DESIGN AND EVALUATION OF A LOAD-SENSITIVE HYBRID POWER SYSTEM WITH WIND DG AND D-STATCOM

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ABSTRACT

The growing integration of renewable energy in residential power systems necessitates a thorough understanding of how electric load profiles affect overall system performance. This study investigates the impact of varying load patterns on the voltage stability, power quality, and dynamic performance of off-grid hybrid renewable energy systems—primarily incorporating wind energy and distributed generation (DG) components. By simulating a 15-bus IEEE test system in MATLAB/Simulink, the research identifies critical nodes prone to voltage instability under different load and generation scenarios. The performance of D-STATCOM as a compensating device is analysed under sudden fault conditions and varying load levels. The findings demonstrate that electric load fluctuations significantly influence reactive power margin and voltage regulation, especially at weaker nodes. Placement of compensation devices at the weakest bus results in improved voltage recovery and reduced system vulnerability to collapse. Furthermore, strategic DG placement enhances reactive power support and system reliability. This research underscores the importance of load-sensitive system planning and advanced control for resilient off-grid energy systems. Future scope includes real-time implementation and extension to solar-integrated networks.

Keywords: Voltage stability, D-STATCOM, reactive power margin, load profile, wind energy integration, hybrid systems, MATLAB/Simulink simulation.

I INTRODUCTION

Electricity generation, a cornerstone of modern infrastructure, is also the world's largest contributor to greenhouse gas (GHG) emissions [1]. The conventional centralized generation model, which transmits electricity over long distances to reach remote consumers, is becoming increasingly unsustainable due to high transmission costs, energy losses, and environmental concerns. Consequently, Distributed Generation (DG) based on renewable energy sources (RES) has emerged as a compelling alternative, drawing significant interest from researchers and policy makers worldwide [2]–[5]. DG systems can be located closer to end users, reducing distribution losses and enhancing energy reliability. However, integrating these systems into existing distribution networks poses unique technical challenges, particularly related to power flow management, voltage stability, and load variability [6][7]. The continuous fluctuation in consumer demand directly affects the load profiles of residential power systems. In areas dependent on off-grid solutions, such variations are even more critical, as they determine the performance and reliability of hybrid renewable energy systems (HRES). The load characteristics—comprising both static and dynamic components—interact with the generation systems in complex ways, sometimes causing system instabilities such as voltage collapse [8][9]. An especially pressing concern is voltage instability, which can severely affect the operational continuity of a power system. To combat this, compensatory devices like shunt capacitors, Synchronous Condensers, Static VAR Compensators (SVCs), and Distribution Static Compensators (D-STATCOMs) are widely employed [10]–[12]. Among these, D-STATCOMs have gained prominence due to their quick dynamic response and precise reactive power compensation capabilities [13].

The role of load modeling is pivotal in evaluating the performance and planning of distributed systems. Traditionally, most studies have employed static load models for simplicity; however, such models fail to accurately reflect real-world conditions where composite load profiles dominate [14]. These composite loads, a combination of static and dynamic elements, directly influence the behavior of distributed systems, particularly when power generators are placed in close proximity to the load centers. The inaccuracy in load modeling can result in ineffective compensation strategies, requiring oversized and costly devices to maintain voltage profiles and power quality [15][16]. The challenge is further intensified by high levels of wind power penetration, which, although environmentally beneficial, introduces variability and uncertainty in the power supply. Wind generators, particularly those based on induction machines, consume reactive power and may exacerbate voltage instability in weak networks [17]–[20]. To ensure system reliability under such conditions, it becomes essential to optimize the placement and capacity of voltage compensation devices. Research indicates that placing a D-STATCOM at the weakest node of the system can significantly enhance the voltage profile and reduce recovery time post-fault conditions [21][22].

