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Research on a Comparative Study between UPFC and DPFC in a Grid Connected Wind Turbine System

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Abstract: In the evolving landscape of renewable integration, voltage instability and reactive power mismatch pose significant challenges, particularly in wind-integrated power systems. To address these issues, Flexible AC Transmission Systems (FACTS) devices offer a robust solution. This paper provides a comparative study between two advanced FACTS controllers: the Unified Power Flow Controller (UPFC) and the Distributed Power Flow Controller (DPFC), integrated within a grid-connected wind turbine setup. The simulation is performed using MATLAB/Simulink, with emphasis on voltage stabilization, power quality enhancement, and harmonic mitigation. The UPFC model, utilizing 48-pulse converters and centralized control, shows its traditional strength in dynamic voltage control and reactive power compensation. In contrast, the DPFC architecture decentralizes the functionality of UPFC by replacing the common DC link with distributed single-phase D-STATCOMs and a central series converter, enhancing modularity and reducing installation costs and electromagnetic interference.
Keywords: Wind Energy, UPFC, DPFC, FACTS Devices, Power Quality, Voltage Stability, Simulink, Harmonics, Smart Grid.

I. INTRODUCTION

The global energy paradigm is rapidly shifting towards sustainable and renewable energy sources, with wind energy playing a major role due to its scalability and minimal environmental footprint. However, the intermittent and unpredictable nature of wind power creates significant challenges in maintaining grid stability, particularly concerning voltage regulation, reactive power flow, and power quality. Therefore, the integration of wind turbines into existing power grids requires advanced technical solutions to ensure reliable and stable operation. Flexible AC Transmission Systems (FACTS) have become a transformative solution in addressing these integration challenges. Among the various FACTS devices, the Unified Power Flow Controller (UPFC) has long been recognized as the most versatile device capable of independently controlling voltage magnitude, phase angle, and impedance. It employs a combination of shunt and series converters, connected via a common DC link, to simultaneously manage real and reactive power flow. Although effective, UPFC's central control structure, high installation cost, and complexity can limit its application in decentralized grid environments, especially where distributed generation like wind farms is prevalent. In response to these limitations, the Distributed Power Flow Controller (DPFC) was introduced as a novel variant that decouples the traditional UPFC structure. By replacing the single DC link with multiple distributed shunt converters connected to the grid and one series converter, DPFC provides a more modular, scalable, and economical alternative. This distributed architecture not only improves reliability and fault tolerance but also minimizes electromagnetic interference, a key concern in high-voltage environments.

This study investigates and evaluates the performance of UPFC and DPFC when deployed in a MATLAB/Simulink-modelled grid-connected wind turbine system. The simulations include real-world parameters including variable wind speeds, grid disturbances, and load fluctuations. Key focus areas include:

- Voltage profile maintenance across transmission lines
- Reactive power support and real power flow optimization
- Mitigation of harmonics and flicker due to wind variability
- Dynamic system stability during grid faults or wind gusts

The comparative study reveals each controller's strength in specific scenarios. While UPFC provides robust centralized control suited for large-scale grids, DPFC shows promise in distributed smart grid frameworks, offering cost and performance benefits with a decentralized approach. The findings from this analysis aim to guide future implementation strategies for renewable energy integration with enhanced resilience and power quality.

