Artificial Intelligence Based STATCOM Control for Hybrid Solar–Wind Energy Systems: A Comprehensive Review

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Abstract:

The growing deployment of solar energy into common AC networks has been aggravating problems of voltage fluctuation, reactive power unbalance, and power quality. Out of the numerous renewable resources, hybrid systems combining solar and wind energy have proved effective under well-sited conditions. The other aspect that constitutes the problem is that, given the intermittency (basically temporal in extent), owing to the natural behavior of renewables, they become a platform from which to push for sustainable development-an exercise that defies human failures of inconsistency and the concept of stability. The STATCOM for the flexible AC transmission system has responded greatly to problems in terms of the enhancement of voltage support and reactive power. Generic controllers of STATCOM based on PI or PID schemes lack the ability to cope with changes such as rapid variations in renewable generation, adaptability, nonlinear conditions, and performance. This paper poses the improvement of artificial intelligence (AI)-applied control strategies for STATCOM in solar and wind hybrid systems. Zealously significant examinations are dedicated to common AI techniques comprising Artificial Neural Networks (ANN), Fuzzy Logic Control (FLC), Adaptive Neuro-Fuzzy Inference Systems (ANFIS), Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and Reinforcement Learning (RL). There is an emphasis on how these intelligent controls underline the contrast between voltage, PQ, reactive power, and fault ride-through capability and the classical control methods. The paper embodies extensive performance comparison and connects the research trends, along with the review of practical implementation issues like complexity, data dependency, and the feasibility for real-time operation. The work therefore rightly brushes up the research gaps, drawing the attention to potential research trajectories, spanning hybrid AI controllers, real-time hardware validation, and integration with Smart Grid frameworks. This review hopes to be beneficial to researchers and industry practitioners alike who are engaged in using intelligent controls for a STATCOM in the realm of hybrid renewable energy systems, aiming toward the production of a stable electrical power system with the highest possible quality.

Keywords: *Artificial Intelligence, STATCOM, Hybrid Solar–Wind Energy System, Reactive Power Compensation, Voltage Stability, Power Quality, FACTS Devices*.

I.INTRODUCTION

In recent decades, renewable energy systems have gained much significance, due to faster depletion of fossil fuel reserves, increased energy demand, and concerns about increasing pollution due to climate change [1]. The burning of coal, oil, and natural gas in conventional power generation gives a huge amount of greenhouse gas emission, which in turn explains the global shift toward low carbon energy sources. These tasks are generally derived from the decentralized renewable resources solar, wind, water bioplast and geothermal energy to comfortably provide electricity-many times with negligible environmental distress [2].

Several renewable energies, as an instance, Solar and Wind, have turned out as the most promising. They are celebrated for their abundance, massive R&D investments, and constantly evading installation costs [3]. Systems allied with other sets of renewable energy may work counterproductively towards the decentralization of power generation; a reduction of dependency upon conventional fuels and improve the security of supply. Above all, being intermittent and dependent largely on weather and environment, renewables can surely not remain all that predictable [4]. The variability will place impacts on the grid's stability and voltage regulation and by extension affect the provision of reliable power. Figure 1. represents Renewable Energy Systems [5]

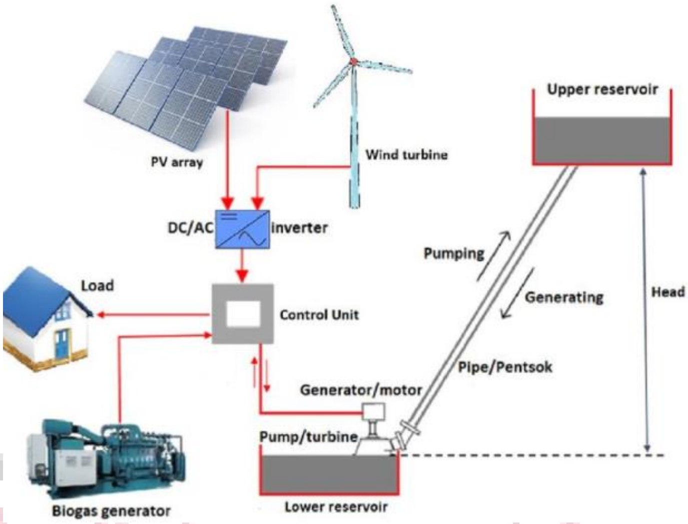

Figure 1: Renewable Energy Systems [5]

Overcoming these obstacles, advanced power electronic interfaces, energy storage technologies, and intelligent controls continue to be the integrating methods applied to modern renewable energy systems [6]. When integrated with large power grids, these renewables make power quality and grid stabilization challenges more critical. Renewable energy systems hence play a key role in reaching sustainable development goals through clean energy generation, carbon emission cuts, and the development of smart energy systems capable of resisting different disruptive conditions [7].

