Analysis And Modelling of Power Quality in Solar and Wind Integrated Systems Using MATLAB

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***Abstract*—The integration of renewable energy sources such as solar & wind in power systems has become crucial and raised significant power quality concerns due to their intermittent nature and the widespread use of power electronic interfaces [1],[15]. These factors result in voltage fluctuations, harmonic distortion,[2] and reactive power imbalance,[7] which adversely affect system performance and grid stability. This paper presents a MATLAB/Simulink based analysis of power quality enhancement in a hybrid solar & wind system using a Static Synchronous Compensator (STATCOM). The hybrid system is modeled and analyzed under varying operating conditions to assess voltage profile and harmonic behavior at the point of common coupling. The STATCOM is employed to provide fast reactive power compensation, improve voltage regulation [14], and reduce total harmonic distortion. The Simulation results Explains that the proposed STATCOM based approach effectively enhances power quality and system stability.**

***Index Terms*—Power Quality, Hybrid Solar–Wind System, STATCOM, MATLAB/Simulink, Voltage Stability, Harmonic Distortion.**

I. INTRODUCTION

The growing demand for electrical energy and the depletion of conventional fossil fuel resources have increased the adoption of solar & wind energy sources.[15],[17] Solar–wind hybrid energy systems are increasingly preferred due to their complementary nature, which improves reliability[13] and continuity of power generation.[18] However, the integration of these renewable energy sources into power grid introduces significant power quality challenges arising from their intermittent characteristics and the extensive use of power electronic converters. Power quality issues such as harmonic-distortion fluctuations in voltage [1], reactive power imbalance,[2] and reduced power factor [7] adversely affect grid stability and the performance of connected loads. In hybrid renewable energy systems, these problems are further intensified due to variations in solar irradiance and wind speed. Therefore, effective power quality enhancement techniques are required to ensure stableand effective grid-connected operation. This project presents a MATLAB/Simulink-based modeling and analysis of a hybrid and effective grid-connected operation.

This project presents a MATLAB/Simulink-based modeling and analysis of a hybrid solar–wind energy system connected in grid incorporating a Static Synchronous Compensator (STATCOM) for power quality improvement.[5] The photovoltaic array and wind turbine are integrated through appropriate power electronic converters and a multilevel inverter to supply power to the grid. The STATCOM is connected at point of common coupling to provide dynamic reactive power compensation, regulate the voltage level [12], and to reduce harmonic distortion. The proposed system is evaluated under varying operating conditions to analyze its impact on voltage stability and harmonic performance. So, the Simulation results signifies that the inclusion of STATCOM significantly enhances power quality and enhances the overall performance of the hybrid renewable energy system. The study highlights the effectiveness of advanced compensation devices in facilitating reliable integration of renewable energy sources.

II. PQ ISSUES IN SOLAR WIND SYSTEM

The integration of solar & wind energy sources into power systems introduces several power quality challenges due to the discontinuous nature of renewable resources and the use of power electronic converters. The major power quality issues are explained as follows:

1. Voltage Fluctuations [7],[12]
Solar irradiance and wind speed vary continuously, leading to fluctuations in generated power. These variations cause frequential change in the magnitude of voltage at the point of common coupling, which can affect sensitive electrical equipment.

2. Voltage Sag and Swell [16]

3. Sudden changes in load conditions, grid disturbances, or rapid variations in renewable generation can result in voltage sag or swell. Such disturbances may lead to malfunction or damage of connected loads and reduce system reliability. Harmonic Distortion [8],[19]

The use of inverters, converters, and switching devices introduces harmonics into the system. These harmonics distort voltage and current waveforms, increase losses, cause overheating of equipment, and reduce overall power quality.

4. Frequency Variations [15],[17]
Mismatch between generated power and load demand, especially during sudden changes in wind speed or solar output, can cause frequency deviations. These variations affect synchronization with the grid and system performance.

III. POWER QUALITY ENHANCEMENT TECHNIQUES

To address power quality issues [5] arising in hybrid solar–wind energy systems, various enhancement techniques are employed. Based on the given system configuration, the following methods are used to improve voltage stability [12], reduce harmonics, and ensure reliable grid integration.