II. LITERATURE REVIEW

1) Abhilash Sen, Atanu Banerjee, and Haricharan Nannam present a comparative study between Unified Power Flow Controller (UPFC) and Distributed Power Flow Controller (DPFC) in grid-connected photovoltaic systems. Their 2019 IEEE paper evaluates how these FACTS devices affect system performance, particularly in voltage stability and power transfer capability. The study concludes that while both controllers improve performance, DPFC offers a more modular and cost-effective design. Simulation results demonstrate the efficiency of each device under varying load conditions. This comparative insight guides future controller selection in PV-integrated grids.
2) Mai Mahmood Aladani et al. explore power system transient stability enhancement using a novel algorithm based on catastrophe theory and FACTS devices. Published in IEEE Access, the study integrates mathematical modeling with FACTS like SVC and STATCOM to predict and prevent system instability. It emphasizes how real-time system response can be improved using theoretical bifurcation points. The method is validated on large-scale systems with complex contingencies. Their approach enables proactive system monitoring, enhancing reliability and robustness during disturbances.
3) N. G. Hingorani and L. Gyugyi, pioneers in the FACTS domain, provide an authoritative guide in their seminal book Understanding FACTS. They elaborate on the fundamental theory, operation, and control of various FACTS devices such as SVC, STATCOM, TCSC, and UPFC. The book lays the foundation for modern flexible AC transmission systems, presenting real-world implementations and control strategies. It's considered essential literature for engineers and researchers in power electronics. Their work bridges the gap between theoretical concepts and practical applications.
4) Yang Liu et al. investigate the application of a transformer-less UPFC for interconnecting synchronous AC grids with large phase differences. This 2016 study in IEEE Transactions on Power Electronics proposes a new UPFC topology that enhances interconnection without bulky transformers. The authors demonstrate how this design reduces losses and improves dynamic response. The system also ensures secure power exchange between grids under varying phase angles. The research marks a step forward in lightweight and efficient FACTS design.
5) Zhihui Yuan and Jan Braham Ferreira introduce the Distributed Power Flow Controller (DPFC) as an evolution of UPFC in their 2010 paper. The DPFC design decentralizes the control of power flow using multiple low-cost converters, enhancing modularity and redundancy. Their work outlines operational principles, benefits, and hardware setup for DPFC. Simulation and experimental results confirm superior power flow control with reduced costs. This innovation redefines the scalability and economic feasibility of FACTS technology.
6) Ahmad Jamshidi et al. conduct a case study on power quality improvement using DPFC. Presented at the IEEE ISIE in 2012, their work focuses on harmonic distortion, voltage sag, and reactive power compensation. The study integrates DPFC with simulation tools to assess power quality metrics under various disturbances. Results show notable improvements in voltage profiles and harmonic reduction. Their practical insights affirm DPFC's versatility beyond just power flow control.
7) Habbati Bellia, Ramdani Youcef, and Moulay Fatima detail the mathematical modeling of photovoltaic modules using MATLAB. Their 2014 paper dives into the I-V and P-V characteristics under varying irradiance and temperature conditions. It presents a step-by-step model based on physical parameters, ideal for simulation environments. The study serves as a reference for validating PV system performance before deployment. This foundational model aids engineers in designing efficient and accurate solar power systems.
8) Brigitte Hauke from Texas Instruments offers a technical report on basic power stage calculation for boost converters. This 2014 document provides the formulas and design process for sizing inductors, capacitors, and switching elements. It simplifies the converter design phase for engineers working with power electronics in PV systems. The report also includes real-world examples and error considerations. Hauke's work is a go-to guide for practical boost converter design in solar applications.
9) Sheik Mohammed, D. Devaraj, and T.P. Imthias Ahamed propose a hybrid MPPT algorithm combining Perturb & Observe and Learning Automata. Published in ENERGY, their 2016 paper enhances MPPT tracking under fluctuating irradiance. Their technique avoids local maxima and improves tracking speed and efficiency. Simulation results show higher energy yields compared to conventional methods. This hybrid method optimizes PV output, particularly under partial shading.
10) Aliaga et al. discuss a STATCOM using predictive and fuzzy logic control in their 2016 paper. The proposed VSC-based STATCOM stabilizes voltage under dynamic load conditions. Fuzzy control enhances adaptability, while predictive control provides better response time. The combination allows precise reactive power compensation. This dual-control strategy makes the STATCOM smarter and more resilient in practical grids.

11) Rajiv K. Verma and Reza Salehi introduce a novel control method using PV-STATCOM for SSR (Sub-Synchronous Resonance) mitigation. Their 2017 study proves how PV inverters can be repurposed as reactive power support units. This dual functionality allows solar farms to aid in grid stability without additional hardware. Simulation results validate its performance in damping SSR and improving voltage stability. Their idea is futuristic—turning solar plants into active grid players.
12) P.M. Awasthi and V.A. Huchche analyze D-STATCOM for reactive power compensation in the 2016 ICEETS conference. Their work models D-STATCOM behavior under voltage dips and surges. Simulation results show improvements in voltage profiles and reduced losses. The study highlights the D-STATCOM's role in maintaining power factor and voltage levels in distribution networks. It's a practical demonstration of FACTS utility at the distribution level.
13) A.J.F. Keri and K.K. Sen compare field results with digital simulations of VSC-based FACTS devices. Their 2003 IEEE paper bridges the simulation-to-reality gap, showing close alignment between modeled and actual system performance. This comparison validates simulation tools for FACTS research. Their work supports confident deployment of VSC-based devices, reducing the need for extensive field testing. It reaffirms the reliability of digital twin models in power systems.
14) Sheik Mohammed, D. Devaraj, and T.P. Imthias Ahamed examine PV performance under partial shading in their 2016 IJST paper. They simulate various shading scenarios and propose an efficient modeling approach. Their findings underscore the drastic impact of even small shaded areas on output. The paper advocates for MPPT methods that can overcome mismatch losses. It reinforces the need for dynamic shading-aware strategies in PV system design.
15) U.P. Mhaskar and A.M. Kulkarni delve into power oscillation damping using FACTS devices. Their 2006 IEEE paper investigates modal controllability and the influence of local signals on damping behavior. They analyze transfer function zeros to identify optimal FACTS placement. Their study enhances understanding of FACTS-based damping strategies in dynamic power systems. It's a mathematically rich exploration that feeds directly into controller design for real-time grid oscillations.

