Trends in
Electrical Engineering

https://journals.stmjournals.com/tee

ISSN: 2249-4774 (Online)
ISSN: 2321-4260 (Print)
Volume 15, Issue 3, 2025
September–December
DOI (Journal): 10.37591/TEE

Research TEE

Techniques for Congestion Mitigation in Hybrid Electricity Markets

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Abstract

In hybrid electricity markets, managing congestion is a crucial issue that impacts market efficiency, grid stability, and the integration of renewable energy sources. In order to efficiently detect and manage crowded zones, this study suggests an enhanced congestion mitigation strategy by introducing the notion of Average Transmission Congestion Distribution Factor (ATCDF). In order to improve grid dependability, the research focuses on integrating Wind Power Generation (WPG) with Battery Energy Storage Systems (BESS) to optimize Available Transfer Capability (ATC). To increase the accuracy of power forecasts, a modified method for calculating wind farm power output is created that takes wake effects, wind direction, and speed into account. In order to improve ATC in emergency situations, the study also takes into account wind turbines' reactive power capabilities. Through the strategic deployment of WPG and BESS, the suggested methodology facilitates effective congestion management, improving market operations, lowering transmission losses, and improving the power flow network. In order to maximize energy transactions while preserving grid stability and economic efficiency, grid operators, legislators, and market participants can benefit greatly from the research's conclusions.

Keywords: Congestion management, hybrid electricity markets, available transfer capability (ATC), average transmission congestion distribution factor (ATCDF), wind power generation (WPG), battery energy storage systems (BESS)

INTRODUCTION

As more wind power enters hybrid power systems, grid operators now face new problems in running and managing the grids. Though wind energy creates more sustainable and clean electricity, its changeable and sudden nature can lead to bottlenecks in transmission lines and unstable voltages [1]. For these reasons, wind farm energy production must be estimated correctly, and reactive power must be managed to support the grid and use renewables well. The research wanted to bring together techniques for wind power estimation and reactive power management so that they could reduce congestion and improve the voltage stability of hybrid power systems. By dealing with those challenges, the framework supports adding more renewable energy to the system and ensures good overall performance in markets that are deregulated and complicated [2].

Background of the study

More use of renewable energy, mainly wind, in the current power system helps protect the environment but also opens up new operational problems. Wind power is always changing and cannot be controlled which increases the chance of clogging transmission lines and unpredictable voltage changes in mixed power grids using traditional and renewable energy [3]. If the capacity to transmit power cannot meet the demand, it leads

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Received Date: June 23, 2025
Accepted Date: June 27, 2025
Published Date: August 08, 2025

Citation: Sabha Khatoon, Kamaljeet Singh, Parwinder Singh. Techniques For Congestion Mitigation in Hybrid Electricity Markets. Trends in Electrical Engineering. 2025; 15(3): 1–6p.

to congestion, bottlenecks, electricity transfer restrictions and increased loss which may threaten how reliable the grid is. Stable voltage is maintained and the safety of the system supported by reactive power, however, since wind turbines are not always on, it can be tricky to manage reactive power [4]. Usually, traditional methods for controlling congestion involve either rescheduling generators or installing FACTS devices, but they rarely use the reactive power from wind farms and similar energy sources. Wind power forecasting is necessary to organize and improve the use of reactive power, but doing so accurately is still not easy because wind power is unpredictable [5]. Thus, it is understood that programmed measures combining detailed wind forecasts and leading reactive power optimization will relieve congestion, keep voltages steady and increase the use of renewables. Resolving these problems will make hybrid power systems better able to provide more energy to support goals of sustainability.

WIND POWER ESTIMATION AND ITS IMPORTANCE IN CONGESTION MANAGEMENT

Proper planning and smooth operation of hybrid systems with a lot of renewables depend on accurate predictions of wind output. Fluctuations in wind speed cause the output from wind energy to be very unreliable. Dealing with such variability in usage is difficult for those operating the system because they must keep a steady balance of supply and demand and try to prevent crowding in the cables. Accurate predictions of wind power make it more possible to arrange and send out both regular and renewable generators, leading to easier control of congestion issues [6]. When wind farm output can be forecast accurately, grid operators are better able to handle reactive power and manage parameters in real time to maintain reliability and prevent unintended overloading of lines. That is why estimating the output of wind energy ensures a more secure power grid and supports greater use of renewables by reducing curtailment and raising system efficiency.