Hybrid Solar–Wind Energy Systems

Designing an integrated hybrid solar-wind energy system entails the cooperation of solar photovoltaic and wind energies for electricity generation in synchronized structure. These days coupled systems are designed to maximize the socioeconomic relationship between sunshine and wind energy resources [8]. Typically, sunshine is utilized during the daytime and cool weather conditions, whilst wind energy acceleration frequently occurs at night-time or under cloudy conditions. The integration of solar and wind sources in the hybrid system increases energy availability, reduces power fluctuations, and enhances the reliability and stability of the entire system [9]. Grid-connected-hybrid solar-wind systems combine the feudal approach to harness the optimal utilization of renewable assets for rugged power generation. Figure 2 represents Hybrid Solar Wind Energy Systems [7]

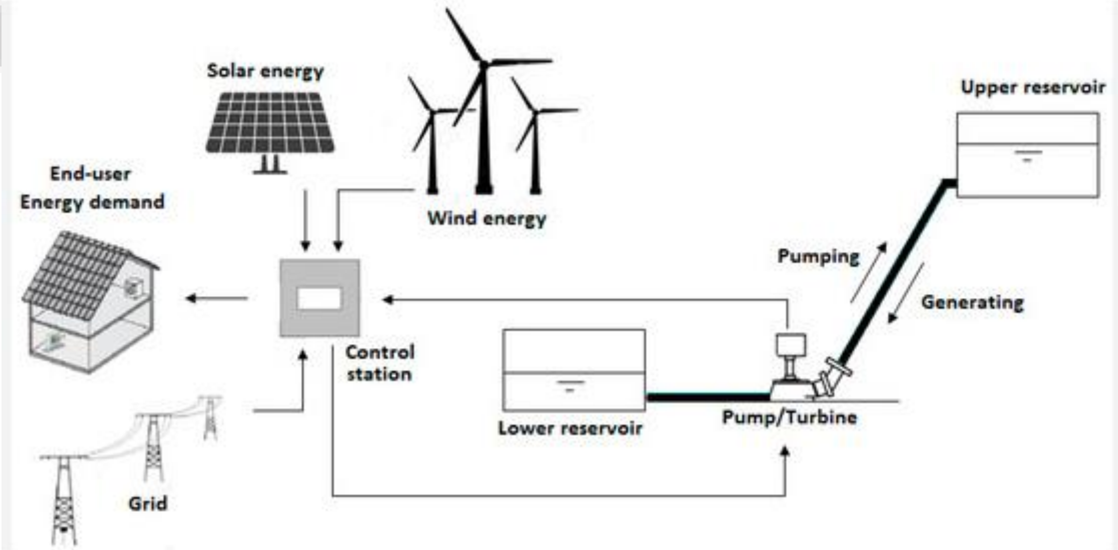

Figure 2: Hybrid Solar–Wind Energy Systems [7]

Need for Hybrid Renewable Systems

The increased uptake of renewable power systems showed the pitfalls of relying solely on one renewable energy source for energy generation. Solar and wind, being very clean and very renewable, suffer from intermittency and dependence on environmental influencers. Solar irradiance can drop unexpectedly due to cloud cover, or wind speeds may increase unexpectedly [10]. Such discrepancies may bring unsteadiness to the power band, stumbling voltages, or reliability concerns. Despite feeding off numerous sources, hybrid renewable systems are needed to address the difficulty, since these sources will have comparisons in terms of generation capabilities.

Indeed, as already alluded to, integration on a given system has best proven to be the way to go, demonetizing, however, the tight elementary string between power of variability and another of the alternative source, subsequently leading to significantly reduced dependency on energy storage systems and fixating the ancillary use of the conventional genet towards power load-matching and grid stability [11]. As such, if some electricity should be needed to make something happen even in the least developed and remote areas-or in the districts that are distances away because of grid prohibitions-this series of renewables is the backbone of power generation when on necessity and sufficient [12].