Reactive Power Planning (RPP) or Var Planning is a critical task in this context. The goal is to identify optimal locations for installing Var sources such as D-STATCOMs and capacitor banks to maintain voltage stability across varying load conditions [23][24]. However, this is a complex problem involving nonlinear objectives and constraints, such as voltage deviation limits, real and reactive power flows, and dynamic load behavior [25]. Advanced optimization techniques are often employed to solve this multi-variable problem, but the foundation lies in accurate system modeling and detailed load analysis. The Q-V method, a traditional technique for evaluating voltage stability, plays an important role in this dissertation. This method involves plotting the reactive power versus voltage magnitude at various load buses to identify weak nodes in the network—those most susceptible to voltage collapse [26]. From this analysis, nodes with the lowest reactive power margin (Q-margin) are flagged as candidates for compensation. These findings are further supported by simulation-based studies using MATLAB/Simulink, which allow for dynamic modeling of complex systems, including wind turbine models and D-STATCOM configurations [27][28].

Another dimension explored in this study is the effect of compensator placement on voltage regulation under steady-state and fault conditions. Simulation results reveal that locating a D-STATCOM at the system's weakest bus—not just the Point of Common Coupling (PCC)—yields more effective voltage stabilization, even with a reduced device capacity [29]. Moreover, such strategic placement improves the system's overall loadability and ensures better recovery performance after disturbances, thereby enhancing operational efficiency and reducing unnecessary cost overheads. Ultimately, this dissertation emphasizes the importance of accurately characterizing electric load profiles and strategically managing reactive power in off-grid residential HRES. With increasing penetration of intermittent renewable sources like wind and solar, the system dynamics are becoming more unpredictable. Thus, understanding the interplay between load profiles and generation sources is crucial for improving system performance, reducing voltage fluctuations, and ensuring long-term sustainability of off-grid solutions [30].

II LITERATURE SURVEY

The transition to distributed generation (DG) based renewable energy systems has sparked considerable interest in improving the reliability and stability of power networks, particularly in off-grid and rural areas. Researchers such as Chakravorty and Das [1] have emphasized the need for robust voltage stability analyses in radial distribution networks due to the variable nature of composite loads. The traditional centralized model of electricity generation is increasingly challenged by geographical and infrastructural constraints, prompting exploration into localized generation units. Roy et al. [2], through simulations on the Kumamoto area distribution system, highlighted how wind-based DGs and reactive power compensating devices like D-STATCOMs significantly affect voltage profiles. As grid-integrated renewables rise, accurately modeling loads becomes crucial. The IEEE Task Force [3] and Mithulananthan et al. [4] underscore that the commonly used static models fail to capture the dynamic behavior of actual loads, which may comprise a mix of constant power, current, and impedance elements.

Voltage instability remains a central challenge in distributed renewable systems, particularly under varying load and generation conditions. Freitas et al. [5] noted that induction generators, widely used in wind systems, can severely depress voltage during faults due to their large reactive power demand. These challenges are addressed through technologies like STATCOMs and SVCs, which can rapidly inject reactive power to stabilize voltage [7]. Comparative studies by Freitas et al. [6] between synchronous and induction generators have shown that while synchronous machines provide better voltage regulation, their cost and complexity often limit their use. Molinas et al. [7] further supported this view by showing that STATCOMs offer superior low-voltage ride-through capabilities compared to SVCs. These compensators are vital in maintaining voltage stability and enhancing the dynamic performance of wind energy conversion systems, especially during grid disturbances [9]. The ability to provide fast voltage support with minimal harmonic distortion makes D-STATCOMs particularly attractive for off-grid networks that rely heavily on renewable energy sources [10].

Beyond hardware solutions, planning and optimization of VAR resources play a crucial role in maintaining system voltage and reactive power balance. Roy et al. [11] proposed a methodology for static and dynamic VAR planning that incorporates Q-loadability as an index to assess the vulnerability of buses to voltage collapse. Kundur et al. [12] and Hingorani and Gyugyi [13] laid the theoretical foundation for modern voltage stability and flexible AC transmission systems (FACTS), providing insights into how reactive power compensation should be strategically deployed across a network. Ghosh and Ledwich [14] elaborated on the application of custom power devices for improving power quality, especially in low-voltage grids with high DG penetration. The performance and placement of these devices are often analyzed using optimization techniques that account for multiple load scenarios and penetration levels, as indicated by Eremia et al. [15] and Cañizares [16].