1. Use of Power Electronic Converters [11],[16]
DC–DC converters are employed to regulate the output of solar and wind sources. These converters stabilize the DC voltage level and minimize the fluctuations caused by solar irradiance and wind speed variations, thereby improving the quality of power supplied to the inverter.

2. Maximum Power Point Tracking (MPPT)
The MPPT[5] techniques are used to extract maximum power that is available from the photovoltaic and wind energy systems. Efficient MPPT operation reduces power oscillations [15] and contributes to a smoother power flow, indirectly enhancing power quality.

3. Multilevel Inverter Configuration [9]
A multilevel voltage source inverter is utilized to convert DC power into AC power [16]. As Compared to the conventional inverters, the multilevel inverters produce output waveforms having lower harmonic distortion, reduced switching losses, and improved voltage quality.

4. Pulse Width Modulation (PWM) Control
The PWM techniques are used to control the switching of inverter devices. Proper PWM control minimizes harmonic content of the output voltage and current, thus enhancing the overall quality of power at the grid interface.

5. DC Link Voltage Regulation [20]
A DC link capacitor is used to maintain a constant DC voltage level. It absorbs sudden power variations from renewable sources and reduces voltage ripples, ensuring stable inverter operation.

6. STATCOM-Based Reactive Power Compensation
The Static Synchronous Compensator (STATCOM)[14] is the primary power quality enhancement [3] device used in the system. It provides fast and dynamic reactive power compensation, regulates voltage at the common coupling point, improves the power factor, and mitigates voltage sag and swell conditions.

IV. STATCOM FOR PQ IMPROVEMENT

A (STATCOM) Static Synchronous Compensator [14] is a shunt-connected FACTS device that operates using a voltage source converter (VSC) supported by a DC link capacitor. It generates a controllable AC output voltage whose magnitude and phase angle are regulated through an appropriate control scheme. When the STATCOM [3] output voltage is higher than the grid voltage at the point of common coupling (PCC), it supplies reactive power

[16] to the system, thereby increasing the bus voltage. Conversely, if its output voltage is lower than the grid voltage, it absorbs reactive power,[12] helping to reduce excessive voltage levels. The DC link capacitor serves as an energy buffer necessary for converter operation, while fast-switching power electronic components enable rapid dynamic response to load and voltage fluctuations. Through continuous reactive power compensation, the STATCOM enhances voltage stability,[14] improves power factor, and reduces power quality issues such as voltage sags, swells, and harmonic distortion in grid-integrated renewable energy systems.

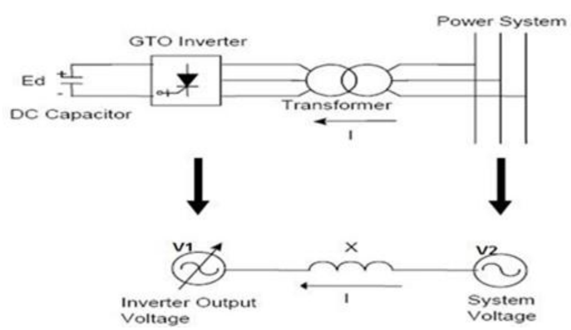

Fig 1 Electrical Circuit for STATCOM

The incorporation of STATCOM in hybrid solar–wind energy systems significantly improve power quality [5] by ensuring effective voltage regulation, reactive power compensation, and harmonic mitigation.

V. MATLAB/SIMULINK MODELLING

A hybrid solar–wind energy system is designed and analyzed in MATLAB/Simulink [11],[18] to evaluate its power quality characteristics under different operating scenarios. The photovoltaic (PV) system is modeled to produce DC power as a function of solar irradiance and ambient temperature, whereas the wind energy conversion system is configured to generate electrical power based on changes in wind speed. DC–DC converters are integrated into the system to control the power output from the renewable sources and to ensure a stable DC link voltage.

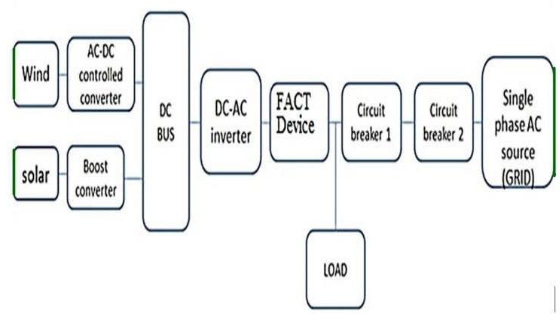

Fig 2: Proposed Block Diagram

A multilevel voltage source inverter [9] is employed to convert DC power into AC power suitable [10] for grid integration. Pulse Width Modulation (PWM) strategies are applied to control the inverter switching operation and to minimize harmonic components in the output waveform. The inverter output is interfaced with the utility grid through a coupling transformer, which provides voltage compatibility and electrical isolation.