Advantages of Solar–Wind Hybridization

Table 1: Advantages of Solar–Wind Hybridization [12]

Aspect	Advantage
Energy Availability	Provides continuous power by utilizing complementary solar and wind resources
Reliability	Reduces power outages caused by single-source intermittency
Power Quality	Improves voltage stability and reduces fluctuations
Grid Stability	Enhances grid support and reactive power management
Cost Efficiency	Lowers operational and maintenance costs over time
Reduced Storage Requirement	Minimizes dependency on large energy storage systems
Environmental Impact	Decreases carbon emissions and fossil fuel usage
Scalability	Suitable for both small-scale and large-scale installations
Utilization Efficiency	Maximizes use of available renewable resources
Applicability	Effective for grid-connected and standalone systems

Grid Integration Issues of Hybrid Renewable Energy Systems

The integration of hybrid solar-wind energy systems in the grid presents a number of quite substantial challenges due to the inherent fluctuating and intermittent nature of renewable energy resources. In comparison with conventional power plants, solar and wind power have no control possibilities, meaning that they certainly produce fluctuations in voltage, frequency, and active power. [13] These behaviors can interfere with grid stability and reliability due to some imbalance between power supply and power consumption. Hybrid systems need to couple to yet more complicated electronic interfaces, which are set up to manage harmonics and reactive power issues. The randomness posed by the renewable power sources and the fluctuations in load demand make it much more difficult to maintain an aspect of managing power quality, voltage regulation, and frequency control [14]. Trying to solve these complications, then, evidently necessitates improved control strategies, energy storage solutions, and reactive compensation devices such as STATCOM. Proper synchronization between the integration of the grid and maintenance is needed to serve for steady, reliable, and reliable electric energy delivery; to simultaneously achieve maximum exploitation of renewable sources. Figure 3: Grid Integration Issues of Hybrid Renewable Energy Systems [13]

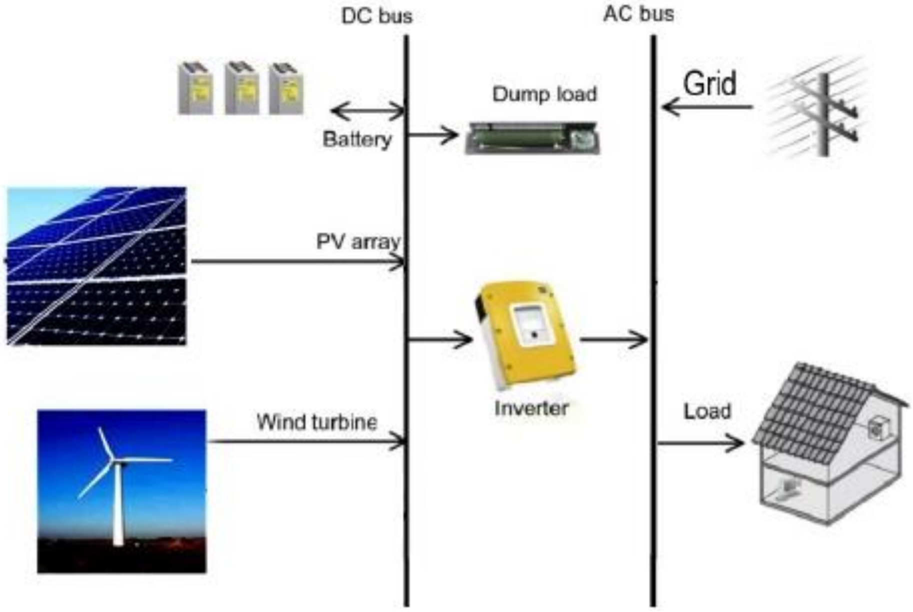

Figure 3: Grid Integration Issues of Hybrid Renewable Energy Systems [13]

Voltage Stability Problems

Voltage stability refers to the abililty of a power system to maintain steady voltages at all the buses after as power frequency deviation occurred, sticking more with the conditions of normal operation and after such disturbances as park outage [15]. Voltage stability is particularly important for the grid-connected hybrid solar–wind energy systems, facing some significance because instead of wind or solar energy the greater obstacle becomes the constantly changing solar irradiance and wind speed [16]. Excess power could build up instead of being drawn by loads at one point and hence the voltage may rise to dangerous levels. Drops in load power consumption will, on the contrary, frequently induce a voltage sag, since the system lacks reactive power consumption capability. In return, generators based on inverters-like the renewable resources-have significant impacts on voltage instability due to a deficit in reactive power support, aggravating the voltage instability problem [17]. With long transmission lengths among far hybrid systems and distant grids, internal transmission resistances and load fluctuations increase the severity of voltage deviations drastically due to the system's consumption of a vast amount of active power. This impairs the load operation and often leads to tripping of protective devices that can result in local or major outages within the system. STATCOM, SVC, and advanced AI-based controllers are solutions applied to balance forces for absorption, absorption and reflection of reactive power and transients to enhance system integrity and ensure the safe integration of hybrid renewable resources into the grid [18].

