ISSN 2277 – 8322

A COMPREHENSIVE REVIEW ON POWER QUALITY ENHANCEMENT IN RENEWABLE ENERGY HYBRID SYSTEMS USING FACTS DEVICES

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ABSTRACT- Increasing penetration of renewable energy sources (res) such as sun, wind, biomass and small hydro have led to the development of hybrid renewable energy systems (HRE) that ensures high reliability and energy security. However, the inherent intermittent, variability and non-lecture properties introduced to resulting important power quality challenges, including voltage fluctuations, hormonics, reactive power imbalance and frequency instability. These problems not only reduce system efficiency, but also danger - proof and reliable operation of sensitive stress. To solve these challenges, flexible AC transmission systems (facts) have emerged as a promising solution for PQ growth in hybrid systems and improved web stability.

The review papers offer a comprehensive examination of fact-based approaches to HRES in the HRRS, focused on devices such as static synchronous compensator (STACOM), Static Var Compensator (SVC), Unified Power Flow Controller (UPFC) and Dynamic Voltage Restorer (DVR). Paper highlights the operating principles, control strategies and the application domains of these devices to reduce power quality problems. Special weight is placed on the use of STATCOM, due to its rapid dynamic reaction, better reactive strength support and adaptability for integration with renewable energy sources. In addition, the review presents a comparative analysis of facts about facts in terms of performance, cost efficiency and suitability for different hybrid system configuration. This article examines recent progress in the intelligent control algorithm, such as unclear logic, artificial neural networks and optimization-based controls, which have been integrated with actual tools to increase the effectiveness of real-time PQ control. In addition, challenges are discussed with large -scale scale, such as economic viability, technical limitations and compliance with online code, hardly discussed.

Keywords: Power Quality, Hybrid Renewable Energy Systems, FACTS Devices, STATCOM, Voltage Stability, Harmonics Mitigation.

I. INTRODUCTION

The term "renewable energy" refers to power that comes from non-traditional sources of energy. Renewable energy is energy that comes from sources that can be used again and again. Most of the time, this kind of energy is added to the human period. The sun, the wind, the rain, the tides, radio waves, and the geothermal heat are all forms of renewable energy. The way that electricity is made from wind has changed a lot. In 1999, the amount of electricity that could be made from wind around the world was about 10,000 megawatts. In the past few years, more units for making electricity with wind power than units for making electricity with nuclear power have been built around the world [17].

From a global point of view, it seems like getting electricity from the wind is a great idea. In 1999, the United States Department of Energy established a goal to install 80,000 megawatts of wind energy by 2020. The organization is now known as "American Wind Energy." De Vries et al. (2007) say that this ability to use wind power to make electricity makes up about 5% of all electricity made. The White Paper on "Europe's Future Energy: Renewable Energy" was published by the European Commission in the latter half of 1997. The title of the report was "Europe's Future Energy." They intend to install 40,000 MW of wind power by 2010. Ultimately, another wind turbine with a capacity of 1,500 MW was established in 1999. This brought the total capacity to about 4,500 MW [18]. According to the conventional wind year agency (2001), Denmark is expected to get 13% of its electricity from wind power by the year 2000. Denmark was the subject of this prediction. At the end of 2002, Denmark's energy plan showed that wind power would pay for about 15% to 16% of the country's total electricity costs. In [19] authors say that around 20% of Denmark's electricity costs in the year 2030 should come from non-traditional sources, especially 4,000 megawatts of onshore wind power. Wind power generation is among the fastest-growing businesses since individuals are always seeking to expand it. The latest data from Danish wind turbine makers indicate that power production has improved sixfold over the past five years, with an average annual improvement rate of 44% [20]. In 2005 discovered that German wind turbine exports have been improving over recent years. The rate of growth was 42% faster in 1999 than it had been in 1998. Wind force is a competitive technology that has been producing pollution-free electricity for over 20 years. Wind power has emerged as the most critical source of energy for the future of the world, just like nuclear power has emerged as the most critical source of energy for the future of the world. Wind power lets countries get more than 10 percent of their electricity from it. When wind energy is added to the grid, it will cause problems with the circulation network or with the whole grid. Because there is no linear load on the other side of the network, the supply network is mostly used to connect the transmission structure and the generation structure in one region. Because of this, the system is thought to be one that doesn't do anything [21].