LITERATURE REVIEW

Kumar and Kumar combined and enhanced several Flexible AC Transmission System (FACTS) devices to regulate congestion when wind farms are part of the graphed power network. Sensitivity factor analysis was used to detect the most critical sections and FACTS devices were added in these places to ease the load on the network. It was proved by their study that managing FACTS devices together results in better power flow, higher system stability, better wind energy use and reduction of congestion in hybrid systems [1].

Nikkhah *et al*. presented a new strategy for handling congestion that works with electric vehicle charging stations (EVCSs), wind farms and demand load control (DLC) at the same time. They applied a strategy to break up the major problem into multiple manageable issues that helped optimize the power flows and reduce issues with congestion. The integration of renewable resources and capable loads through advanced techniques made the grid more flexible, avoided overcrowding and enabled hybrid power systems to work well in all kinds of conditions [5].

Ogunwole and Krishnamurthy performed research on managing transmission congestion by altering the timings of power generation of active and reactive means through a PSO algorithm. They considered the sensitivity of generator sizing to pick changes in the emission of power that would cut congestion most notably. According to their findings, PSO-based rescheduling gave a solid and efficient answer, relieved a lot of congestion and still stabilized the system voltage through reactive power [6].

Sahoo *et al*. focused on managing congestion more effectively by using FACTS devices alongside optimal ways of scheduling energy distribution in deregulated markets. The research pointed to the advantages of having FACTS devices in the power transmission system for quick reactive power management. It was shown in the study that using FACTS devices and proper dispatch algorithms helped handle issues of congestion, reduced losses through the grid and improved how the market worked in hybrid systems with many renewable sources [7].

Singh *et al*. introduced and used an upgraded version of the monarch butterfly optimization approach for handling transmission congestion by adjusting the schedules of power generators. They made sure that generators produced the right amounts of both active and reactive powers to reduce congestion while maintaining security limits. The research proved that the suggested metaheuristic method managed to resolve congestion issues and helped stabilize voltage conditions, pointing to potential benefits in practical use for grid systems facing congestion [8].

METHODOLOGY

An integrated analytical strategy was used to estimate what wind farms could generate and find the best reactive power setting to reduce grid overloads in hybrid networks. Historical data from different meteorological stations were gathered first to set up a model for predicting wind power. To make accurate estimates, the forecasting scheme included both Weibull distribution and time-series analytics at the wind farm [9, 10].

Next, a model joined together a few conventional generation stations, wind farms and energy storage systems, using MATLAB/Simulink. Factors like line thermal limits, minimum and maximum voltage and possible reactive power by generators were put into consideration in the system [11].

A multi-objective optimization method using a genetic algorithm (GA) was applied to minimize possible congestion and make sure voltage values remain within the acceptable range. The parameters used with the GA were adjusted to guarantee the algorithm quickly reached a solution. The method involved looking at wind turbine generators and static compensation instruments installed near key bus bars [12].

Simulations using a variety of wind power and load scenarios were done to check the framework. Metrics used in the performance analysis were transmission line loading, indices of system voltage stability and available transfer capability (ATC). The system's performance in handling congestion and improving reliability were all examined through the results.

RESULT AND DISCUSSION

The results obtained from the research framework are laid out for both wind farm power estimation and overcoming congestion in hybrid power networks. The outcomes were found by using simulations that modelled wind power and the percentage of the grid the power served. The estimated power from wind, the loading on transmission lines, the voltage profile and ATC were examined to determine the success of the suggested approach. There is a focus on how the study helped ease congestion and secured system stability as shown by comparisons between cases [8].

Wind Power Estimators Should Produce Precise Results

The model for estimating wind power worked very well, relying on past weather records. The measured power and the modelled power are compared in Table 1 for chosen time frames.