Recent advances in load modeling and distributed resource optimization have significantly contributed to system reliability and planning. Singh et al. [17] demonstrated how a STATCOM-based voltage regulator could enhance the performance of self-excited induction generators in standalone applications. In parallel, works by Chowdhury et al. [18] and El-Khattam and Salama [19] presented comprehensive overviews of microgrids and DG benefits, ranging from improved reliability to reduced transmission losses. Ackermann et al. [20] proposed clear definitions for DG, highlighting its role in decentralizing energy and improving energy equity. Research by Hatziargyriou [21] emphasized the importance of microgrid architectures in enabling seamless integration of renewable energy sources. To facilitate interconnection and ensure interoperability of these systems, the IEEE Standard 1547 [22] outlines protocols that govern voltage regulation, frequency response, and fault detection in DG-connected systems. Studies like those of Ochoa et al. [23] and Qiu and Yu [24] have integrated optimization algorithms such as PSO for effective VAR planning and DG placement. Furthermore, Yazdani and Iravani [30] underscored the relevance of voltage-sourced converters in enabling dynamic control of DGs within smart microgrids.

III PROPOSED SYSTEM CONFIGURATION

The proposed system is modeled using the IEEE 15-bus test distribution system, which serves as a benchmark for evaluating the performance of hybrid renewable energy configurations under different load profiles. The distribution network has a total load demand of 6.301 MW and 0.446 MVAr, with bus 1 connected to the main grid and bus 13 identified as the weakest node based on reactive power margin analysis. Initially, the system operates without any distributed generation (DG), allowing a baseline study of voltage profiles and stability using the Q-V method. Simulation results show that lower reactive power margins at specific buses—particularly bus 15—indicate vulnerability to voltage instability, justifying further analysis with added DG sources. To assess the impact of renewable DG integration, a 2 MW wind generator using an induction machine is connected at the weakest node (bus 13). Multiple scenarios with wind penetration levels of 30%, 50%, 80%, and 100% are simulated. It is observed that while wind energy supports the real power demand, it adversely affects reactive power margins due to the wind generator's inherent reactive power consumption. This leads to decreased voltage magnitudes, particularly under medium penetration scenarios. For instance, at 50% penetration, several buses register voltage drops below acceptable thresholds, highlighting the need for reactive power compensation to maintain system voltage stability. To mitigate the negative effects of high wind penetration, a Distribution Static Compensator (D-STATCOM) is introduced. Various locations are tested to determine the optimal placement of the device, guided by the Q-loadability index. Simulation shows that placing the D-STATCOM at the weakest bus (bus 15) significantly improves the voltage profile and Q-margin of the system. Comparatively, when the device is placed at strong buses such as bus 2 or 3, the voltage recovery is less effective. Q-loadability increases by up to 10.65% at bus 15, establishing it as the most effective location for dynamic reactive compensation.

The system is subjected to a sudden three-phase fault at bus 2 to evaluate the dynamic response with and without D-STATCOM. When D-STATCOM is placed at the PCC (bus 13), voltage at the PCC recovers to 0.98 pu in 1.8 seconds. However, when the D-STATCOM is placed at bus 15, the system exhibits faster recovery with a slightly reduced capacity of 1.8 MVAr and voltage stabilization at 0.95 pu in just 1.6 seconds. These results underscore the advantage of placing compensating devices at the most vulnerable points in the network rather than conventional locations like PCC. Another important aspect evaluated is steady-state voltage regulation under varying load conditions. This is quantified using a global voltage index, which compares voltage deviations between maximum and minimum demand states. With D-STATCOM installed at the weakest bus, voltage regulation across all tested buses is improved significantly compared to its installation at the PCC. For instance, regulation at bus 13 drops from 1.71% to 0.31%, enhancing system stability and reliability under fluctuating load conditions. This demonstrates that strategic compensation placement can effectively minimize voltage fluctuations and safeguard equipment performance.