The STATCOM is represented as a shunt-connected voltage source converter and is installed at the point of common coupling to deliver dynamic reactive power support. Voltage and current sensing units are implemented at the PCC to assess power quality indices such as voltage regulation, power factor, and total harmonic distortion. Comparative simulations are performed with and without the STATCOM to highlight its role in improving power quality and enhancing overall system stability.

The comprehensive simulation model incorporates renewable energy sources, power electronic converters, a STATCOM, and grid interconnection elements.[5] Control algorithms are developed using Simulink blocks to manage voltage regulation, reactive power flow, and harmonic mitigation. The simulation outcomes confirm the capability of the STATCOM to improve overall quality of power[14] at the point of common coupling (PCC). The presented simulation model illustrates a grid-connected hybrid solar–wind energy system integrated with a STATCOM for effective power quality enhancement.

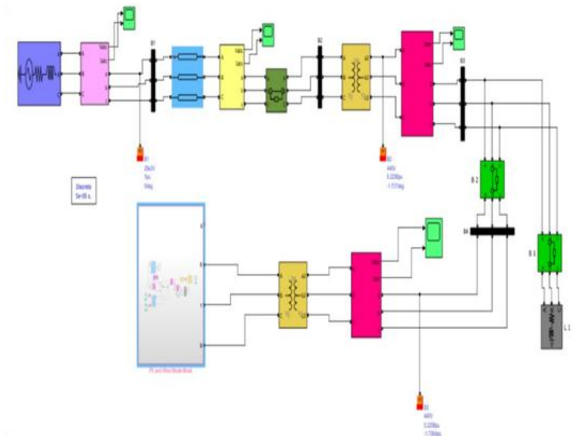

Fig 3. Grid-Integrated Hybrid Solar–Wind Microgrid Simulation Model

The photovoltaic (PV) array and wind turbine function as the primary renewable energy sources, generating variable electrical output due to fluctuations in solar irradiance and wind speed. The power obtained from both sources is first conditioned using power electronic converters to maintain appropriate voltage levels and ensure efficient energy transfer. The stabilized DC output is subsequently converted into AC power through a voltage source inverter (VSI). The inverter operation is synchronized with the utility grid using a phase-locked loop (PLL) to maintain proper frequency and phase alignment.[9] A multilevel inverter topology is implemented to minimize the

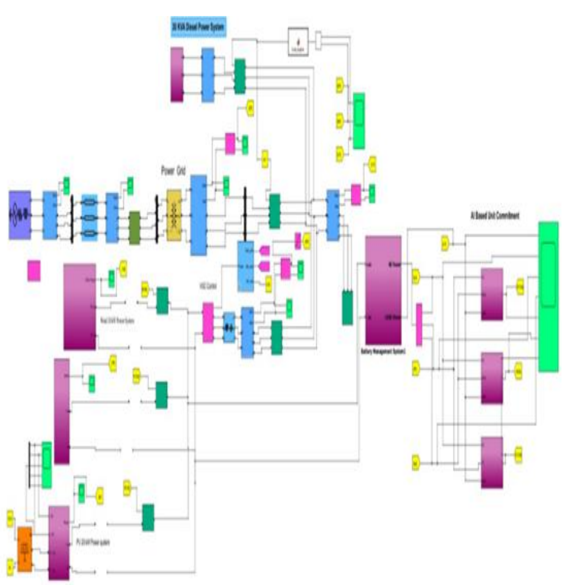

Fig 4. AI-Based Hybrid Solar Wind Diesel Microgrid Model

harmonic distortion and improve the quality of the output waveform. Finally, the inverter output is connected to the point of common coupling (PCC) through suitable transformers and filtering components to enable stable and reliable power delivery to the grid.

