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Enhancing Power Quality in Hybrid Solar-Wind Energy Systems with Unified Power Quality Conditioner (UPQC): A Review

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Abstract: *With the increasing adoption of hybrid solar-wind energy systems, ensuring high power quality is crucial for reliable and efficient operation. This review paper examines the integration of the Unified Power Quality Conditioner (UPQC) to enhance the performance and stability of these hybrid systems. The UPQC is an advanced power conditioning device designed to mitigate a range of power quality issues, including voltage sags, swells, harmonics, and imbalances. By incorporating distributed generation sources like photovoltaic arrays and wind turbines, UPQC effectively addresses disturbances in grid voltage and load current. This paper provides a comprehensive analysis of UPQC components, functionalities, and control strategies, and discusses the benefits of its application in hybrid energy systems, highlighting its potential to improve power quality and system efficiency.*

Keywords: *Hybrid Solar-Wind Systems, Unified Power Quality Conditioner (UPQC), Power Quality, Distributed Generation (DG), Voltage Source Converter (VSC), Renewable Energy Integration*.

I. INTRODUCTION

As hybrid solar-wind systems become increasingly popular, ensuring high power quality is essential for reliable and efficient operation. One effective solution to address power quality issues in such systems is the use of a Unified Power Quality Conditioner (UPQC). UPQC is a comprehensive power conditioning device designed to mitigate various power quality problems, enhancing the performance and stability of hybrid energy systems. Here are key points on the role and benefits of UPQC in hybrid solar-wind systems: Nowadays, due to energy scarcity and environmental issues, distributed generation (DG) sources like photovoltaic (PV) arrays have been significantly increasing. In distribution power systems, grid voltage disturbances, e.g., voltage sags and swells, harmonics, and load current disturbances, e.g., current harmonics or unbalancing, are the most common power quality problems. A unified power quality conditioner (UPQC) is a versatile device as it mitigates voltage disturbances in the grid side and current disturbances in the load side simultaneously [1]. With the ever-growing number of DG sources, the combination of a traditional UPQC with DG is an emerging trend in modern distribution power systems. It integrates DG, such as that facilitated by PV modules, at the dc link of the UPQC.

For the directly connected UPQC-DG, DG sources are directly coupled to the dc link, which supplies active power required by the load through the parallel converter and also provides active power consumed by the series converter for grid voltage compensation. To meet the grid-connected requirement, the common dc-bus voltage is relatively high, which leads to more cascaded modules. In practical applications, the DG voltage can be relatively low and vary in a wide range.

Today, interests on hybrid ac/dc micro-grids, which contain the advantages of both ac and dc micro-grids, are growing rapidly. In the hybrid ac/dc micro-grid, the parallel-operated ac/dc bidirectional interfacing converters (IFCs) are increasingly used for large capacity renewable energy sources or as the interlinking converters between the ac and dc subsystems. When unbalanced grid faults occur, the active power transferred by the parallel-operated IFCs must be kept constant and oscillation-free to stabilize the dc bus voltage [2]. To address these issues, the major contribution of this paper is to propose a hybrid connected unified power quality conditioner integrating distributed generation (HCUPQC-DG). A comprehensive analysis for the topology, control and modulation strategies, and active power flow is presented in detail to understand the nature of the proposed HCUPQC-DG [3].

Components of a Unified Power Quality Conditioner (UPQC)

A Unified Power Quality Conditioner (UPQC) is a comprehensive power conditioning device designed to address various power quality issues in electrical systems. The UPQC combines both series and shunt active filters to provide a wide range of power quality solutions. Here are the key components of a UPQC:

