Role of Energy Storage Systems in Power Quality Enhancement for Renewable Energy Integration

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Abstract

Incorporating renewable energy sources such as solar and wind into the power grid is essential for achieving a sustainable and low-carbon energy system. Although renewable energy sources have the potential to improve grid stability and electricity quality, their intermittent and unpredictable nature poses challenges in these areas. To combat these issues, Energy Storage Systems (ESS) are vital, since they improve power quality by reducing variations in renewable supply. Renewable Energy Sources (RES) inverters linked to the grid are the subject of this paper's control technique. The grid linked inverters may be used to their full potential in a three-phase, four-wire distribution system. Distribution systems that use power electronic converters/inverters are progressively connecting Renewable Energy Sources (RES) to meet the rising demand for electricity. We confirm this novel control paradigm with laboratory experimental findings based on digital signal processors and show it off with comprehensive MATLAB/Simulink simulation simulations. Modern power distribution networks may improve power quality, grid stability, and energy efficiency by combining renewable energy sources, improved APFs, and VSCs, as this research highlights.

Keywords: Renewable Energy, Power Quality, Grid, Voltage, Circuit

I. INTRODUCTION

There is now a greater focus on sustainable, low-carbon energy solutions due to the dramatic shift in the global energy environment caused by the rising need for renewable energy sources. There is hope for a future without traditional fossil fuels thanks to renewable energy sources like solar and wind power. Nevertheless, incorporating these resources into current power networks is made more difficult by their intermittent and fluctuating characteristics. Energy Storage Systems (ESS) have become an important tool for overcoming these obstacles and guaranteeing a consistent and dependable energy supply. ESS may improve power quality and make renewable energy sources more easily integrated into the grid by reducing power production variations caused by renewables' unpredictability. Ensuring that the transmitted power is steady, clean, and free of disturbances that might adversely impact sensitive electrical equipment and devices is what power quality is all about. This includes keeping voltage, frequency, and other electrical characteristics within acceptable ranges.

As a buffer between demand and renewable production, energy storage is crucial for better power quality. For instance, ESS may store extra energy during times of strong renewable energy output, which helps to minimize grid overload and waste. By releasing stored energy at times of high demand or low renewable production, ESS contributes to grid stability and ensures a steady supply of electricity. When dealing with power quality concerns like harmonics, voltage sags, and frequency deviations—all of which may be caused by renewable energy generation—this feature is very important for regulating voltage and frequency changes. Power quality is guaranteed to be enhanced by ESS since it helps to maintain the optimum operating conditions for power systems by smoothing out these variations.

Battery energy storage systems (BESS), pumped hydro storage, flywheels, and compressed air energy storage (CAES) are among the frequently used energy storage technologies for improving power quality. Because of its scalability, rapid reaction time, and great energy efficiency, BESS, especially flow and lithium-ion batteries, have become more popular. These systems provide solutions for both the short and long term of energy management by storing excess production and releasing it when required. In addition, BESS is now in a better position to be a practical choice for large-scale renewable energy integration because to developments in battery technology, which have boosted storage capacity, decreased prices, and improved cycle life.

Pumped hydro storage, on the other hand, has a history of use for large-scale energy storage. In order to generate electricity when demand is high, water is pumped to a higher level and then released via turbines when demand is low. Geographic and environmental limitations restrict its application, despite its great efficiency and ability to provide large-scale energy storage. The fast responsiveness and long cycle life of flywheels make them ideal for stabilizing short-term variations in power quality; they store energy via rotating motion. CAES is an additional potential technology that uses compressed air to store energy. When demand is low, this compressed air is released into subterranean caverns to power turbines. The need for certain geological formations prevents CAES from being widely used, despite its bigger operational size.

To guarantee that power quality is continuously improved, the integration of ESS into renewable energy systems also poses the difficulty of selecting the best size, location, and operating methods of the storage. To get the most out of energy storage systems in terms of improving power quality, grid operators need to think about things like energy demand, generation predictions, and system characteristics. To make sure that ESS works well and fits in with the grid's needs and renewable energy sources, sophisticated control mechanisms are necessary. These include automated demand response and real-time monitoring. Along with smart grid technologies that improve the functioning of the overall energy system, the synergy between ESS and renewable energy sources goes beyond mere energy storage.

Financial considerations are critical when deciding to use ESS for the purpose of improving electricity quality. Improved power quality, grid stability, and decreased demand for backup fossil fuel production may give a significant return on investment, even though the initial capital expenditures of energy storage technologies remain a barrier to wider implementation. A more sustainable, reliable, and cost-effective electricity grid is within reach, thanks to the growing recognition of ESS by both utilities and policymakers. Therefore, incentives, subsidies, and enabling regulatory frameworks are being put in place to encourage the use of energy storage technology. Additionally, ESS are anticipated to have future cost reductions because to ongoing innovation in storage technologies and economies of scale, which will make them more accessible and financially feasible for renewable energy projects of all sizes and locations.