II. Overview of Renewable Energy Hybrid Systems

Renewable energy is energy from natural assets, including solar, wind, waves, or geothermal energy. These assets are renewable and recyclable naturally. Thus, as opposed to depleting traditional fossil fuels [27], such sources of information are deemed inexhaustible. Clean, renewable energy is experiencing new growth due to the global shortage of electricity [28]. Apart from the reality that fossil fuels are being phased out worldwide in the use of transport, the pollution that comes from the combustion of these fuels is a significant factor contributing to their ineffectiveness. Conversely, it's common sense that the use of renewable sources of energy does not contribute to pollution like traditional energy does [29].

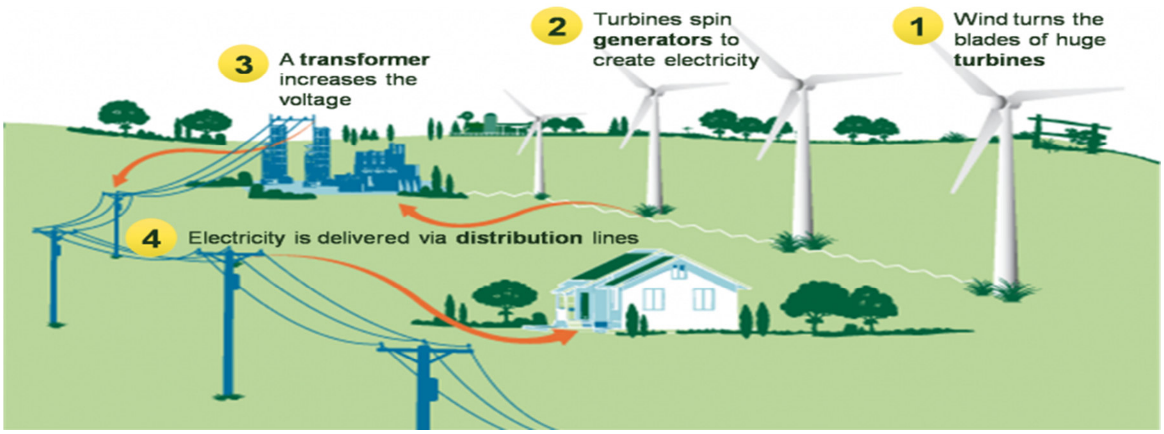


Fig 1. Solar and Wind Power Hybrid Energy Plant [29]

2.1 Wind Power

One way to tap into the energy of wind is by installing wind turbines [30]. Each day, turbine power ranges from 600 kW to 5 MW [31]. Since the output power is proportional to the wind speed, it grows exponentially with increasing wind speed. Wind turbines, which are more ingenious than improved aerodynamic architecture, are a recent innovation.

2.2 Solar Power

British astronomer John Herschel [32] pioneered solar cooking while traveling through Africa by using solar collectors. You may use solar power in two primary ways. The first purpose for the heat that is retrieved is to heat the atmosphere using solar energy. Alternatively, we may harness the sun's rays and turn them into electricity, the most essential energy source. Solar photovoltaic cells [6] or power stations that run on solar energy can achieve this goal.

2.3 Biomass

The process of photosynthesis allows plants to harness the energy of the sun. Burning these plants releases energy. Here, biomass plays the role of a natural battery, storing solar energy for later use.

2.4 Geothermal

Geothermal power is thermal energy produced by the storage within various layers of the earth [9]. The gradient created in this manner leads to a steady transfer of heat from the bottom to the surface of the ground. This media can be employed to warm water to generate extremely hot steam and employ it to operate a gas turbine to generate electricity. Large losses of geothermal power are usually located in regions close to the boundary of the tectonic plate, though recent technological advancements have led to widespread popularity [34].

III. Power Quality

Disturbances in Hybrid Systems

Power quality is an important concern for large industrial users because of the advanced industrial control procedures and the associated equipment. Power quality issues can arise due to the unpredictable nature of the power system or the features of connected devices [147].

3.1 Interruptions

Interruptions are defined as a sudden drop in the RMS voltage value to below 10% of the nominal value or a total loss of voltage. The length of time an interruption lasts determines whether it is considered long or short term.