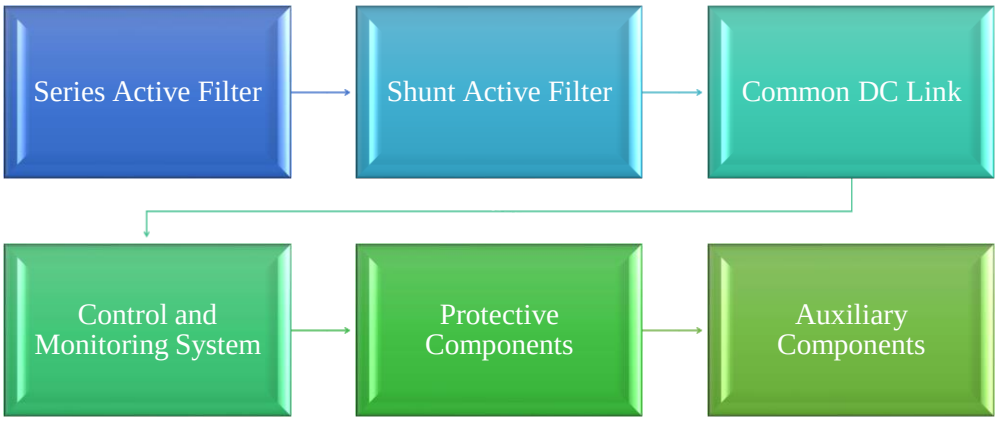

Figure 1 Components of UPQC

The Unified Power Quality Conditioner (UPQC) consists of several key components: the Series Active Filter and Shunt Active Filter. The Series Active Filter includes a Voltage Source Converter (VSC) that converts DC voltage from the common DC link to AC voltage to inject or absorb voltage in the power line, a Series Transformer that connects the VSC to the power line to inject compensating voltage, a DC Link Capacitor that provides the necessary DC voltage for the VSC, and a Control System that monitors supply voltage, detects disturbances like sags, swells, and flickers, and controls the VSC to compensate for these disturbances. The Shunt Active Filter similarly has a VSC that converts DC to AC to inject compensating current, a Shunt Transformer or Inverter that connects the VSC to the load side, a shared DC Link Capacitor, and a Control System that monitors load current, detects harmonics, reactive power, and imbalances, and controls the VSC for compensation. The Common DC Link, consisting of a DC Link Capacitor and optionally a DC Link Inductor, provides stable DC voltage for both filters. The Control and Monitoring System includes Sensing and Measurement Devices to detect power quality issues, Control Algorithms to generate reference signals for the VSCs, a Digital Signal Processor (DSP) or Microcontroller to execute control algorithms and process real-time data, and a User Interface for monitoring and configuring the UPQC. Protective Components such as Circuit Breakers, Fuses, and Surge Protectors ensure protection against faults and voltage spikes. Finally, Auxiliary Components like the Cooling System ensure safe operating temperatures and Communication Interfaces facilitate integration with other power system components and control systems.

A. SOLAR ENERGY

World′s energy demand increasing significantly because of population growth and industrial evolution. It is important to note that the population has increased by 2 billion just in one generation and major contribution has been given by developing countries. Preventing an energy crises in one of the most casual issues of the 21st century. Energy demand is therefore increasing fast as to meet the requirements of growing population in the world [4].

Considering energy sources is therefore very important as they play a key role in satisfying the need of the world and living population. Accessible energy is not sufficient to people, because of several reasons such as developmental profile of a country, economic status of people and nature of technological advancements of the country. Ecosystem is polluted heavily because of the emission of various gases generated from burning of fossil fuel which are readily available and commonly used for satisfying energy demand of the world. Developing countries are now put into pressure to search for the sources of energy as their population growth is high and they are seeking for economic development to become economically viable.

All the countries should be in a position to use the resources to recover energy for setting up an environment conducive for human survival for long time. However, it is not practiced properly at the moment to carry out such task since many countries relay on exhaustible energy sources than renewable energy sources. It is the known fact that many controversial issues, which lead to heavy disaster, are going on among countries because dominant parties tend to access the places which are abundant in fossil fuel reserves. Further, continuous use of non-renewable energy sources may lead to climate change, which may in turn end up with heavy natural disasters damaging ecosystems of the planet.