Reactive Power Imbalance

Reactive power support plays an indispensable role in preserving voltage levels and ensuring that each and every electrical appliance in a power system operates efficiently. Solar and wind energy systems that harness power from both sources do face significant challenges in ensuring reactive power management [19]. Equally though, randomness in the output of both solar panels and wind turbines due to changing atmospheric parameters can lead to a large reactive power shift, raising voltage levels or dropping them, and create excess losses in the transmission grid as reactive power becomes unbalanced. Additionally, inverters also possess an array of reactive power limitations that make it impossible to respond quickly when any change in system voltage is bound to occur [20]. The existing grid systems have been charged with supporting a steady state of harmonious reactive power flow, as any unplanned unbalancing by the comparatively new breed of hybrid systems ultimately destabilizes the grid. Such reactive power imbalances can throw off the operation of protection systems from their norm, ruin power-quality-related demands, and pull down energy delivery efficiency [11]. Potential solutions include the inclusion of items relating to reactive power compensation, such as STATCOM and SVC, using intelligent AI-controlled control schemes to adjust the reactive power flow in real-time, and coordinating the operation of hybrid generation with energy storage systems within the network to maintain voltage profiles that enhance grid reliability [12].

Power Quality Issues

The quality of power refers to its level of conformance with contractually agreed requirements by the majority of electrical loads involved in operations. The technology of wind power and solar power, which embodies the basic characteristic of wind and solar energy sources, results in severe power quality issues. Rapid changes in solar irradiance and wind speed give rise to voltage fluctuations, flickers, and harmonics. Harmonic contribution is one of the main consequences [13]. The inverter converts DC power from solar PV and variable-frequency AC power from wind turbines to grid-compatible AC power. It is common from an analysis of the effects that inverters may cause harmonics under nonlinear circumstances. For that, normal operation of electronic devices will get adversely affected, while electrical machinery would be subjected to reduced lifespan and wrong responses on protective devices due to such strange circumstances [14]. Toxic layers of voltage sags combining with other problems such as swells and frequency deviations could well offset grid stability. Strong ideas would have to linger around those perk technicalities designing great controls, thereby completing mitigation needs commensurate with the needs for high quality in the power of hybrid systems [15]. That means sophisticated control strategies with an intelligent AI-based basis, continuous monitoring, and the notion of employing reactors that could bolster such a system like a STATCOM is an absolute must. An offer of these types of control measures would ensure that objectives like voltage regulation and mitigation of harmonics are met while integrating renewable energies into the grid smoothly [16].

Role of Reactive Power Compensation

The use of the reactive energy compensator systems is crucial for the modern power system, for their reliability, stability, and efficiency, especially with the increasing ratio of renewable energy sources such as hybrid photovoltaics wind power systems [17]. For the maintenance of voltage levels on the grid and the correct operation of electrical equipment, the reactive power is paramount. Due to intermittency and variability of solar and wind generation in hybrid renewable systems, active and reactive power go into continuous fluctuations causing voltage instability, increased losses, and reduced system reliability.

Capacitor banks, synchronous condensers, and Flexible AC Transmission System (FACTS) devices, including Static Synchronous Compensators (STATCOM) and Static VAR Compensators (SVC) and so on are deployed in compensation for reactive power [18]. Among those, the STATCOM itself has an application of providing fastest dynamic response and offering best voltage support, rendering it most effective for hybrid systems such as those with sub-second-rate transient. STATCOM injects or absorbs power as required to maintain bus voltage within reasonable bounds, reduce voltage sags and swells, and minimize the risk of system collapse during emergencies.

Control of reactive power, accompanied by the management of active power, is indeed something considerable in keeping a hybrid solar-wind-based system operational within varying environmental and load conditions [19]. An added focus on the AI-based action allows for an increase in the perforation of devices regulating reactive power; this is done by allowing adaptive and real-time control. Its role in ensuring optimal voltage regulation, system stability, and reliable grid operation cannot be overstated. It is therefore concluded that each step of reactive power control relates to hybrid renewable energy source integration with the modern power grid [20].