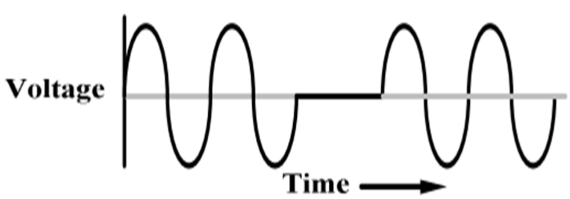


Fig. 2 Interruption

Fuse, switch, re-closure, or circuit breaker malfunctions can cause a brief outage, usually lasting less than three seconds. In Fig.4.1, we can see a brief voltage interruption. An interruption that lasts longer than three seconds is considered to be sustained. A planned maintenance break could cause a long-term disruption. In the event of a prolonged voltage outage, a human being must step in to rectify the situation.

3.2 Sag

When the voltage drops below 90% of its final value, it is said to have sagged. For the most part, sag only lasts anywhere from half a cycle to under a minute.

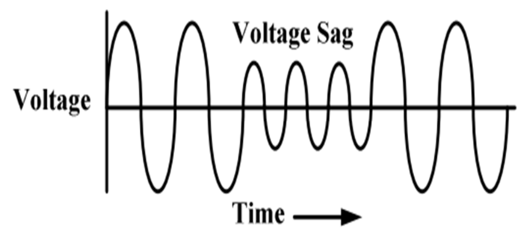


Fig. 3 Sag

When the voltage drops for longer than one minute, it's called a long-term sag, or under-voltage. Figure 4.2 displays the voltage sag. Sagging occurs when the voltage, which has been kept at nominal values, suddenly drops below that level. The voltage is then returned to its regular, final value. One possible cause of voltage sag is a short circuit [148].

3.3 Swell

The phrase "voltage swell" describes an increase in the RMS value of voltage that exceeds 110% of its ultimate value. In most cases, a swelling sensation will only last anywhere from half a cycle to under a minute.

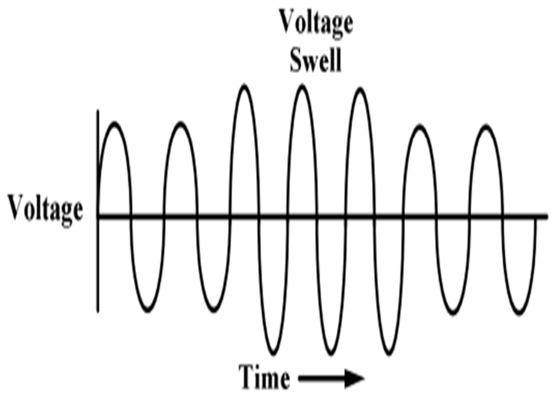


Fig. 4 Swell

One definition of over-voltage is a long-term surge in voltage that lasts longer than one minute. See Fig. 4.3 for the voltage swell figure. When the voltage is kept at nominal values, it suddenly shows a surge and rises over those values. Following that, the voltage is returned to its regular, final value of 100%. Potential causes of voltage spikes include the abrupt activation of capacitor banks and the abrupt deactivation of heavy loads.

3.4 Voltage Flickers

Flickers in voltage cause variations in load current due to abrupt drops or spikes in voltage. Sawmills, welders, wood chippers, rock crushers, and other machinery that uses a lot of reactive power often cause the voltage flicker shown in Figure 4.4.

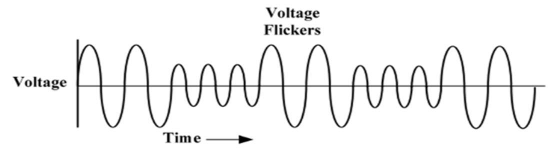


Fig. 5 Voltage flicker

3.5 Harmonics

Periodic waveforms with frequencies multiples of the fundamental frequency are known as harmonics. Modern power systems rely heavily on electronic circuits for power flexibility, made possible by technological developments. Motor drive systems and PLCs are also used in the majority of industrial applications. All of the aforementioned contribute to the generation of harmonics inside the electrical grid. A non-linear load, such as a power converter or motor drive, draws exclusively the non-linear components of the source elements and ignores the harmonic components.