Solar energy could be a best option for the future world because of several reasons: First, solar energy is the most abundant energy source of renewable energy and sun emits it at the rate of 3.8×1023 kW, out of which approximately 1.8×1014 kW is intercepted by the earth [8]. Solar energy reaches the earth in various forms like heat and light. As this energy travels, majority of its portion is lost by scattering, reflection and absorption by clouds. Studies revealed that global energy demand

can be fulfilled by using solar energy satisfactorily as it is abundant in nature and freely available source of energy with no cost. Asian countries have highest potential to receive solar radiation compared to other temperate countries as sunshine duration in such countries is high in an year. It is important to note that much of solar radiation is not used and basically wasted [11]. In many countries, particularly developing countries, solar radiation is intrinsic in quantity which makes beneficial utility [12]. For example, Sri Lanka′s average solar radiation of about 15–20 MJ/m2/day (4.2 to 5.6 kWh/m2/day).

Third, utilization and tracking of solar energy do not have any harmful impact on ecosystem in which natural balance is kept consistent for the betterment of living organisms. Exploitation of fossil fuel leads to ecosystems damage which in-turn damages natural balance. Forth, solar system can effectively be used for village system, industrial operations and homes, since it is easily affordable and applicable. It has been indicated that such reserves will be running out in 2300 because of increasing energy demand. Its use however has already created significant CO2 emission with an increasing trend from 1980 to 2010 as of increased energy demand.

Therefore, this paper trends to bring overall fundamental view of solar energy for future world with logical justification. Photovoltaic technology, world′s energy scenario, remarkable research highlights of solar PV industry, application of solar energy and barriers to such industry have been discussed systematically. Readers of this paper can simply develop clear picture on solar industry and its importance for future world to be energy wise sustainable with little emissions.

Power generation by solar energy: The energy from the sun can be converted into electricity or used directly. Electricity can be generated from solar energy either directly using photovoltaic (PV) cells or indirectly using concentrated solar power (CSP) technology. Progress has been made to raise the efficiency of the PV solar cells that can now reach up to approximately 34.1% in multi-junction PV cells. Electricity generation from concentrated solar technologies has a promising future as well, especially the CSP, because of its high capacity, efficiency, and energy storage capability. Solar energy also has direct application in agriculture primarily for water treatment and irrigation [5].

Advantages of Solar Energy

The more we can capture the benefits of solar energy, the less we will rely on fossil fuels. Adding a solar energy system to your home allows you to tap into these solar energy advantages:

1. Solar energy is a renewable energy source and reduces carbon emissions -Solar energy is a renewable energy source, meaning you don’t ever use it up. Solar energy is clean. It creates no carbon emissions or other heat-trapping “greenhouse” gases. It avoids the environmental damage associated with mining or drilling for fossil fuels. Furthermore, solar energy also uses little to no water, unlike power plants that generate electricity using steam turbines.

2. Solar energy can reduce your home’s electricity bill -A solar energy system for your home can reduce your reliance on the grid and help you save on your electricity bill. Some owners of residential solar energy systems may even have excess power that they can sell to the utility. Instead of paying a utility for electricity, homeowners get paid by the utility. You may not have to buy an entire solar energy system to cut your home’s electricity bill. Simply choose solar lights, lights that are powered by the sun instead of your home’s electrical system, to help save money.

3. Solar power can get you money back through Solar Renewable Energy Credits (SRECs)-Some states offer solar renewable energy certificates (SREC). Each one represents a megawatt-hour of electricity generated through solar energy. Electricity suppliers buy these certificates to satisfy their state’s Renewable Portfolio Standard, a requirement that a certain amount of their renewable energy come from solar. You can sell SRECs for your system's output, which is another way to earn money from your investment.

4. Homes with solar panels installed may improve home value-Home buyers will likely pay more for a house with solar panels installed. Considering solar energy pros and cons, the savings on electricity bills and the money earned selling power back to the utility, all count in the plus column. Residential solar energy systems are highly valued and can increase a home's resale value. The property value of a home with solar panels can be worth up to $15,000 more than its neighbors. Solar systems are fairly easy to install and require very little maintenance. Both are handled by your solar provider, if you opt for a solar lease or power purchase agreement (PPA). Consider this as you ask yourself is solar energy worth it.