II. OVERVIEW OF FACTS DEVICES FOR RENEWABLE ENERGY INTEGRATION

Flexible AC Transmission System (FACTS) devices are made of a variety of power electronic systems which will enhance controllability, stability, and the efficiency of the power networks. They will provide dynamic control of voltage, current, and reactive power to control the particular renewable energy sources that are sporadically operational, say solar or wind. [21] Commonly used FACTS devices are Static VAR Compensators (SVC), Static Synchronous Compensators (STATCOM), Thyristor Controlled Series Capacitors (TCSCs), and Unified Power Flow Controllers (UPFCs), these being extremely necessary for scaling power flow and voltage regulation for an increase in grid reliability, followed by reduced losses and support for the stabilized operation of hybrid renewable energy systems during variations in loads and generation. [22] Figure 4 represents Flexible AC Transmission System (FACTS) Devices

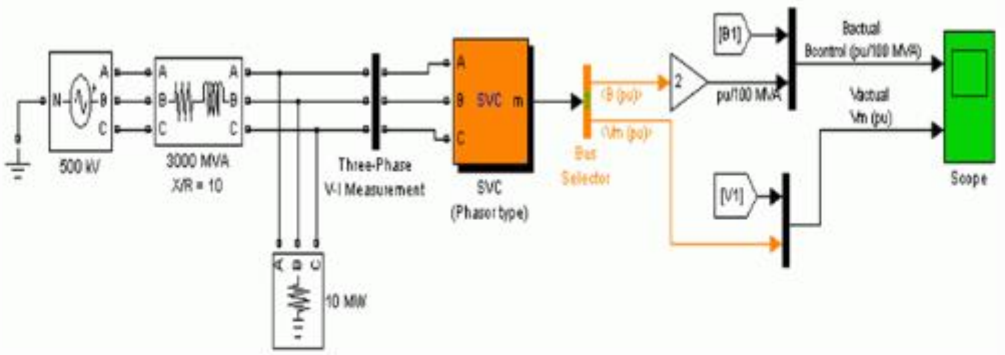

Figure 5: Flexible AC Transmission System (FACTS) Devices [22]

Voltage Regulation and Stability Enhancement

Voltage regulation and stability are challenges to any modern power system, especially in these days of global warming, in which higher and higher penetration of renewable energy is being rigorously pursued. The unpredictable power output of solar PV and wind turbines can quite possibly lead to voltage sags, swells, or, in extreme cases, grid instability [23]. The STATCOM and SVC devices, as a part of the FACTS family, have the distinct advantage of continuously supporting dynamic voltage by injecting or absorbing reactive power. Thus, the bus voltage stays within limits and averts voltage collapse brought about by the sudden changes in load or generation [24].

By improving transient and dynamic voltage stability, the FACTS devices help the power system withstand large disturbances like faults or a sudden loss of generation that Johnny cannot withstand. Voltage regulation, moreover, lessens the stress on the transformers, transmission lines, and delicate electrical apparatus [25]. The FACTS devices manage temperamental solar-wind systems' voltage profile with varying renewable energy fluctuations and add reliability and resilience to the grid. With their adaptive and AI-enriched control, they smoothen out voltage sagging even farther and enlarge the horizon by performing a system operation speedier in response to changing system parameters. [26]

Power Quality Improvement

Power quality is the measure of how well the electric power is being conveyed, without disturbances that might affect the power system performance or equipment. Hybrid solar wind energy systems are often afflicted by harmonics, voltage sag, flicker, and unbalanced loads due to variable quantities and power electronics interfaces. This issue mainly finds relief in the armor of special devices: the FACTS devices [27].

An example is STATCOM and SVC both of which can effectively control the flow of reactive power dynamically and compensate for voltage sags and swells when produced by erratic outputs in the renewable energy effect. Besides, these devices help in the suppression of wave harmonics and flicker by stabilizing the voltage and flow of the supply current [28]. Hence, enhanced power quality ensures that vulnerable loads, for instance, industrial machinery and electronic equipment, can be effectively operated without the possibility of malfunction or degradation.

The additional functionalities provided by AI-based control for FACTS devices include the augmentation of PQ improvement capacities. Thus, an intelligent controller can anticipate disturbances, optimize the amount of reactive power compensation applied, and adapt quickly to improve the system conditions and reduce the adverse effects from time-varying renewable sources [29]. In general, FACTS incorporated with AI-based control ensures the quality and reliability in terms of stable power supply within hybrid RE systems, to the extent of running the grid and maintaining the life of systems, from utility to the connected AC equipment [30].

Integration with Hybrid Renewable Energy Systems

Incorporating hybrid solar-wind energy systems into the current grid poses significant challenges due to the intermittent and variable nature of renewable generation. FACTS devices play a critical role in ensuring smooth integration by providing dynamic voltage support, reactive power compensation, and power flow control. [31] The devices help to mitigate fluctuations caused by the abrupt change in solar irradiance or wind speed; these fluctuations would otherwise induce voltage instability, power quality issues, or potential grid disturbances.