The final proposed system configuration integrates a 2 MW wind generator at bus 13 and a 1.8 MVAr D-STATCOM at bus 15. This hybrid configuration ensures optimized voltage stability and system robustness, even under high penetration of variable renewable energy and sudden disturbances. The simulation-based case studies confirm that system performance depends significantly on the location of both DG and compensating devices. Strategic placement not only enhances voltage profiles and recovery times but also improves loadability and operational reliability of the off-grid residential distribution network.

IV RESULTS AND DESCRIPTION

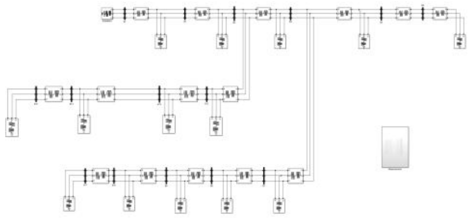
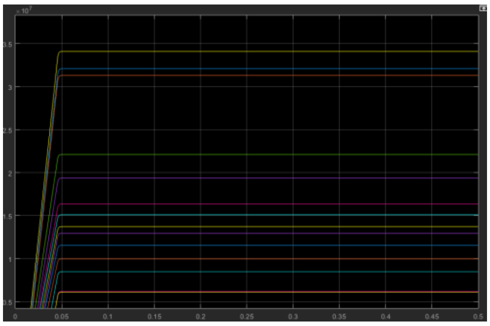


Fig 4.2 MATLAB SIMULINKModelwithout wind generator

This figure presents the MATLAB Simulink model of the IEEE 15-bus distribution test system operating without any distributed generation (DG). It is used as a baseline configuration to evaluate system behavior under standard load conditions. The model includes loads, buses, transformers, and lines modeled with R + jX parameters. It provides a reference to assess the voltage profile, reactive power margins, and stability prior to the integration of renewable sources. By simulating this base model, critical buses and voltage fluctuations under static load conditions are identified, establishing a foundation for comparing future enhancements using wind and compensation devices.



4.2.1 Reactive power margin of the load buses of base case (without DG)

This simulation result evaluates the reactive power margin (Q-margin) for each bus in the 15-bus system under base conditions without any distributed generation. The Q-V analysis is applied to identify weak and strong buses in terms of voltage support. The margins represent how much additional reactive power a bus can support before voltage instability occurs. The weakest bus, identified as bus 15 with the lowest Q-margin, is most prone to voltage collapse. This insight guides decisions on where to integrate DG and reactive power support devices to enhance voltage stability and system resilience under varying load profiles.

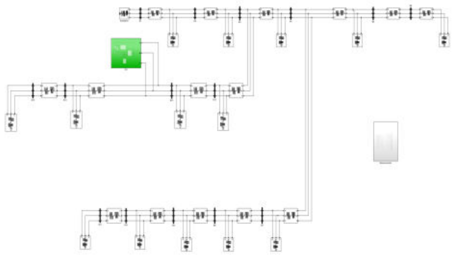


Fig 4.5 MATLAB- SIMULINKmodelofthe 15bus test system with wind DG

This Simulink model introduces a 2 MW wind generator at the weakest bus (bus 13) in the IEEE 15-bus system to study the impact of renewable energy penetration. The wind generator is modeled using an induction machine, representing a common configuration in real-world distributed wind power applications. The model evaluates the changes in voltage magnitude and reactive power margin under different penetration levels (30% to 100%). It serves to analyze how the addition of wind DG affects the system's voltage stability and identifies the limitations of such integration without reactive compensation, particularly under high wind penetration conditions.

