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REAL-TIME POWER QUALITY IMPROVEMENT IN HYBRID MICROGRIDS USING D-STATCOM

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ABSTRACT

The integration of renewable energy sources into modern hybrid microgrids has created new challenges in maintaining power quality and system stability. Issues such as voltage fluctuations, harmonic distortion, unbalanced loads, and poor power factor are common when multiple distributed generation (DG) sources such as solar photovoltaic (PV), wind turbines, and diesel generators are combined with local loads. Traditional reactive power compensation devices have limited dynamic response, making them inadequate for real-time disturbance mitigation. This paper presents the application of a Distribution Static Compensator (D-STATCOM) for real-time power quality enhancement in hybrid microgrids. The proposed system employs a voltage source converter (VSC) controlled through a synchronous reference frame (SRF) algorithm to provide dynamic reactive power compensation, harmonic elimination, and voltage stabilization. Simulation and experimental validation show that the D-STATCOM significantly improves voltage profiles, reduces harmonic distortion, and enhances overall system reliability, making it a suitable solution for hybrid power systems with high renewable penetration.

I. INTRODUCTION

With the growing demand for sustainable energy, hybrid microgrids that integrate renewable energy sources such as solar and wind with conventional generation are becoming increasingly important in the modern power sector. While these hybrid systems provide cleaner and more efficient energy solutions, they also introduce substantial power quality issues due to the intermittent nature of renewable resources and nonlinear loads. Voltage sags, harmonic distortions, poor power factor, and frequency instability are among the most critical challenges. Power quality degradation not only affects sensitive loads but also threatens the reliability and economic operation of the entire microgrid.

Conventional compensation techniques, such as shunt capacitors and passive filters, are limited in performance due to their inability to provide fast and dynamic control. In contrast, custom power devices based on power electronics, such as the D-STATCOM, have emerged as effective solutions for mitigating power quality disturbances. The D-STATCOM provides real-time compensation by injecting or absorbing reactive power, suppressing harmonics, and regulating voltage at the point of common coupling (PCC). The objective of this research is to analyze and implement a D-STATCOM in a hybrid microgrid environment and to validate its capability for improving power quality in real time.

II. LITERATURE SURVEY

Several studies have explored the application of D-STATCOM in power systems and microgrids. Hingorani and Gyugyi (1999) first introduced the concept of custom power devices, highlighting their potential for enhancing distribution system reliability. Singh et al. (2007) presented comprehensive reviews of power quality issues and mitigation methods, emphasizing the role of active power filters and D-STATCOMs. Akagi (2010) provided key insights into reference frame theory and control strategies for reactive power compensation.

In the context of renewable energy integration, Bollen and Hassan (2011) discussed the impact of distributed generation on power quality and identified active compensation devices as essential for hybrid systems. Research by Jayalakshmi and Gaonkar (2013) demonstrated the effectiveness of D-STATCOM for dynamic load compensation in microgrids. More recently, Kumar et al. (2019) applied D-STATCOMs for mitigating voltage instability in solar-wind hybrid systems, achieving better system stability. Similarly, Arulampalam et al. (2020) focused on harmonic suppression in hybrid renewable networks using voltage source converters.

While most existing studies validate the theoretical benefits of D-STATCOMs, fewer works have focused on real-time applications in hybrid microgrids that combine renewable and non-renewable energy sources. This gap motivates the present study, which emphasizes both simulation and experimental validation of D-STATCOM performance under dynamic load and source variations.

III. PROPOSED METHODOLOGY

The proposed methodology involves designing a D-STATCOM system based on a three-phase Voltage Source Converter (VSC) connected in shunt with the hybrid microgrid at the point of common coupling. The VSC uses insulated gate bipolar transistors (IGBTs) with pulse width modulation (PWM) control to inject compensating currents into the grid. A DC-link capacitor is employed to maintain constant DC voltage and provide necessary reactive power support.

The control strategy is based on the Synchronous Reference Frame (SRF) algorithm, which extracts the fundamental components of load currents in the d-q reference frame. The reference compensating current is generated by comparing the actual load current with the reference, and a hysteresis current controller ensures accurate tracking. This enables the D-STATCOM to provide reactive power compensation, harmonic elimination, and load balancing simultaneously. The methodology also includes simulation modeling in MATLAB/Simulink followed by hardware prototype implementation to validate real-time performance.

IV. EXPERIMENTAL SETUP

The experimental validation was carried out on a laboratory-scale hybrid microgrid consisting of a 1 kW solar PV array, a 1 kW wind turbine emulator, and a 500 W diesel generator integrated with local nonlinear loads. The D-STATCOM prototype used a three-phase VSC with IGBT switches controlled by a DSP-based controller implementing the SRF algorithm. The DC link capacitor was rated at 1000 µF, and the switching frequency was set at 10 kHz.