It is known through numerous research experiments that efficient energy utilization can be achieved by the deployment of Flexible AC Transmission System (FACTS) and Static Synchronous Compensator (STATCOM). Furthermore, from the perspective of the fate of hybrid tandem generation systems, FACTS and STATCOM provide an immediate advantage because they can respond rapidly and have the highest possible accuracy, the latter being mostly related to controlling the voltage [32]. Therefore, it is proven that with STATCOM to support wind farms, solar towers, etc., and at any time maintaining the voltage within the specified limits during the cycling use, a certainty factor has been established that can ensure a very effective operation.

Moreover, the integration of AI-based control strategies enhances the performance of FACTS devices in hybrid systems. With intelligent controllers, the system can continually monitor its status, predict fluctuations in renewable generation, and augment output of reactive power in real time [33]. That thereby enhances voltage stability and power quality of hybrid systems, thereby helping them meet grid codes and operational requirements. That is why FACTS devices play an essential role in linking efficient, reliable integration between hybrid solar wind energy systems.

III. STATIC SYNCHRONOUS COMPENSATOR (STATCOM): PRINCIPLE AND APPLICATIONS

A static synchronous compensator (STATCOM) is a FACTS voltage-source device based on the converter used to supply dynamic speed components, along with power quality, as well as support for the determination of system parameters in the energy industry. STATCOM does so by starting and stopping the control of reactive power, separated entirely from the voltage at the grid, depending on the conditions of load fluctuation and the intermittent nature of renewable energy sources [34]. Hybrid wind–solar energy systems commonly make use of STATCOM for voltage stabilization, while supporting voltage sags or swells, hence assuring the system's integration with the grid. STATCOM's quick reaction, diminished size that implies that there are any benefits to come more for existing reactive power devices when compared to the SVC. Figure 6 represents Static Synchronous Compensator (STATCOM) [30]

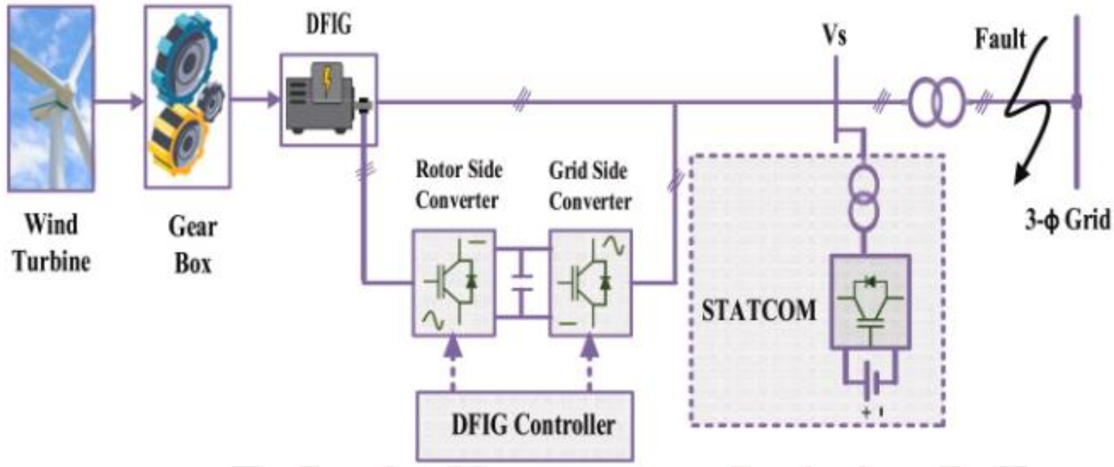

Figure 7: Static Synchronous Compensator (STATCOM) [30]

Basic Operating Principle of STATCOM

The Static Synchronous Compensator (STATCOM) is a FACTS shunt-connected device that provides fast theoretical reactive power support for stabilizing the voltage respectively, improving system performance. The transmission line is connected to the STATCOM as well as the coupling transformer. The STATCOM compensates the phase currents necessary to regulate the output of the VSC [35]. The VSC creates an operational voltage using controllable amplitude and phase; by adjusting the magnitude or phase between STATCOM output voltage and bus voltage, the STATCOM can inject or absorb reactive power into or from the system [36].

During sags, STATCOM provides support to the grid voltage by delivering reactive power during normal conditions and (capacitive operation) improper voltage versus the grid voltage. During high voltage conditions, on the contrary, STATCOM sinks reactive power (inductive operation) to avoid high voltage situations [37]. In contrast to the shunt reactive compensation affords, STATCOM maintains reactive power provision at low bus voltages, making itself an ideal reflexive machine in cases of severe voltage dips.