Role of Energy Storage Systems in Power Quality Enhancement

Because renewable energy sources are intermittent and changeable, incorporating them into current power systems has presented considerable hurdles. Although these sources are crucial for meeting sustainable energy targets and lowering carbon emissions, power quality problems such voltage fluctuations, frequency instability, harmonic distortions, and transient disruptions are common due to their unpredictability. In order to alleviate these problems and guarantee a consistent and high-quality supply of electricity, Energy Storage Systems (ESS) are crucial. Voltage regulation, frequency stability, load balancing, and harmonic reduction are just a few of the many functions that ESS offers, which is why it is an essential component of contemporary energy systems.

1. Voltage Regulation

One of the most important aspects of power quality is voltage stability. Voltage fluctuations are a common side effect of using renewable energy sources such as solar and wind. Cloud cover or a slowing wind speed, for example, might cause voltage sags by drastically reducing power production. Voltage spikes, on the other hand, may occur when there is an excess of generation during times of low demand. As a reactive power source or sink, ESS assists with these problems. To maintain consistent voltage levels, systems such as supercapacitors and battery energy storage systems (BESS) may absorb reactive power or inject it within milliseconds. Additionally, ESS allows for accurate voltage management across various grid points when linked with modern power electronic converters, guaranteeing that voltage stays within permissible limits.

2. Frequency Stabilization

In order to keep the grid frequency stable, it is essential that power production and consumption be in balance. Large spinning generators' inertia is used by conventional power systems to dampen small imbalances. On the other hand, frequency variations are more likely to occur on the grid when renewable energy technologies do not have intrinsic inertia. In response, ESS offers synthetic inertia and rapid frequency responsiveness. Technologies like flywheels, supercapacitors, and advanced BESS can rapidly inject or absorb energy to stabilize frequency during disturbances. When renewable supply suddenly drops, ESS may release stored energy to keep the grid running at a constant frequency; when renewable generation is abundant, it can absorb the extra power. In order to meet frequency stability norms, this capacity is vital for grids that have a large penetration of renewable energy sources.

3. Harmonic Mitigation

Devices used in renewable energy systems, such as inverters, may create harmonics due to their nonlinear nature, which is a major problem with power quality. Problems with equipment, higher losses, and overheating may result from these distortions. A key component in harmonic mitigation is ESS in conjunction with active power filters. Electric power system harmonic suppression (ESS) works by introducing grid currents that cancel each other out, so restoring the integrity of the waveform. In addition, by actively modifying the current waveform to reduce distortions, ESS systems that include state-of-the-art inverters may operate as harmonic compensators. This feature is especially useful in distributed energy resource and microgrid configurations, where harmonic pollution is more noticeable.

4. Load Leveling and Peak Shaving

Periods of over-generation or under-generation may occur when renewable energy production does not match consumption patterns. ESS solves this problem by doing peak shaving and load leveling operations. By storing extra energy, ESS prevents voltage spikes and reduces the need to limit renewable sources when demand is low and renewable output is high. On the other side, ESS releases its stored energy at times of high demand, relieving grid pressure and cutting down on costly peaking power units. In addition to making renewable energy systems more economically viable, this improves power quality by optimizing energy usage and keeping the energy flow steady.

5. Support during Grid Faults

When grid faults or disruptions occur, ESS is there to help, improving the dependability and quality of electricity. An important feature of ESS is fault ride-through capability, which allows the system to keep running even when there is a temporary drop in voltage or change in frequency. This is especially helpful in renewable energy systems since they are less likely to be unstable during breakdowns due to the absence of mechanical inertia. On top of that, ESS can help with black start capabilities, which is providing the initial power needed to restore the grid during a blackout. Isolated microgrids and hybrid renewable energy systems benefit greatly from this feature.

6. Energy Time-Shifting

Energy time-shifting, also known as arbitrage, is a crucial ESS feature that indirectly improves power quality. A more stable and predictable energy flow may be achieved using ESS by storing energy during times of low demand and releasing it during times of high demand. This lessens the possibility of voltage and frequency oscillations brought on by unexpected shifts in demand and supply. Energy time-shifting on a large scale is often accomplished using technologies like Pumped Hydro Storage (PHS) and Compressed Air Energy Storage (CAES), although BESS works well for smaller-scale applications.

II. REVIEW OF LITERATURE

Ali, Muftah. (2023) Issues with the compensation of power quality (PQ) are becoming more prevalent in the modern day. Renewable energy source (RES) solution implementation is of utmost importance in this scenario. Smart grids, which replace conventional electrical power networks, rely heavily on renewable energy sources (RES) and power electronics converters.

Important technologies such as electric mobility, renewable energies, and energy storage systems cannot be implemented without these converters. Therefore, in this setting, PQ issues become more important. This article seeks to shed light on the main occurrences, causes, and effects of PQ problems in smart grids from a variety of angles. In addition, the study classifies and analyzes the main PQ difficulties in detail, sorting them according to how well they match up with existing standards. Also included is an evaluation of PQ issues related to RES and electric transportation integration.