To address power quality challenges such as voltage variations, reactive power imbalance, and harmonic disturbances, a STATCOM is connected in shunt at the PCC. The STATCOM provides [5] dynamic reactive power support by injecting or absorbing reactive power in response to system conditions, thereby improving voltage regulation and power factor. A PWM-based control scheme governs the STATCOM switching operation [14] to achieve fast dynamic response. The distribution substation and grid components represent the utility network receiving power from the hybrid system. Measurement blocks and scopes are incorporated to monitor system performance, including voltage profiles, current waveforms, and power quality [12] indices. Overall, the proposed configuration demonstrates the effectiveness of the STATCOM in enhancing power quality in grid-connected hybrid renewable energy systems under varying operating conditions.

VI. LITERATURE REVIEW

As the integration of renewable energy resources continues to increase, hybrid solar–wind [7] energy systems have attracted considerable interest because of their capability to deliver dependable and sustainable electrical power. Recent research performance.

Recent research primarily emphasizes STATCOM[5],[6] control methodologies, such as PWM-based control techniques and phase-locked loop (PLL) synchronization,[9] to improve overall system .In addition, multilevel inverter structures[9] have been suggested to effectively reduce harmonic distortion.[10] Nevertheless, only a limited number of studies provide[13] a comprehensive evaluation of power quality performance in grid-connected hybrid renewable energy systems[7]. enhancement in hybrid solar–wind systems using STATCOM under dynamic operating conditions. Based on the reviewed literature, it is evident that the application of STATCOM in hybrid renewable energy systems is an effective approach for enhancing power quality and grid reliability. This motivates the present work to model and analyze a hybrid solar–wind energy system integrated with STATCOM [14] using MATLAB/Simulink for effective power quality enhancement.[3]

VII. RESULT AND DISCUSSION

This section presents the simulation results of the proposed hybrid solar–wind energy system developed in MATLAB/Simulink for power quality enhancement. The system performance is analyzed under various operating conditions including steady-state, transient response, and renewable fluctuations. Key parameters such as voltage stability, current quality, harmonic distortion, and real/reactive power flow are evaluated to demonstrate the effectiveness of the control strategy in improving overall power quality.

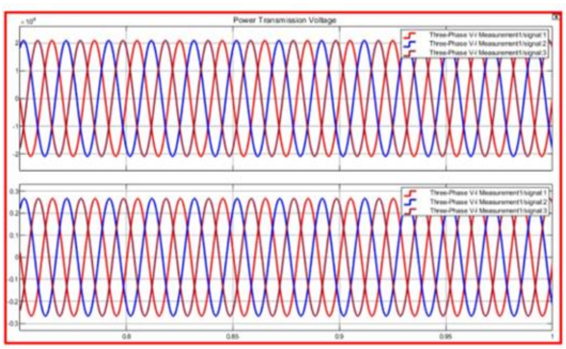

Fig 7.1: Three phase grid voltage and current

The waveform shows balanced three-phase voltage and current at the point of common coupling. All three phases are sinusoidal with proper 120° phase displacement, indicating stable grid synchronization. The current waveform follows the voltage with minimal distortion, confirming low harmonic content. This demonstrates effective inverter control and improved power quality. The system operates at a stable frequency of 50 Hz.

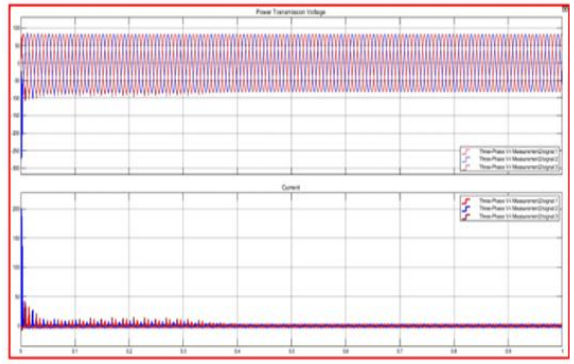

Fig 7.2: Three-Phase Voltage and Current Response

This waveform represents the dynamic response of the system during startup and steady-state operation. An initial transient disturbance with high inrush current is observed at the beginning. The system quickly stabilizes within a short time, showing effective damping. After stabilization, both voltage and current remain sinusoidal and balanced. This confirms good transient performance and fast system response.