Fig. 6 Harmonic distortion [150]

3.6 Source of Harmonics from Commercial Loads

Commercial loads include things like hospitals, shopping malls, department stores, and office buildings. Electronic ballasts in fluorescent lights, elevator variable speed drives (VSDs), room ventilation systems, and air conditioners are examples of commercial loads that contribute to harmonics. In order to protect delicate loads, they employ switch mode power supplies (SMPS). Because they are all non-linear, the aforementioned loads employed in commercial applications are harmonic generators.

3.7 Voltage Spike

The waveform is momentarily distorted by a little noise called a voltage spike. A voltage spike, also known as a surge, is a brief and relatively tiny increase in the voltage waveform. As seen in Figure 4.8, the waveform displays the voltage spike.

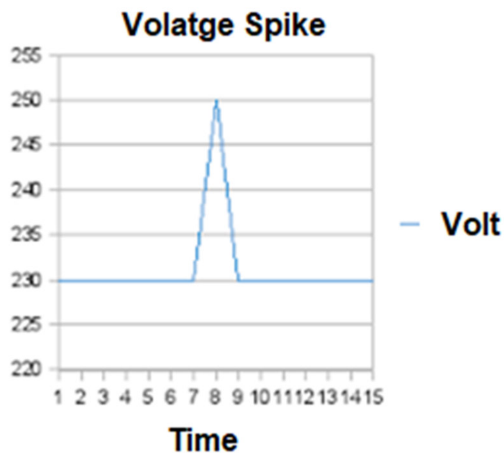
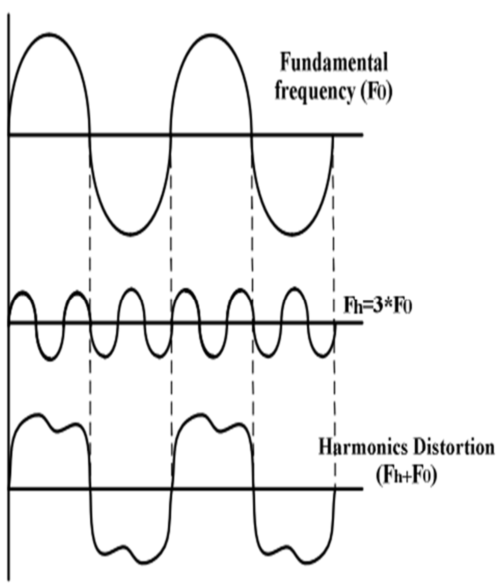


Fig. 7 Voltage Spike



IV. Flexible AC Transmission System (FACTS) Devices

Flexible AC Transmission System (FACTS) devices represent a significant advancement in modern power systems, designed to improve controllability, enhance power transfer capability, and optimize the quality of electrical energy. With the rapid integration of renewable energy sources (RES), particularly in hybrid configurations that combine solar, wind, and other distributed energy resources, the traditional grid infrastructure has become increasingly vulnerable to dynamic disturbances such as voltage instability, harmonics, and reactive power imbalance. FACTS devices address these challenges by offering dynamic reactive power support, voltage regulation, power factor correction, and improved transient stability. These devices are based on power electronics, particularly voltage source converters (VSC) and thyristor-controlled circuits, which allow real-time control of current, voltage, and phase angle within the transmission system. FACTS devices are broadly categorized into shunt controllers (e.g., Static Var Compensator, STATCOM), series controllers (e.g., Thyristor Controlled Series Capacitor, Static Synchronous Series Compensator), combined series–shunt controllers (e.g., Unified Power Flow Controller), and custom power devices (e.g., Dynamic Voltage Restorer). Their flexibility makes them indispensable in hybrid renewable systems, where the variability of solar irradiation and wind speed causes frequent fluctuations in power output. By compensating reactive power and mitigating voltage sags, FACTS devices enable stable power delivery to sensitive loads while enhancing system reliability and efficiency. Moreover, FACTS devices contribute to minimizing transmission losses, improving voltage stability margins, and reducing the need for bulky passive compensation equipment. Recent developments focus on modular, compact, and cost-effective FACTS technologies, making them more viable for distributed renewable energy applications. Overall, FACTS devices provide an essential technological bridge for the integration of intermittent renewable energy into conventional power networks, ensuring both quality and reliability in hybrid energy systems.