5. Solar panels have low maintenance costs-Solar panels are easy to maintain, as they have no moving parts that wear out over time. Just keep them clean and in good physical condition to keep them working properly. Between their low maintenance costs and average lifespan of 25 years, it can be easy to get your money’s worth when investing in solar panels.

6. Solar energy can generate electricity in any climate-Solar energy systems can generate electricity in any climate. One of the disadvantages of solar energy is that it’s subject to temporary weather disruption. Cloudy days reduce the amount of electricity you produce. Cold, however, doesn’t affect productivity. Snowfall can actually help your solar system, as the snow cleans the panels as it melts and sun reflected off the snow increases the amount of light hitting your panels. The result is more electricity production.

A micro-grid is a local power supply system that combines renewable energy sources, energy storage technologies, local loads, communication technology, protection components, and the control center. A PV system that is connected to the utility grid by a power inverter allows photovoltaic panels or an array to run in parallel with the electrical utility grid..A standalone PV system stores solar energy using photovoltaic panels and deep cycle batteries, creating a fully independent solar power system. However, as long as there is sufficient solar radiation during the day to recharge the batteries for use at night, this type of solar system is functional. As they are typically used in remote and rural areas, stand-alone solar systems are self-contained fixed or portable solar PV systems that are not connected to any local utilities or the main electrical grid. This typically indicates that the electrical appliances are far from the closest fixed electrical supply or that it would be expensive to extend a power line from the local grid.

However, there are now significantly more solar-powered homes that are connected to the local electricity grid than there were previously. These PV systems that are connected to the local electrical grid network at night have solar panels that can meet all or a portion of their power requirements during the day. PV systems powered by solar energy can occasionally produce more electricity than is required or used, particularly during the long, hot summer months. In most grid-connected PV systems, the excess or extra electricity is either stored in batteries or fed back into the electrical grid network.

The most important factor when integrating a PV system with the grid is power quality. This is defined as the utility's ability to give customers steady, noise-free power. The electrical equipment and components used for power distribution would start to suffer from poor power quality as frequency variations would cause processes to occur in undesirable places. There are some challenges with regard to power quality when integrating a PV system into an existing power system.

Disadvantages of Solar Energy

The disadvantages of solar energy are becoming fewer as the industry advances and grows, creating economies of scale. Technological advances are helping solar go mainstream. Here are how the disadvantages of solar energy and the pros and cons stack up.

1. The high initial costs of installing panels- The most commonly cited solar energy disadvantage, cost, is declining as the industry expands. The initial cost to buy and install the equipment is not cheap. Still, if cost is an issue, leasing options may reduce the amount of your initial outlay. If you do choose to buy, you will need to live in your home for a number of years before the system pays for itself. It's a long-term investment better suited to property owners than renters.

2. Solar energy storage is expensive -Of the disadvantages of solar energy, the temporary decline in energy production during bad weather has been a major issue. Days with low solar energy, however, are having less of an effect due to advances in battery technology. Old technology for storing solar energy, like lead acid batteries are being replaced by alternatives. Lithium ion batteries offer greater power at a lower cost. Nickel-based batteries have an extremely long life. New technologies, like flow batteries, promise scale and durable power storage.

3. Solar doesn't work for every roof type- Not every room will work well with solar panels. Orientation matters. If your roof doesn't face the sun, you won't be able to capture enough solar energy. Roofs that angle into the sun tend to work better than flat roofs. Roofing materials like asphalt shingles, metal and tiles make installing solar panels easier. If your room is made with other materials, installation may be more expensive. Part of what makes energy-efficient roofs is their ability to support solar panels.

4. Solar panels are dependent on sunlight-It obvious that solar panels need sunlight to generate electricity. They won't produce electricity at night when you need it for light and they can be inefficient during storms and gloomy days. Your solar energy system needs batteries if you plan to fully depend on solar energy to power your home. Batteries are one of the more expensive components of your system. Unlike solar panels, they do wear out and need careful maintenance to lengthen their lives. Comparing wind power vs. solar power, wind will keep generating electricity at night and during storms, as long as there is enough wind. Many people use both in residential systems.