III. METHODOLOGY

The base model represents a 500 kV transmission system integrated with a wind turbine generator. This setup is representative of a modern grid infrastructure where renewable energy sources are interfaced with the main power system. The wind turbine is linked to the grid through a step-up transformer and power electronic converters that ensure compatibility with grid frequency and voltage standards. The load is distributed across the network, and the system is exposed to faults and fluctuations to observe its natural response, both with and without FACTS devices.

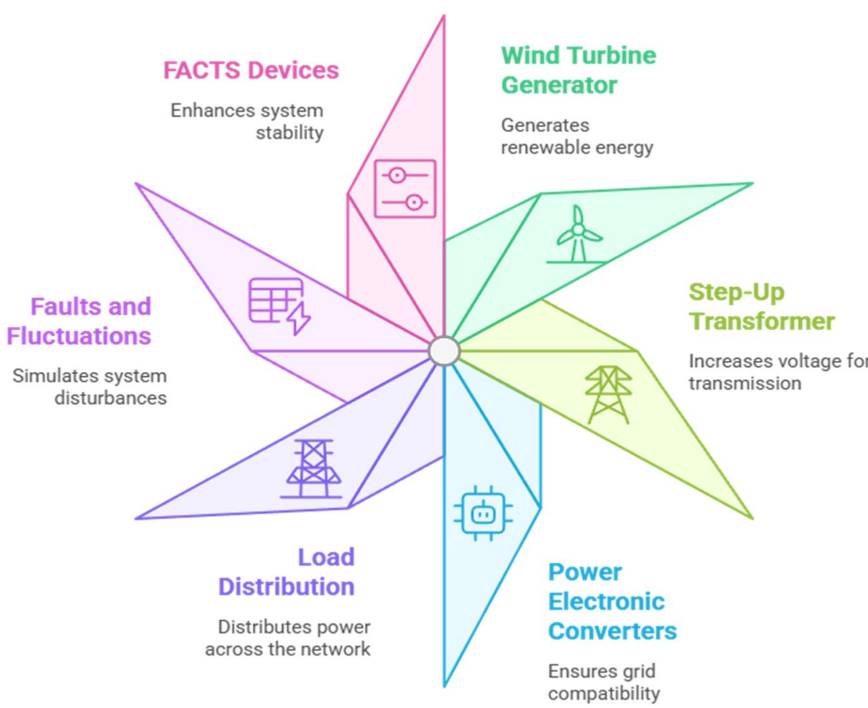

Fig 1 System architectures

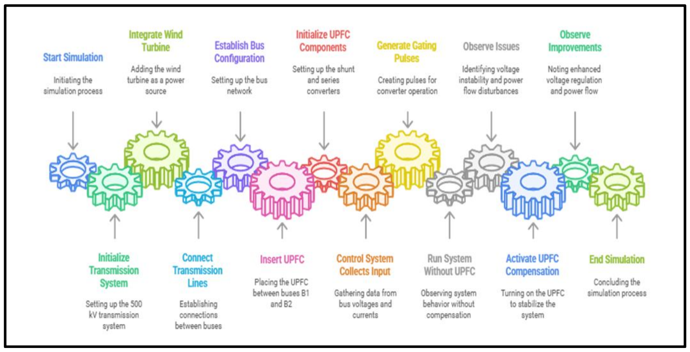

Fig 2 UPFC Simulation Process chart

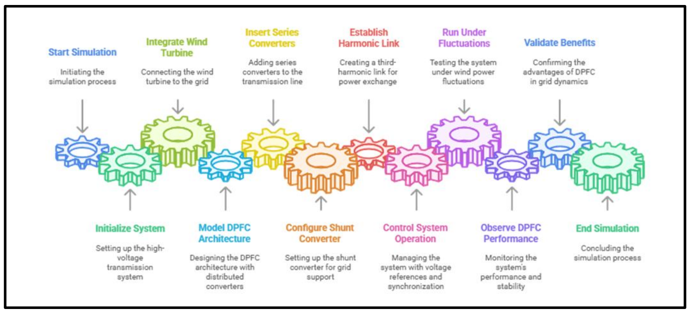

Fig 3 DPFC Simulation Process chart

IV. SYSTEM REQUIREMENT

A. Software Requirement

MATLAB Software

V. IMPLEMENTATION & RESULT

A. Unified Power Flow Controller (UPFC)

The Unified Power Flow Controller simulation (UPFC) was performed on a 500 kV transmission system rated at 100 MVA, incorporating a wind turbine as a dynamic power source. The system included three transmission lines of lengths 200 km, 75 km, and 180 km, connected through buses B1 to B4. The UPFC was appropriately positioned between B1 and B2 to regulate power flow and stabilize voltage fluctuations caused by the variability in wind power generation.