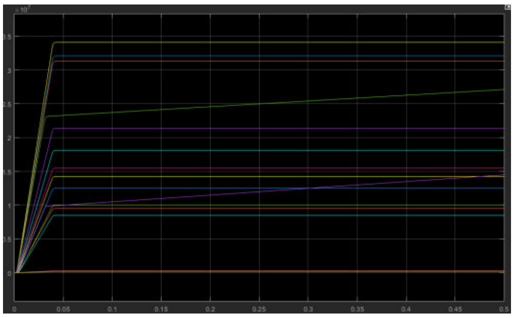


Fig 4.5.1: Reactive power margin with wind DG

This figure depicts the simulation results of reactive power margins across various buses under increasing levels of wind power penetration. As the wind generator is added at the weakest bus (bus 13), the reactive power support becomes more critical. The Q-margins decrease progressively with higher penetration (30%, 50%, 80%, 100%), especially at already weak buses, indicating a degradation in voltage stability. These findings highlight the challenges of maintaining stability in systems with high renewable energy contributions and underscore the need for proper placement of reactive compensation devices such as D-STATCOM to mitigate the destabilizing effects of wind integration.

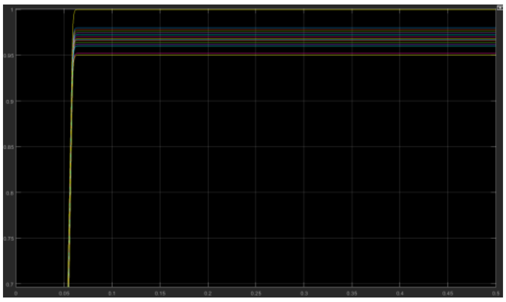


Fig 4.5.2: Voltage magnitude with wind DG

This figure illustrates the voltage magnitudes at all 15 buses for different wind penetration levels. As the level of wind power integration increases—from 0% to 100%—a noticeable drop in voltage is observed at several buses, especially those close to the generator, such as bus 13 and 15. For moderate penetrations (30–80%), the voltage falls below acceptable thresholds, posing a risk to equipment and system stability. At 100% penetration, the voltage levels slightly recover, suggesting some balancing effect at full capacity. This analysis highlights the nonlinear impact of wind energy on voltage and the importance of reactive compensation.

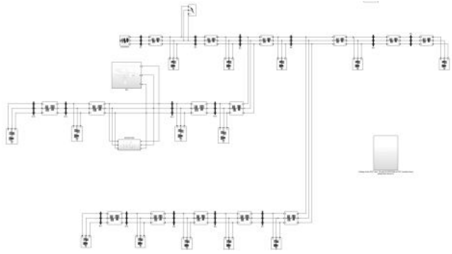


Fig 4.6 Matlab Simulink Model With DSTATCOM

This figure shows the updated Simulink model of the IEEE 15-bus system with a D-STATCOM integrated. The compensator is connected either at the Point of Common Coupling (PCC) or at the weakest bus (bus 15) depending on the simulation scenario. The D-STATCOM is modeled as a voltage source converter with energy storage, designed to inject or absorb reactive power dynamically to stabilize voltage profiles. This configuration allows the study of system recovery from disturbances and the enhancement of reactive power margins. The model is used to determine the optimal placement and sizing of the D-STATCOM for improved performance.

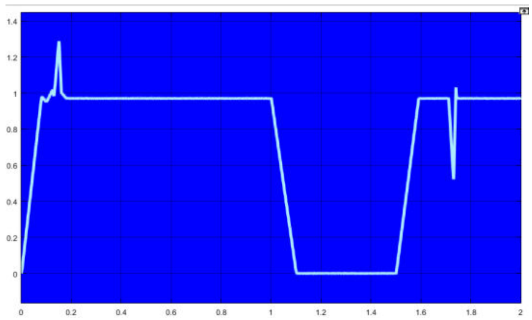


Fig 4.7 Voltage at the PCC (bus 13) without D-STATCOM (sudden three phase fault at bus 2)

This figure presents the voltage profile at the PCC (bus 13) following a sudden three-phase fault at bus 2 in the absence of any compensation device. The graph shows a significant voltage dip with a slow recovery, indicating the system's vulnerability to fault-induced disturbances. The response reflects insufficient dynamic support, particularly in weak networks with renewable integration. The prolonged low-voltage condition could lead to protection system misoperation or equipment damage. This case underscores the system's need for reactive compensation to enhance voltage stability and shorten recovery times after disturbances, especially in scenarios with high wind energy penetration.