B. HYBRID ENERGY OF SOLAR AND WIND

As the world transitions towards sustainable and renewable energy sources, the hybridization of solar and wind energy has emerged as a promising solution to meet the growing energy demands while mitigating environmental impact. Combining the strengths of both solar and wind energy, hybrid systems offer a more reliable, efficient, and resilient approach to power generation. Solar energy harnesses the power of the sun through photovoltaic (PV) cells, converting sunlight into electricity. This technology has seen significant advancements in efficiency and cost-effectiveness over the past decades, making it a popular choice for renewable energy. However, solar power generation is inherently intermittent, as it depends on daylight hours and weather conditions. Wind energy, on the other hand, captures the kinetic energy of wind through turbines, converting it into electrical power. Wind power is also subject to variability, influenced by geographic location, time of day, and seasonal patterns. Despite these challenges, wind energy remains one of the fastest-growing renewable energy sources due to its high energy yield and decreasing costs. By integrating solar and wind energy systems, hybrid energy

solutions can leverage the complementary nature of these resources. Typically, when solar energy production dips at night or during cloudy periods, wind energy can compensate, and vice versa. This synergy enhances the stability and reliability of energy supply, reducing the need for extensive energy storage or backup systems. Moreover, hybrid solar-wind systems can optimize land use and infrastructure, as both technologies can share the same site and electrical grid connections. This integration not only maximizes energy output but also reduces the overall environmental footprint of energy production. The adoption of hybrid solar-wind energy systems is poised to play a critical role in achieving global renewable energy targets and combating climate change. As technology continues to advance and economies of scale are realized, these hybrid systems are expected to become even more efficient and cost-competitive, paving the way for a sustainable energy future.