As shown in Table 1, the wind power estimation models matched the true power output for each time period, with discrepancies not exceeding 0.6 MW. The percentage of errors did not go above 2.14% which highlights that the model offers good accuracy and dependability for predicting wind farm power output. This high accuracy indicates that estimating methods can give solid support to planning and optimizing operations in hybrid power systems. Additionally, Figure 1 shows the wind power estimation accuracy at various time intervals.

Table 1. Wind power estimation accuracy at various time intervals.

Time interval	Actual power output (MW)	Estimated power output (MW)	Absolute error (MW)	Percentage error (%)
00:00–01:00	25.4	24.9	0.5	1.97
06:00–07:00	18.7	19.1	0.4	2.14
12:00–13:00	30.2	29.6	0.6	1.99
18:00–19:00	22.8	23	0.2	0.88

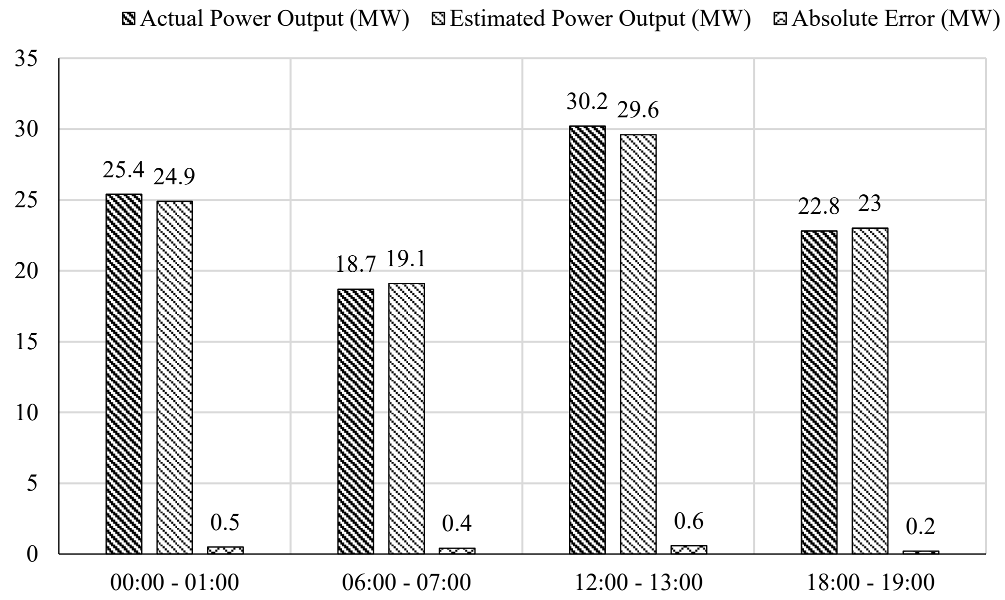

Figure 1. Wind power estimation accuracy at various time intervals.

Optimized Reactive Power and Problems with Grid Congestion

Experiments were performed under three situations: not optimizing reactive power, optimizing it with the help of conventional generators and as a combination of wind turbines and static compensators. In Table 2, it can be seen what are the maximum line loadings and the highest voltage variation for every scenario (Figure 2).

Table 2. Impact of reactive power optimization on congestion and voltage stability.

Scenario	Maximum line loading (%)	Maximum voltage deviation (p.u.)
Without reactive power optimization	105	0.12
Conventional generators only	98	0.08
Integrated reactive power support	89	0.04