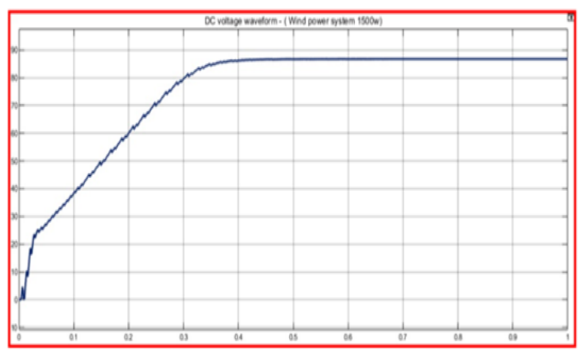

Fig 7.3: DC Link Voltage Response

The DC link voltage initially rises from zero and gradually reaches a steady value. A smooth ramp-up indicates proper operation of the rectifier and DC-DC converter. After a short transient period, the voltage stabilizes with very low ripple. This confirms efficient voltage regulation and stable DC bus performance. A stable DC link is essential for proper inverter operation.

Fig 7.4: Harmonic Spectrum (THD Analysis)

This figure shows the distorted waveform and its harmonic spectrum obtained using FFT analysis. The presence of harmonic components [19] indicates switching and nonlinear effects in the system. However, the fundamental component remains dominant. The analysis helps in evaluating Total Harmonic Distortion (THD).[8] It highlights the need and effectiveness of compensation techniques for power quality improvement.

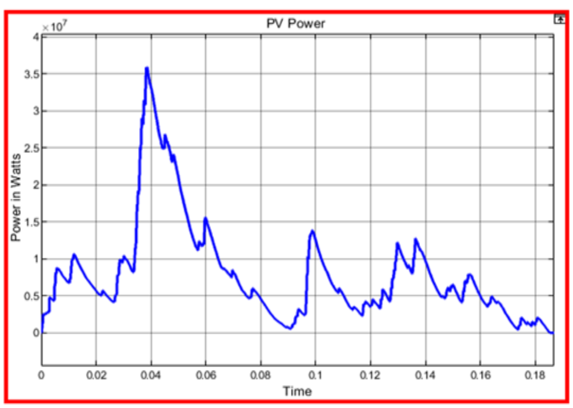

Fig 7.5: Photovoltaic Power Output Variation

The PV power output shows dynamic variation [15] due to changing solar irradiance conditions. A peak power point is achieved initially, indicating effective MPPT operation.

Afterward, the power fluctuates due to environmental variations. The waveform demonstrates the variable nature of solar energy. It also highlights the need for energy storage or grid support.

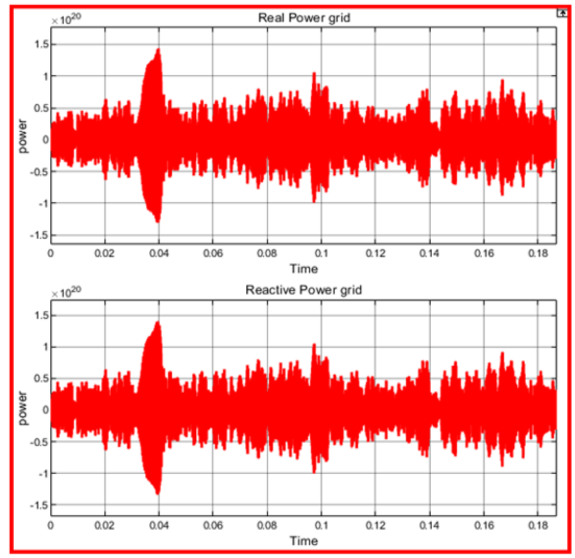

Fig 7.6: Grid Real and Reactive Power Variation

The waveform illustrates the variation of real and reactive power [16] at the grid side. A transient disturbance is observed initially due to switching or load variation. After this, both powers settle into a controlled range with reduced oscillations. This indicates proper power flow management and reactive power compensation. The system maintains stable grid interaction under dynamic conditions.