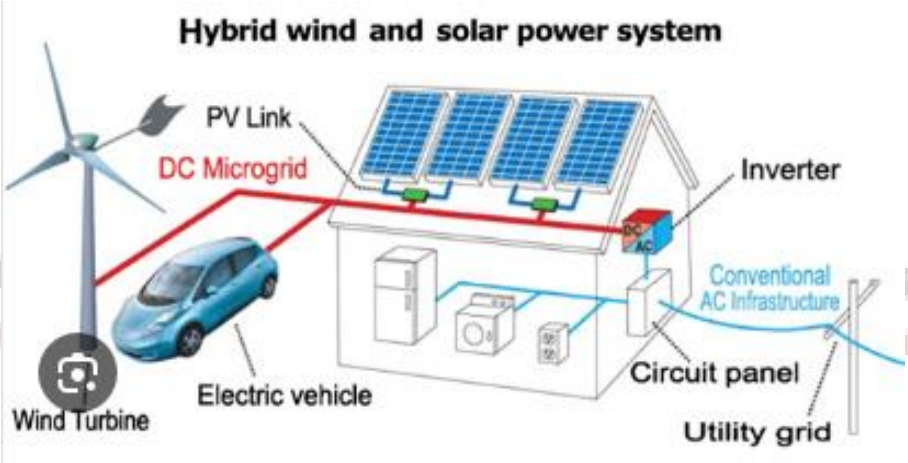

Figure 2 Hybrid wind and solar power system

C. Wind Energy System

There is a lot of wind almost everywhere in the universe. The earth's revolution and uneven warming have resulted in its presence, which suggests that wind resources will generally have an opportunity to be accessible. The wind's energy will be tiny compared to Tom's reading speed through those streams of air are by Fig. 2. It has to do with dynamic energy; at the moment, we use wind farms to generate electricity [4]. Discusses advanced power electronics technologies for wind power, global market trends, turbine concepts, and future solutions, addressing challenges and future solutions in the growing renewable energy sector [5]. A well-established renewable energy resource with significant wind potential for power generation is wind energy. It has benefits including affordability, green power, and cleanliness. Upcoming technological developments must result in wind turbines that are more reliable, strong, and affordable. This study offers creative, useful solutions together with an analysis of the wind energy markets in Romania, Europe, and the rest of the world. A windmill could be a device that modifies wind energy under rotational energy. Tom eventually developed his examining technique for vanes called cruises or blades. In the beginning, grain was processed by windmills to create sustenance [6]. There is almost always a lot of wind in the universe. Due to uneven warming, it is present throughout nature. Throughout the course of history, the windmill may have undergone numerous mechanical adjustments. Pump water may have been the subject of an urgent request. Generally speaking, wind turbines are windmills that are used to generate electricity. [7] The study presents a novel control technique that outperforms DSTATCOM in terms of power quality improvement in wind energy conversion systems by utilizing an ANN-based Distribution Static Compensator. The traditional methods of producing electricity by using non-renewable resources like coal, natural gas, oil, and so forth have a tremendous negative impact on the environment because they release a constant amount of carbon dioxide into the atmosphere, raising global temperatures.

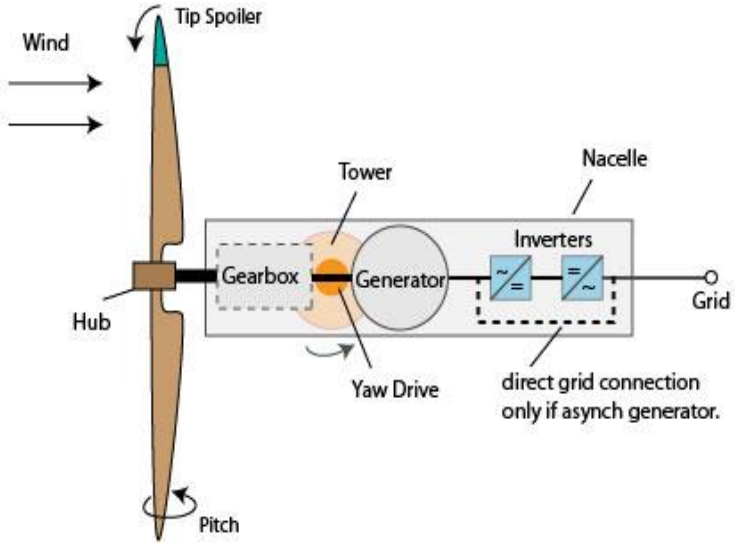

Figure 3 : Wind Energy System [8]

This phenomenon is referred to as the "greenhouse effect." Thus, with those advances in science and technology, avenues for producing energy from renewable resources—such as wind—were established. In comparison to the cost of producing power from coal and oil, the cost of claiming wind energy that is connected to the grid these days may be as high. As a result, the growing popularity of green power suggests that demand for electricity produced from non-renewable energy sources may also rise appropriately.

Since wind originates from the sun's uneven heating of the surrounding atmosphere, imperfections in the earth's ground, and the earth's rotation, wind is theoretically considered a form of solar energy. Wind power is generated by using wind turbines, which use the kinetic energy of the earth's natural airflows to generate electricity. To place it quickly, wind turbines turn flowing air into energy, which powers a power driven generator to make modern. Electricity is produced by the generator as the wind propels the blades, which turn a shaft.

Types of Wind Energy

These are the three main categories of wind power.

- **Utility-Scale Wind:** Electric utilities or power providers supply the electricity from wind turbines with capacities ranging from 100 kW to multiple megawatts to the grid and thereafter deliver it to the final user.
- **Offshore Wind:** Windmills placed in broad stretches of water. These are often larger than onshore turbines, and as turbine efficiency increases with size, larger turbines may produce more electricity.
- **Distributed or "Small" Wind:** This term refers small wind turbines under 100 kW in size that are utilized to provide direct electricity to a non-grid dwelling, farm, or small company.

II. LITERATURE REVIEW

Vítor Monteiro et al. (2023) The present study proposes a novel three-phase multi-objective "unified power quality conditioner," taking consideration into account interfaces with solar PV panels and battery energy storage. In addition to injecting electricity into the grid from PV panels or batteries or charging batteries from PV panels or the grid, the MO UPQC may compensate for power quality issues in the load side voltages and power grid side currents. Empirical findings derived from a three-phase, four-wire lab configuration showcase the efficiency and adaptability of the suggested MO-UPQC.