V. Role of STATCOM, SVC, UPFC, and DVR in Power Quality Improvement

Hybrid renewable energy systems (HRES), which integrate solar, wind, and other distributed sources, are prone to severe power quality issues such as voltage instability, harmonics, frequency deviations, and reactive power imbalances. FACTS devices, particularly STATCOM, SVC, UPFC, and DVR, play a crucial role in addressing these challenges. Each device has specific operating principles, applications, and performance characteristics that make it suitable for enhancing power quality in renewable-dominated networks.

1. Static Synchronous Compensator (STATCOM)

STATCOM is one of the most widely applied FACTS devices for renewable energy integration. It is a shunt-connected device based on a voltage source converter (VSC), which injects or absorbs reactive power by generating a controllable voltage. STATCOM provides rapid dynamic response, excellent voltage support, and effective harmonic mitigation. In solar–wind hybrid systems, where sudden irradiance changes or wind gusts can lead to voltage fluctuations, STATCOM stabilizes bus voltage and improves overall power factor. Compared to SVC, STATCOM exhibits superior performance under low-voltage conditions, making it particularly beneficial for weak or rural grids where many renewable installations are located.

2. Static Var Compensator (SVC)

SVC is an older but reliable FACTS device that uses thyristor-controlled reactors (TCR) and thyristor-switched capacitors (TSC) to provide reactive power compensation. While its response time is slower compared to STATCOM, SVC remains cost-effective and efficient in improving voltage stability in large interconnected systems. In hybrid renewable energy applications, SVC helps regulate voltage, suppress flicker, and minimize losses caused by reactive power imbalance. For instance, in large wind farms, SVC reduces voltage flicker due to variable wind speeds, thereby maintaining steady output to the grid.

3. Unified Power Flow Controller (UPFC)

UPFC is the most versatile FACTS device, combining both shunt and series compensation through a dual-converter arrangement. It can control multiple parameters simultaneously, including bus voltage, transmission line impedance, and phase angle, thus offering comprehensive power flow management. In renewable hybrid systems, UPFC ensures efficient utilization of transmission lines, mitigates congestion, and provides enhanced dynamic stability. Its capability to regulate both active and reactive power makes it particularly suitable for grids with high renewable penetration where bidirectional power flow and fluctuations are common.

4. Dynamic Voltage Restorer (DVR)

DVR is a custom power device primarily used for protecting sensitive loads against voltage disturbances such as sags, swells, and harmonics. It operates by injecting a compensating voltage in series with the supply, ensuring that end-users receive uninterrupted and high-quality power. In renewable energy hybrid systems, DVR plays a crucial role in safeguarding industrial and commercial loads that require stringent PQ standards. For example, during sudden dips caused by wind or solar fluctuations, DVR restores the voltage to acceptable levels within milliseconds. Additionally, DVR helps mitigate harmonics introduced by nonlinear loads, thereby extending equipment life and ensuring compliance with grid codes.

5. Comparative Perspective

While each device has unique advantages, their effectiveness depends on system requirements and scale. STATCOM is ideal for fast dynamic compensation in weak renewable grids, SVC is cost-effective for large-scale systems with moderate PQ issues, UPFC offers holistic control for complex networks, and DVR ensures load-side reliability. Together, these devices form a complementary suite of technologies capable of addressing the diverse PQ challenges in hybrid renewable energy systems.

VI. Control Strategies and Intelligent Techniques for FACTS Devices

The performance of FACTS devices is not solely determined by their hardware design but also by the sophistication of their control strategies. As renewable hybrid systems exhibit nonlinear dynamics, intermittency, and uncertainties, advanced control and intelligent techniques are required to ensure optimal performance of STATCOM, SVC, UPFC, and DVR.

1. Conventional Control Techniques

Traditionally, FACTS devices have been controlled using Proportional-Integral (PI) and Proportional-Integral-Derivative (PID) controllers due to their simplicity and ease of implementation. These controllers regulate parameters such as reactive power, DC-link voltage, and current balance. However, their effectiveness diminishes in highly nonlinear environments, as they are unable to adapt to rapid variations in renewable energy generation. Vector control and direct power control (DPC) methods have also been employed for improved accuracy and faster response. These methods provide better regulation of active and reactive power, making them suitable for devices like STATCOM and UPFC in hybrid systems.