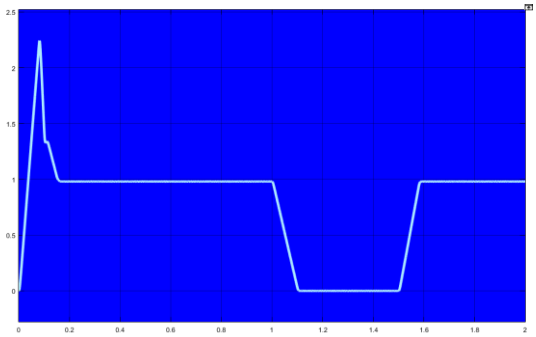


Fig 4.8 Voltage at the PCC (bus 13) with D-STATCOM at PCC (sudden three phase fault at bus 2)

This figure shows the voltage recovery behavior at bus 13 (PCC) when a D-STATCOM is installed directly at the PCC and a three-phase fault is introduced at bus 2. Compared to the previous scenario (without D-STATCOM), the voltage stabilizes faster and reaches a higher post-fault level. The reactive power injection from the D-STATCOM helps maintain system stability and prevents deep voltage collapse. However, although the response is improved, this configuration does not offer the most optimal performance compared to compensation at more critical buses. The result demonstrates the partial effectiveness of conventional compensator placement strategies.

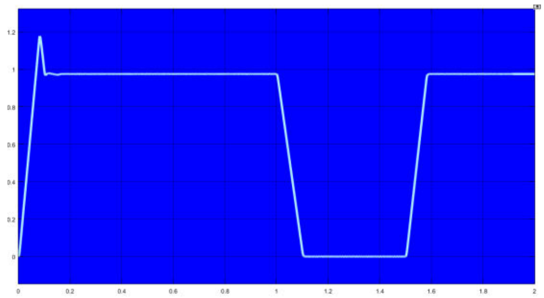


Fig 4.9 Voltage at the PCC (bus 13) with D-STATCOM at bus15(sudden three-phase fault at bus 2)

This simulation result illustrates the voltage profile at bus 13 during a fault at bus 2, with a D-STATCOM placed at the system's weakest bus (bus 15). The voltage recovery is both faster and more stable compared to placing the D-STATCOM at the PCC. The improved performance is attributed to the strategic location of the compensator at a node with the lowest reactive power margin, enhancing dynamic response across the network. This scenario confirms that optimal D-STATCOM placement improves system resilience, allows for downsizing of the device, and reduces voltage instability more effectively than conventional configurations.

V CONCLUSION

The reviewed literature emphasizes the critical role of electric load profiles and reactive power management in the performance and stability of off-grid residential hybrid renewable energy systems. A growing reliance on distributed generation (DG), particularly from wind and solar sources, introduces both opportunities and challenges for voltage regulation, system stability, and efficient power delivery. Conventional static load models have proven inadequate in capturing real-world load dynamics, necessitating composite and time-domain approaches for accurate system analysis. Reactive power compensating devices like D-STATCOMs and STATCOMs have emerged as effective solutions to mitigate voltage instability, especially under high DG penetration. Studies have shown that strategic placement of these devices—particularly at the weakest buses—can significantly improve voltage profiles and reduce system vulnerability to faults. Furthermore, optimal VAR planning using indices such as Q-loadability ensures cost-effective and reliable deployment of compensation resources. Recent advancements in simulation tools like MATLAB/Simulink and optimization algorithms enhance the capability to model, analyze, and improve off-grid hybrid systems under variable load and generation conditions. Overall, integrating intelligent compensation strategies with accurate load profiling forms the foundation for a resilient and efficient off-grid power infrastructure, especially critical in remote and underserved regions. Future research should explore adaptive control and AI-based optimization for enhanced real-time system performance.

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