Q. Xu et al. (2016) focuses on The goal of a modular multiple-level matrix converter (M3C)-based single-phase unified power quality conditioning (UPQC) is to enhance the power quality of medium- and high-voltage distribution power systems. The M3C-UPQC is composed of four identical multilayer converter arms and associated filtering inductors. The design parameters for the arm inductance and sub-module capacitance are analyzed, and the operation principle and power balance of each arm are theoretically evaluated in accordance with the established equivalent circuit of M3C-UPQC. After that, an integrated control mechanism that leverages the dc circulating current to balance the instantaneous active power of each arm is designed in order to prevent the capacitive voltages from diverging intra- and inter-arm and to achieve voltage balance for M3C-UPQC. Finally, the effectiveness of the recommended control strategy is verified using an 8kVA prototype.

S. Gade et al. (2021) gives a thorough explanation of the (Unified Power Quality Conditioner) and how commonplace it is in distribution systems. The most recent addition of the active power filter family is the UPQC. Power factor correction,

integrating renewable energy systems into the distribution network, and fixing voltage and current PQ issues are all aided by it. This study examines a number of topologies, control theories, compensation schemes, and new technology advancements. The characteristics of UPQC have been distilled for future applications in more than 160 research papers. The investigation's findings are used to discuss the UPQC's future course. It is anticipated that this work would be crucial in assisting researchers in applying the UPQC.

M. Makkiabadi et al. (2021) Due to the awareness of renewable energy technology like solar farms, wind turbines, heat sources, and even waves, the amount of power produced globally has increased. Due to its closeness to the equator (25.2969°N), Iran is a prime location for solar power. Approximately 900 MW of solar power, or roughly 480 solar power plants and 420 MW of residential solar power plants, were used to meet Iran's electricity needs in 2020. This compares favorably to the global average. Yazd, Fars, and Kerman are Iran's three largest provinces, with respective solar energy output of 68 MW, 58 MW, and 47 MW. There is a sizable area of undeveloped land in Iran that might be utilized to construct solar power facilities. This article investigates Iran's electricity production capacity. According to the results, the Sirijan solar power plant can be built for $16.14 million with a payback period of 4 years. According to Homer Software, July is the month with the highest electricity production.

D Kamani et al. (2023) This research has two primary parts. (a) A long-term prediction (EEC) of the amount of electricity consumed in a subset of industrialized and developing countries; (b) an examination of several scenarios for the usage of wind and solar energy at 1%, 2%, and 3% EES. Artificial neural network (ANN) modeling is used to make predictions based on socioeconomic data from the last 30 years (1990-2019), including GDP, population, imports, exports, and import-export (IMP, EXP, and EEC). The developed nations of the US and the OECD, as well as the growing economies of China, India, and Iran, are the subjects of the analysis. ANN structure was optimized for long-term EEC prediction using Particle Swarm Optimization (PSO) and Extended Particle Swarm Optimization (E-PSO) algorithms. The results show that the E-PSO-ANN model can significantly reduce both EEC and CO2 emissions when applied to the SRE-3% scenario (3% solar and wind energy usage), achieving average reductions of 55% and 54%. It is therefore consistent with the objectives of the Paris Agreement.

III. CONCLUSION

The integration of the Unified Power Quality Conditioner (UPQC) in hybrid solar-wind energy systems marks a significant step forward in addressing the power quality challenges associated with renewable energy sources. Hybrid systems that combine solar and wind energy can achieve improved reliability and efficiency, thanks to the UPQC's ability to mitigate voltage and current disturbances. The UPQC's series and shunt active filters are essential in maintaining a stable and high-quality power supply. As the use of distributed generation sources continues to grow, the application of UPQC in hybrid systems offers a promising solution to enhance power quality and overall system performance. Ongoing research and advancements in UPQC design and control strategies are expected to further increase its effectiveness, contributing to the development of more resilient and sustainable hybrid energy systems.

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