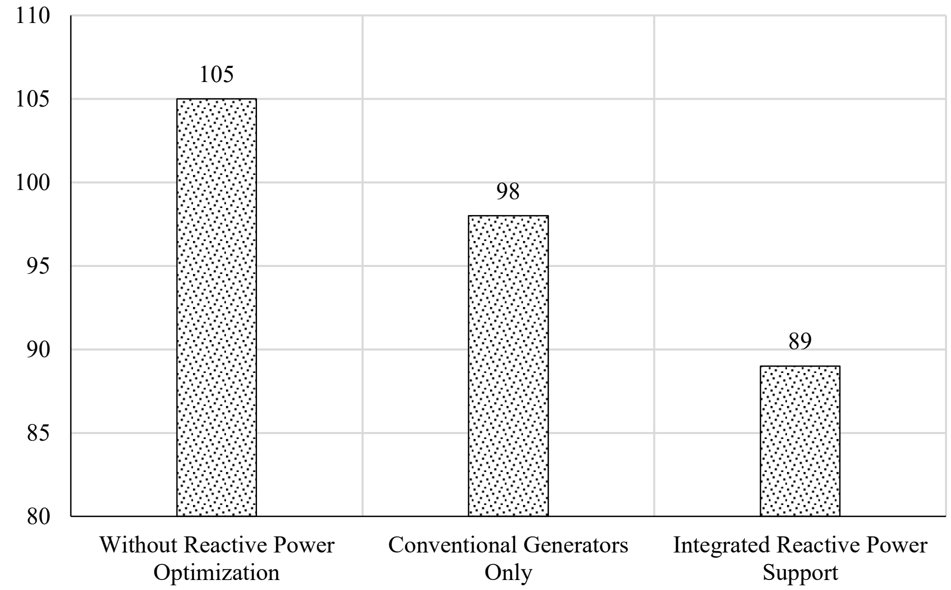

Figure 2. Maximum line loading (%) for different scenario.

The results in Table 2 prove that optimizing reactive power greatly improved handling congestion and securing stable voltage in the system. Because there was no reactive power optimization, the maximum level of loads on lines reached 105% and caused a significant deviation in voltage [13]. With only conventional generators helping out, the line did not get overloaded so much and the voltage from the source stayed close to normal which showed an improvement of moderate magnitude. The highest impact was found when reactive power was taken from generators, wind turbines and static compensators together and not just by one source of energy. Since, maximum line loading was decreased to 89%, staying safely below the limits, while the voltage changed by just 0.04 p.u. which proved better voltage stability and a well-balanced system. So, it stresses the need for several reactors to cooperatively respond to issues and prevent voltage problems. Moreover, Figure 2 highlights the maximum line loading (%) for different scenarios.

Better-Functioning Systems for Aircraft Transfer Capability

The system's capability to transmit energy was measured both before and after using the reactive power optimization. Table 3 shows the data for ATC when the system experiences peak load and plenty of wind energy.

Table 3 displays how the maximum amount of electricity that can be moved across the transmission lines varies depending on the amount of reactive power being optimized. Measured at peak loads, the ATC capacity was 150 MW, while it fell to 140 MW when there was a lot of wind. After using the integrated reactive power optimization technique, the ATC increased by 20 and 25%, coming out to 180 and 175 MW. Because of this, it is clear that the optimization scheme made the system transfer more power, reducing overcrowding and enabling more variable renewable energy sources to be included.

Table 3. Available transfer capability improvement due to reactive power optimization.

Condition	ATC before optimization (MW)	ATC after optimization (MW)	Percentage improvement (%)
Peak Load Scenario	150	180	20
High Wind Output	140	175	25

DISCUSSION

The use of the framework made it possible to obtain accurate results for wind power and improve the use of reactive power. Proper estimation of wind power helped in planning the necessary steps for easing grid congestion. Successfully using multi-objective optimization, it was possible to divide reactive power workload between various sources, limit overloads on lines and raise the stability of the system [14].

The rise in Available Transfer Capability demonstrated that the system became more versatile and secure which is vital for using a high amount of renewable energy. They show that the framework can be helpful for system operators who wish to balance grid stability and incorporate renewable energy [15].

The propose that future studies might include live monitoring from the system and find ways to apply the method in real-life scenarios.

CONCLUSION

The research found that using correct wind power estimates and reactive power optimization greatly reduces overloaded areas and helps keep electricity stable in mixed power systems. The use of a multi-objective genetic algorithm to operate reactive power from both conventional and renewable sources allowed the framework to lessen transmission line overloads and increase the possible amount of power transfer by up to 25%. These updates demonstrate that the framework can increase the use of renewables and keep the system reliable which makes it an important resource for today's grids and future energy planning.

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