STATCOM has two primary modes of operation: voltage regulation and reactive power control. In the voltage regulation mode of operation, the device adjusts its reactive power outputs dynamically, thereby maintaining a given bus voltage level. On the other hand, while operating in reactive power control mode, it interacts directly with the grid, adjusting amounts of reactive power [38]. Modern STATCOM controllers feature AI or adaptive algorithms to optimize operation, together with varying levels of renewable energy penetration, while still further accelerating the assimilation of the STATCOM's large capacities for quicker voltage regulation and enhanced power quality [39].

IV. HYBRID SOLAR–WIND ENERGY SYSTEMS: ARCHITECTURE AND POWER QUALITY CHALLENGES

Significant research has been centered on power quality improvement within hybrid renewable energy systems with top importance placed on compensation and filtering techniques. Utilization of shunt active power intended to improve PV–wind–fuel cell hybrid systems by harmonics hailing, rendition toward reactive power in circumstances of non-linear load, and variable availability of renewable resources [1]. Validation detected from hardware-in-the-loop demonstrated remarkable decrease in THD magnitude and certification with IEEE 519 standards; nevertheless, the control algorithm used was deficient in adaptability and predictive capabilities.Universally accepted intelligence has been dedicated for four-legged applications of power quality control strategies for the same category [2]. Performance of hybrid UPQC controllers did show promise of good voltage regulation, reduction in THD, and improved power factor (PF) under voltage sag/swell and grid disturbances in comparison to traditional methods based on the PI method. However, the system was not incorporated with learning-based or intelligent optimization algorithm techniques.Deep learning-based smart inverter control for hybrid PV-wind systems has great potential to provide significant power quality improvement [3]. This control managed the voltage within the acceptable range while minimizing harmonic distortions that traditionally gave better performance than the other controllers for current dynamic operating conditions. Together with advantages, it was challenging because the approach is high in terms of data dependency and training.The enhancement of power quality in wind-solar AC microgrids has been addressed using modified least mean square control techniques (Zhang, 2016). Experimental results validate harmonic compensation and voltage improvement were efficiently supporting reliable autonomous operation. However, the lack of adaptive intelligence makes the operation system not very flexible. Similarly, active power filters have been applied for grid-connected PV systems to eliminate harmonics due to inverter switching and nonlinear loads achieving compliance with a few IEE standards, but sensitivity to irradiance variations remained a matter of concern.Many reviews give comprehensive guidance on the capacity to detect power quality disturbances, with a rapidly increasing usage of artificial intelligence and identification algorithms, such as neural networks, fuzzy logic, and hybrid soft-computing systems. Despite possible improvements in the accuracy of the overall system, their sensitivity to noise and probable computational load remain unaddressed. Possible improvement could be advanced utilization of optimization and STATCOM control for better voltage staggering in solar–wind microgrid [7] although pertinent impediments in real-time implementation forestalled the manifestation of the method.Techno-economic studies show the wind-based photovoltaic system to have higher reliability and lower diesel dependency in remote areas [8], hereby rendering out matters of power quality and compensation. High PV penetration in a grid leaves the issue of the flicker for discussion from the grid operator's perspective [9]. Consequently, nonconventional options outside those that already exist might require some coordination for long-term gain.

Facts-based solutions for grid connections high in renewable energy sources have received much appraisal [10] and have brought important issues of STATCOM, DSTATCOM, and UPQC into the limelight while referring to rule-based control as a possible way forward. Critical reviews of power-quality issues regarding grid-connected renewable energy systems have enlarged the view of prevailing causes of PQ degradation and brought into sympathy with the necessity of using intelligent adaptivities [11].Adaptive algorithms have been developed recently for the compensation of reactive power and suppression of harmonics in the wind and solar systems with faster convergence and better steady-state properties [12], but this came at the expense of increased computation. Voltage regulatory-based techniques by the multilevel inverter have shown less harmonic distortion and fulfillment of all criteria stipulated by norms [13], yet a more complex control procedure has resulted with an increase in the number of inverter levels.Renewable integration with Hybrid UPQC makes it possible for improved voltage and current compensation, thanks to enhanced efficiency [14]; several drawbacks are still in existence, including increasing cost and interference complexity. The Cyber-Physical Architecture of Wind Energy Systems facilitates real-time monitoring of the systems and fault detection [15] in a setup that could potentially result in communication latency and security issues.Several instances of adaptive real-time shunt active filters have been fitted to solar farms to improve power factor under dynamic conditions and attenuate harmonics [16]; these filters, by far, do not have learning infinite adaptability. Literature investigating power quality issues like supraharmonics in micro-grids has been abundant, hinting to the perceived necessity of integrated monitoring with AI-powered mitigation strategies [17].Recent findings suggest that deep learning techniques based on convolutional auto encoders and long short-term memory (LSTM) networks have been successful in the automatic classification of different power quality disturbances, the downside being that they require high computer participation and have small hardware. On the plus side, grid-interfaced solar water pumping systems make improvements in power quality and ensure operational stability during abnormal grid conditions [19]. But there is also a lack of predictive programming concerning the grid system.It has been established by research in the past that the optimal sizing and techno-economic evaluation of off-grid hybrid solar-wind-biomass systems is fit for rural electrification [20], but the work failed to address power quality control and active compensation mechanisms.