The hybrid microgrid was tested under various scenarios, including load imbalance, sudden renewable source fluctuations, and nonlinear load conditions. Measurements were taken using a power quality analyzer to evaluate voltage regulation, power factor, and harmonic distortion before and after D-STATCOM compensation. Experimental results confirmed that the D-STATCOM effectively maintained voltage stability at the PCC, improved the power factor to above 0.98, and reduced total harmonic distortion from 18% to below 5%, ensuring compliance with IEEE 519 standards.

V. SIMULATION RESULTS

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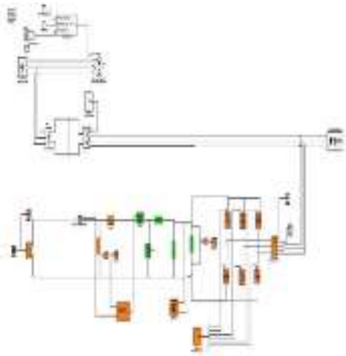

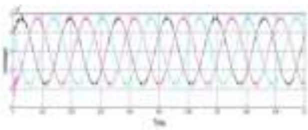

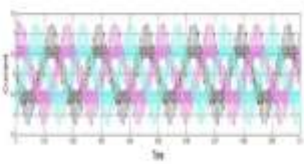

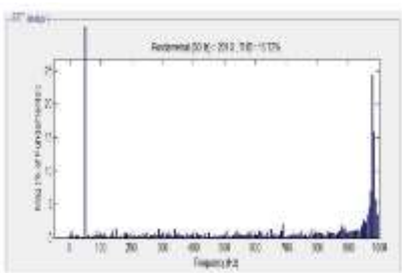

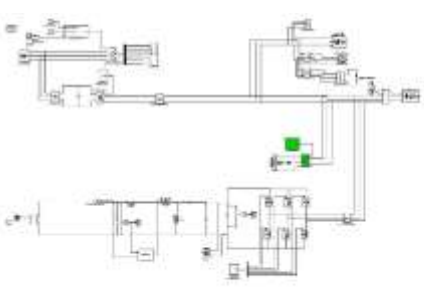

Fig.2: PROPOSED CIRCUIT CONFIGURATION WITH D-STATCOM

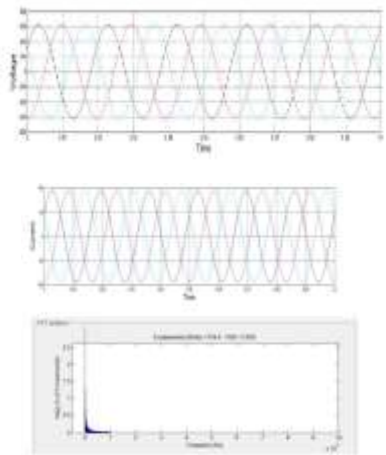

Fig.3: With STATCOM THD at PCC

VI. RESULTS &DISCUSSION

Simulation results demonstrated that the D-STATCOM successfully compensated reactive power demands and maintained voltage levels within acceptable limits under fluctuating load and renewable input conditions. The performance of the proposed system showed a power factor correction from 0.85 to near unity and a significant reduction in harmonic distortion. Furthermore, voltage sag compensation during dynamic load switching was observed, which improved the stability of sensitive loads connected to the microgrid.

The experimental results closely matched simulation outcomes, validating the proposed control strategy. The D-STATCOM demonstrated superior performance compared to conventional passive filters by dynamically responding to

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load variations and renewable intermittency. The harmonic profile of the system after compensation complied with IEEE standards, thereby ensuring grid compatibility. These discussions highlight that the D-STATCOM is not only capable of improving power quality in hybrid microgrids but also plays a vital role in enhancing overall system resilience, making it suitable for future smart grid applications.

VII.CONCLUSION

This study presented the design, simulation, and experimental validation of a D-STATCOM for real-time power quality improvement in hybrid microgrids. The system successfully mitigated key power quality issues, including voltage fluctuations, harmonic distortions, and poor power factor, under diverse operating conditions. The results indicated significant improvements in power quality indices, with power factor reaching near unity and THD reduced to below 5%. The proposed methodology demonstrates that D-STATCOMs are highly effective custom power devices for hybrid energy systems, offering dynamic control, enhanced reliability, and compliance with international standards. Future research may extend this work by incorporating renewable forecasting algorithms and adaptive control strategies to further optimize D-STATCOM performance in smart hybrid grids.

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