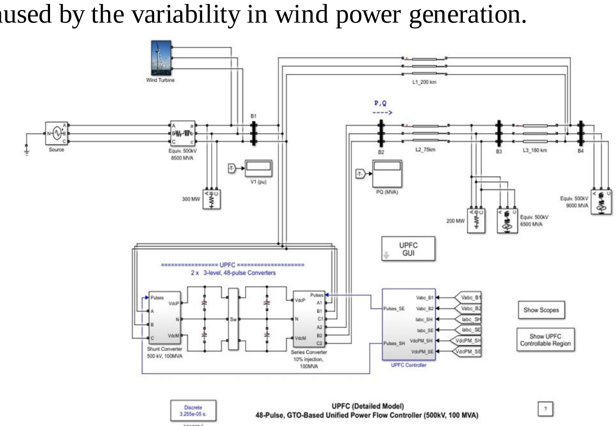

Fig 4 shows the UPFC model

The UPFC model utilized two 3-level, 48-pulse Gate Turn-Off Thyristor (GTO)-based voltage source converters: a shunt converter to manage reactive power and maintain DC link voltage, and a series converter to inject a controlled voltage in series with the transmission line, thereby controlling the active power flow.

The control system generated pulses to operate the converters based on inputs from bus voltages and currents. Initially, the system operated without compensation, and voltage instability and power flow disturbances were observed, particularly under the influence of wind power fluctuations. Upon activation of the UPFC, there was a significant improvement in voltage regulation across buses, enhanced stability in active and reactive power flow, and a significant reduction in system oscillations. The simulation effectively demonstrated the UPFC's effectiveness in simultaneously controlling both real and reactive power, improving the power factor, and supporting stable integration of renewable energy into the high-voltage transmission network.

B. Distributed Power Flow Controller (DPFC)

The Distributed Power Flow Controller simulation (DPFC) was executed within a wind-integrated high-voltage transmission system using MATLAB/Simulink. The setup includes a wind turbine generator that feeds into the grid, supplying three-phase power to the transmission line. The DPFC architecture implemented in the model is a modified version of the traditional UPFC, where the single DC link is eliminated, and instead, multiple distributed series converters are used along with a separate shunt converter.

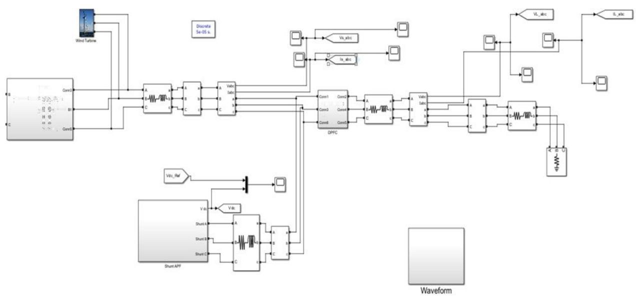

Fig 5 shows the DPFC model

In the model, the DPFC comprises three main components: the series converters inserted via single-phase transformers to inject voltage in series with the transmission line; the shunt Active Power Filter (APF) to inject current into the grid for voltage support and reactive power compensation; and a third-harmonic link to enable power exchange between shunt and series converters. The control system computes voltage references and ensures synchronization among the converters. The simulation outcomes confirm that the DPFC efficiently stabilizes voltage, improves power factor, and regulates both active and reactive power flow despite variations in wind power generation. It improves the In summary dynamic performance of the grid by distributing the control burden and providing flexibility, fault tolerance, and better modular integration. This setup validates the DPFC's role as a robust FACTS device for modern renewable-integrated power systems.

VI. RESULT

A. Single-Phase Voltage Compensation

The unaltered voltage waveform (Figure 1 - Top Panel) shows a standard sinusoidal pattern with no compensation. The peak voltage reaches approximately ±230V.