Table 2: Power Quality Improvement and STATCOM Applications in Hybrid Renewable Systems

Ref.	System	Technique	Major Contributions	Research Gap
[1]	PV–Wind–Fuel Cell hybrid system	SAPF with HIL testing	Harmonic mitigation and reactive power compensation under dynamic conditions; IEEE-519 compliance achieved	Conventional control; no intelligent adaptation
[2]	Wind energy system	Hybrid-controlled UPQC	Improved voltage regulation, reduced THD, enhanced power factor	Controller complexity; absence of learning
[3]	PV–Wind hybrid microgrid	DNN-based smart inverter	Adaptive voltage and harmonic control outperforming PI	High training data dependency
[4]	AC microgrid	Modified LMS algorithm	Reduced current harmonics and improved voltage quality	No AI-based optimization
[5]	Grid-connected PV	Active Power Filter	THD reduction under varying irradiance	Limited reactive power support
[6]	Power quality monitoring	Signal processing & soft computing review	Comprehensive PQ disturbance classification	Real-time AI deployment not addressed
[7]	Solar–Wind microgrid	GA & BFA optimized STATCOM	Improved voltage stability and loss reduction	Lack of experimental validation
[8]	Hybrid RES planning	Techno-economic optimization	Cost-effective rural electrification	PQ mitigation not considered
[9]	LV grid with PV	EV-based voltage control	Reduced voltage fluctuations	FACTS devices ignored
[10]	Renewable-rich grid	Distributed FACTS review	Detailed control strategies comparison	AI-based controllers missing

[11]	Distributed generation	PQ challenges review	Identified key PQ issues and solutions	Adaptive intelligence lacking
[12]	Wind–Solar DG	Adaptive ε-LMF algorithm	Faster convergence and harmonic suppression	Computationally intensive
[13]	Solar inverter system	Multilevel inverter control	Reduced THD and improved voltage profile	Increased controller complexity
[14]	DG integrated grid	Hybrid UPQC	Improved efficiency with reduced rating	High cost
[15]	Wind CPS	Wireless sensor networks	Enhanced monitoring and coordination	PQ not primary focus
[16]	PV grid system	Adaptive SAPF	Effective harmonic compensation	No learning-based control
[17]	Microgrids	Supraharmonics review	Standards and mitigation overview	AI solutions absent
[18]	PQ classification	CNN autoencoder + LSTM	High classification accuracy	Heavy computation
[19]	Solar water pumping	PMSM drive control	Improved PQ during disturbances	Classical control only
[20]	Off-grid hybrid system	Techno-economic analysis	Reliable rural electrification	PQ control not addressed

V. CONCLUSION AND FUTURE WORK

This review comprehensively examined artificial intelligence (AI)–based STATCOM control strategies for hybrid solar–wind energy systems with emphasis on voltage stability, reactive power compensation, and power quality improvement. FACTS devices, particularly STATCOMs, come as formidable solutions on the basis of their instantaneous dynamic response and quality reactive power supply. However, conventional PI/PID controllers are easily adapted and are often in minor performance control when it comes to rapidly changing renewable and load conditions. Therefore, effective AI controls, mainly with ANN, FLC, ANFIS, evolutionary algorithms, and deep learning, do show dramatic superiority regarding voltage control, harmonic mitigation, fault-ride-through capability, and conformance to many power quality standards compared with classical approaches. Despite the above, the implementation of these AI techniques faces hindrances stemming from high computational burden, data dependence, lack of real-time validation, nonscalability, and lack of security considerations. Therefore, future work must focus on laying down AI-based hybrid control frameworks able to merge multiple intelligent mechanisms, creating lightweight mathematical models for real-time operations, and validating these models with HIL and field implementations. It is very important that the AI-controlled STATCOMs are further integrated into smart grids with IoT-based monitoring systems, which are refined through multi-objective optimization to cope with stability and efficiency with cost criteria.

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