2. Intelligent Control Approaches

To overcome the limitations of conventional methods, intelligent techniques such as Fuzzy Logic Control (FLC), Artificial Neural Networks (ANNs), and Adaptive Neuro-Fuzzy Inference Systems (ANFIS) have been integrated with FACTS devices.

Fuzzy Logic Control (FLC): Offers robust performance under nonlinear conditions without requiring an accurate mathematical model. It is highly effective for real-time PQ management in systems with fluctuating renewable inputs.

Artificial Neural Networks (ANNs): Provide self-learning capabilities and can adapt to varying conditions, making them suitable for dynamic environments. They have been applied to STATCOM for improved harmonic compensation and voltage regulation.

ANFIS: Combines the adaptability of neural networks with the reasoning ability of fuzzy logic, delivering improved robustness and accuracy in hybrid systems.

3. Optimization-Based Controllers

Modern research has increasingly focused on optimization algorithms to fine-tune controller parameters. Techniques such as Particle Swarm Optimization (PSO), Genetic Algorithms (GA), and Differential Evolution (DE) are employed to optimize gain settings, minimize total harmonic distortion (THD), and enhance dynamic response. These metaheuristic algorithms are particularly useful in complex hybrid renewable systems where multiple objectives such as voltage regulation, power loss minimization, and stability improvement must be achieved simultaneously.

4. Model Predictive Control (MPC)

MPC has emerged as a powerful control framework for FACTS devices. By predicting system behavior over a finite time horizon and optimizing control actions accordingly, MPC offers superior adaptability and stability. In renewable applications, MPC ensures real-time adjustment to variations in solar irradiance and wind speed, thereby maintaining power quality. Despite its computational intensity, advancements in digital processors and embedded systems have made MPC more feasible for practical applications.

5. Artificial Intelligence and Machine Learning Integration

The latest trend in control strategies is the integration of Artificial Intelligence (AI) and Machine Learning (ML) with FACTS devices. Techniques such as reinforcement learning and deep learning enable controllers to learn optimal policies over time, enhancing their adaptability in uncertain and highly dynamic environments.

6. Hybrid Control Frameworks

Given the complexity of renewable hybrid systems, hybrid control approaches that combine conventional, intelligent, and optimization-based techniques are becoming popular. For instance, a PI controller may handle steady-state operations, while fuzzy or ANN-based controllers address dynamic disturbances. Such multi-layered frameworks ensure both stability and adaptability, making them highly effective for real-world deployment.

VII. Results and Discussion

The review of FACTS devices and their role in renewable hybrid systems highlights significant improvements in power quality, grid stability, and system efficiency. Studies consistently demonstrate that FACTS-based solutions, particularly STATCOM and UPFC, provide superior reactive power support, voltage regulation, and harmonic mitigation compared to traditional compensation techniques. For instance, STATCOM shows faster response time and better dynamic performance than SVC in handling sudden power fluctuations caused by wind gusts or solar intermittency. Similarly, UPFC offers comprehensive control over both active and reactive power, enabling effective integration of large-scale hybrid systems into weak grids. DVR applications show marked improvement in the quality of power supplied to sensitive loads, reducing downtime and minimizing economic losses associated with poor PQ. Comparative analyses also reveal that while STATCOM and UPFC deliver advanced capabilities, their higher cost remains a limitation, especially for small-scale distributed renewable systems. However, advancements in semiconductor technology, modular designs, and intelligent control have significantly reduced operational costs and enhanced the viability of these devices. Moreover, the adoption of AI-based control strategies has demonstrated considerable improvements in the adaptability and resilience of FACTS devices, making them more effective in complex and uncertain operating environments. Challenges remain in terms of large-scale deployment, such as high initial investment, maintenance complexity, and grid code compliance, but the long-term benefits in terms of reduced losses, improved reliability, and enhanced renewable energy penetration outweigh these barriers. Overall, FACTS devices have proven to be indispensable in achieving stable, efficient, and sustainable integration of renewable hybrid energy systems. Future research should focus on cost reduction, scalability, and advanced AI-driven control to fully realize their potential in next-generation power systems.

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