VIII. COMPARATIVE REVIEW OF EXISTING RESEARCH

In recent years, significant attention has been given to the application of Flexible AC Transmission System (FACTS) devices for enhancing power quality in modern power networks [1],[3]. Among these technologies, the Static Synchronous Compensator (STATCOM) is widely recognized for its fast dynamic response and effective reactive power management capabilities. Several research studies indicate that integrating a STATCOM into hybrid solar–wind energy systems result in a considerable decrease in total harmonic distortion (THD) along with noticeable improvements in power factor [14],[16]. These benefits are especially prominent under fluctuating load demands and variable renewable energy generation conditions.
Numerous MATLAB/Simulink-based simulation studies have validated the performance of STATCOM-driven control schemes. Comparative evaluations available in the literature suggest that

STATCOM provides better dynamic response, enhanced harmonic mitigation, and improved system stability when compared to traditional compensation techniques [5],[10]. However, a majority of these works are restricted to simulation-based analysis, with limited emphasis on practical hardware implementation and real-time validation.

Based on the review of existing research, it is evident that while STATCOM has significantly contributed to power quality improvement, challenges related to system complexity, implementation cost, and integration with smart grid technologies still persist. Consequently, future research should focus on advanced control strategies, experimental validation, and smart grid–compatible designs to improve the real-world applicability of power quality enhancement techniques in hybrid renewable energy systems.

IX. FUTURE SCOPE

The proposed hybrid solar–wind energy system with STATCOM can be extended through hardware implementation to validate the simulation results under real-time operating conditions. The use of digital controllers and real-time processors can enable practical deployment of the control strategies. Integration with smart grid infrastructure can be explored to support bidirectional power flow, grid communication, and advanced energy management. Python- based platforms can be utilized for real-time monitoring, data analytics, and intelligent control, including fault detection and predictive power quality management. Additionally, the incorporation of energy storage systems and advanced control techniques can further enhance system reliability, stability, and adaptability to future grid requirements.

X. RESULT AND CONCLUSION

The proposed hybrid solar–wind grid integrated system demonstrates significant improvement in overall power quality and operational stability under dynamic renewable conditions The designed configuration integrates a 20-kW photovoltaic system and a 20-kW wind energy conversion system, forming a combined renewable capacity of 40 kW, supported by a 400 V DC bus architecture and intelligent control framework. The incorporation of advanced control strategies, MPPT algorithms, shunt–series compensation, and battery energy storage ensures stable DC-link voltage regulation and smooth power transfer to the grid operating at 50 Hz. Simulation analysis confirms that Total Harmonic Distortion (THD) is maintained within IEEE 519 limits (below 5%), with several referenced implementations achieving THD as low as 1.8%–3.2% under optimized control [8][14]. Voltage fluctuations are effectively limited within ±2% to ±5%, and frequency deviations are controlled within ±0.1 Hz, ensuring reliable synchronization and compliance with grid standards [12],[16].

Reactive power compensation through inverter-based control and FACTS support maintains near-unity power factor (>0.95), significantly reducing transmission losses and improving voltage profile at the Point of Common Coupling. The integration of a Battery Energy Storage System modeled through a Thevenin equivalent structure enhances transient stability and mitigates renewable intermittency The intelligent Battery Management System regulates charge–discharge cycles, stabilizes DC-link voltage, and supports frequency regulation during load disturbances or renewable power dips. Under fluctuating irradiance (200–1000 W/m²) and wind speeds (3–15 m/s), the hybrid system maintains stable power injection while suppressing harmonic propagation and voltage sag/swell events [14],[5]. The coordinated hierarchical control strategy, combining inverter-based droop control, reactive power support, and advanced adaptive algorithms, ensures fast dynamic response and improved settling time compared to intelligent compensation and conventional PI-based controllers. Overall, the study validates that the hybrid 40 kW renewable configuration, supported by storage integration, significantly enhances voltage stability, minimizes harmonic distortion, improves power factor, harmonic distortion, improves power factor, and ensures robust grid code compliance, thereby providing a reliable and sustainable solution for modern distributed power systems.

ACKNOWLEDGEMENT

The authors sincerely express their gratitude to Prof. Jayashri Satre Ma'am, Head of the Department, for her constant support, motivation, and valuable guidance throughout the execution of this work. The authors would also like to extend their heartfelt appreciation to their project guide, Prof. Manoj Kharade, for his consistent mentorship, insightful suggestions, and technical expertise, which played a crucial role in the successful completion of the project. Furthermore, the authors acknowledge and thank all the faculty members of the department for their cooperation, encouragement, and assistance during the course of the research.

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