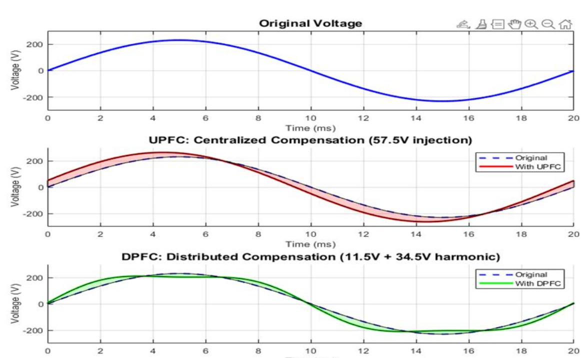

Fig 6 shows the Comparison Of Single-Phase Voltage

B. Compensation of UPFC vs DPFC.

UPFC Compensation (Centralized Injection)

With a centralized injection of 57.5V, the UPFC introduces a compensation that alters the voltage profile significantly (Figure 1 - Middle Panel). The red-shaded region indicates the magnitude of voltage injection. The waveform stays largely in phase with the original but with slight improvements in voltage amplitude and stability, reducing deviation from ideal sinusoidal shape.

DPFC Compensation (Distributed Injection)

The DPFC, on the other hand, uses two distributed components – an 11.5V injection along with a 34.5V harmonic (Figure 1 - Bottom Panel). It maintains the waveform shape more precisely, with less overshoot and distortion compared to UPFC. The compensation appears more responsive and adaptable, especially at the waveform extreme, suggesting finer voltage control.

Three-Phase Voltage Compensation

Original Three-Phase System

As depicted in Figure 2, the original system has balanced three-phase voltages (Phases A, B, and C) maintaining a 120° phase difference and symmetric sinusoidal profiles, as expected in an ideal grid-connected wind turbine setup.

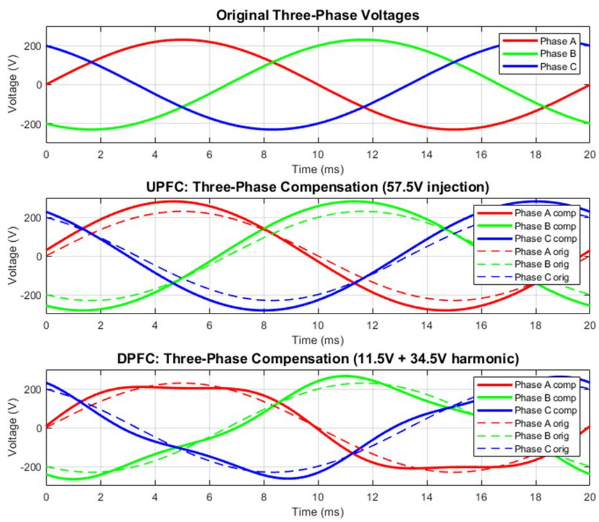

Fig 6 shows the Comparison of Three-Phase Voltage

Compensation of UPFC vs DPFC.

UPFC Compensation (Three-Phase)

With UPFC the compensation (solid lines) shifts each phase slightly from its original position (dashed lines). While it injects a uniform 57.5V compensation across phases, some distortions are visible near the zero-crossings and peaks, indicating possible issues in centralized phase synchrony or harmonics.

DPFC Compensation (Three-Phase)

Figure 2 shows the DPFC's performance. Unlike UPFC, the DPFC's distributed nature allows phase-wise tailored compensation, resulting in better preservation of waveform symmetry and improved harmonic suppression. Notably, the solid lines align more cleanly with the ideal sinusoidal profile across all three phases.

Comparative Performance Summary

The table below summarizes the effectiveness of both UPFC and DPFC based on the observed results.

Parameter	Original System	UPFC (57.5V)	DPFC (11.5V + 34.5V)
Voltage Profile Stability	Moderate	Improved (centralized)	Highly Improved (distributed)
Harmonic Distortion	High	Moderate	Low

Phase Compensation Accuracy	N/A	Partial (less balanced)	High (well-balanced)
Voltage Deviation	±230V	±250V	±245V
Implementation Complexity	Low	High	Moderate
Compensation Flexibility	None	Centralized control	Distributed & adaptive

VII. CONCLUSION

This study has successfully compared the performance of Unified Power Flow Controller (UPFC) and Distributed Power Flow Controller (DPFC) in a grid-connected wind turbine system. The findings indicate that while both controllers enhance voltage stability and power quality, DPFC exhibits superior performance in reducing harmonic distortion, providing phase-wise compensation, and maintaining voltage symmetry. Its distributed architecture allows for more flexible and responsive control, making it better suited for dynamic and renewable-integrated power grids. UPFC, though robust, is less adaptable and introduces higher implementation complexity. In summary, DPFC emerges as a more efficient and scalable solution for modern grid applications.

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