials Today: Proceedings 34 (2021): 787-792.
[2] N. K. Yadav, "Optimal ATC enhancement model: analysis of the effect of thyristor-controlled series compensation." J. Network. Commun. Syst. 2 (2019): 42-51.

[3] N. K. Yadav, "Optimizing TCSC configuration via genetic algorithm for ATC enhancement." Multimedia Tools and Applications 82, no. 25 (2023): 38715-38741.
[4] A. I. Gautam, G. Sharma, P. N. Bokoro, and M. F. Ahmer. "Available transfer capability enhancement in deregulated power system through TLBO optimised TCSC." Energies 15, no. 12 (2022): 4448.
[5] A. A. Sadiq, M. Buhari, S. S. Adamu, and H. Musa. "Coordination of multi-type FACTS for available transfer capability enhancement using PI–PSO." IET Generation, Transmission & Distribution 14, no. 21 (2020): 4866-4877.
[6] K. Bavithra, S. Charles Raja, K. Anadhakumar, and R. Latha. "Parameter optimisation of FACTS using cuckoo search algorithm for ATC enhancement in restructured power systems." *Int Energy J* 18, no. 2A (2020): 247-254.
[7] M. V. Rao, S. Sivanagaraju, and C. V. Suresh. "Evaluation and enhancement of available transfer capability in the presence of static synchronous series compensator." In 2017 IEEE International Conference on Power, Control, Signals and Instrumentation Engineering (ICPCSI), pp. 1365-1371. IEEE, 2017.
[8] M. S. Sureban, and S. G. Ankaliki. "Sensitivity factors based computationally efficient approach for evaluation and enhancement of available transfer capability." International Journal of Electrical & Computer Engineering (2088-8708) 15, no. 4 (2025).
[9] D. Shukla, S. P. Singh, A. K. Thakur, and S. R. Mohanty. "ATC assessment and enhancement of integrated transmission and distribution system considering the impact of active distribution network." IET Renewable Power Generation 14, no. 9 (2020): 1571-1583.
[10] V. Durković, and A. S. Savić. "ATC enhancement using TCSC device regarding uncertainty of realization one of two simultaneous transactions." International Journal of Electrical Power & Energy Systems 115 (2020): 105497.
[11] L. Hou, W. Li, K. Zhou, and Q. Jiang. "Integrating flexible demand response toward available transfer capability enhancement." *Applied Energy* 251 (2019): 113370.
[12] A. Narain, S. K. Srivastava, and S. N. Singh. "A novel sensitive based approach to ATC enhancement in wind power integrated transmission system." *SN Applied Sciences* 3, no. 5 (2021): 563.
[13] W. Liu, T. Zhang, X. Yang, and J. Wang. "Calculation and optimization of inter-regional available transfer capability considering wind power uncertainty and system improvement measures." *Frontiers in Energy Research* 11 (2023): 1177754.
[14] A. Narain, S. K. Srivastava, and S. N. Singh. "An ATCDF approach for ATC enhancement using charging/discharging of wind-battery system considering wind direction and wake effect of WTs." *International Transactions on Electrical Energy Systems* 31, no. 11 (2021): e13086.
[15] K. T. Venkatraman, B. Paramasivam, and I. A. Chidambaram. "Optimal allocation of TCSC devices for the enhancement of ATC in deregulated power system using flower pollination algorithm." *J. Eng. Sci. Technol* 13, no. 9 (2018): 2857-71.