Sayed, Enas et al., (2023) The need for sustainable and environmentally friendly alternatives to fossil fuels has been on the rise due to the fact that their usage has accelerated climate change and global warming. Everyone agrees that renewable energy sources will soon be the best alternative to fossil fuels. Solar, wind, and biomass energy are just a few examples of the renewables that have made great strides toward commercial-scale production at reasonable rates. Innovations in technology have allowed for more efficient and cost-effective utilization of renewable energy sources, which has contributed to this achievement. The dispatchability of renewable energy sources, of which storage is a critical component, needs more investigation in order to optimize their capacity. A well-managed hybrid renewable energy system is also required to strike a balance between the production, consumption, and storage of the several renewable energy sources. Solar, wind, biomass, and hybrid renewable energy sources are the primary ones covered in this study, along with their advancement on a commercial scale. Additionally, we cover energy management in relation to different renewable energy sources and storage technologies. The study concludes by outlining the latest developments in environmentally friendly hydrogen generation and fuel cells, which may open the door for widespread commercial use of renewable energy.

Worku, Muhammed. (2022) There has been tremendous recent progress in securing more reliable electric power and reducing emissions of greenhouse gases. Over the last decade, there has been a dramatic growth in the integration of PV and wind, two types of intermittent RESs, into the current system. But there are a lot of operational and control issues that this integration causes, which makes the grid less dependable and stable. Among the many obstacles are concerns with reactive power support, power quality, voltage and angular stability, and fault ride-through capabilities, as well as generation unpredictability. Unpredictable meteorological factors, such wind speed and sunlight, cause RES-generated electricity to vary. By storing and making available on demand the extra electricity that is produced, energy storage systems (ESSs) are crucial in reducing the volatility. This article provides a comprehensive overview of energy storage systems, touching on topics such as the many types of storage technologies, the power converters that run some of these systems, and the primary uses for grid integration. Researchers choose the most effective and technologically advanced energy storage technology according to its practicality and cost-effectiveness; this study will serve as a reference for power utilities.

Atawi, Ibrahem et al., (2022) Several problems with dependability, stability, and power quality are caused by the intermittent nature of the electricity that is generated by renewable energy sources (RESs), which is being used more often. ESSs provide a potential answer to these connected RES problems in some cases. So, several ESS methods were put out there to address these problems; nevertheless, there isn't just one ESS that can handle everything; each one has its own set of advantages and disadvantages when it comes to system performance as a whole. The effectiveness in terms of price, lifetime, power and energy density, and dynamic responsiveness, as well as the limitations of a single ESS, are major contributors to this. Hybrid energy storage systems (HESSs) that combine two or more ESSs seem to be a good way to get around the tradeoff problem that comes with employing just one ESS system. In light of the many benefits of combining many ESSs into a single system, numerous studies have recently examined developing and proposing various HESSs for various purposes. The literature does not yet provide a thorough examination of HESS-integrated RE, despite the fact that these individual approaches have been extensively reported. This work is to examine and assess the significance and effect of HESSs in the presence of renewable energy towards sustainable development. Its innovative addition to the literature will help scholars in this area better understand this burgeoning subject. Specifically, this article discusses and analyzes the current state and emerging trend of HESSs in RESs on a worldwide scale, as well as their idea, design, classifications, and a thorough comparison with the primary ESS characteristics. We have examined the growing significance of HESSs by looking at their uses and advantages. We have examined the benefits and drawbacks of recent control and optimization approaches of HESSs linked to RESs. Lastly, this article has also brought attention to new obstacles and open topics in the pursuit of greener, more efficient energy. We expect that more work will be put into developing an improved HESS for optimum operation of renewable energy in the future, thanks to all the highlighted insights of this research.

Daud, Muhamad Zalani et al., (2012) When it comes to operational concerns with distributed generation (DG) technology integration into power grids, energy storage systems (ESS) have lately emerged as an essential answer. The majority of these applications deal with managing the energy between distributed generation and electrical grids, or with improving power quality. The current state of ESS applications and research on a global scale is reviewed in this study. Methods employed in studies of power system modeling and the implementation of battery energy storage system (BESS) technology to support utility grids are of special interest. Methods for both static and dynamic modeling using BESS are also covered.

Nieto, Alejandro. (2016) The quality of the provided power has degraded due to the growing number of distributed generating units connected to power grids. This is shown in variations in current, voltage, and frequency from their normal values, which may cause equipment to malfunction or operate incorrectly. A possible answer to this issue is ESS, which may stabilize the grid by regulating the electricity fed into it from distributed generating units. In this research, we first examine the effects of a wind power plant—a dispersed generating unit—on the power grid. Then, we incorporate ESS with varying capacities into the system to see how the power quality improves. Results like this may be lifesavers for system operators as they demonstrate the many benefits of integrating ESS into electricity networks.

III. SYSTEM FRAMEWORK

Topology

By injecting a compensating current that eliminates harmonics in the line current, active power filters eliminate undesirable harmonic currents in power electronic systems. Shunt active power filters inject a current that is equivalent to but opposite of the load current's harmonics in order to compensate for them. The use of four leg converters has traditionally been the basis for four-wire APFs. When compared to the traditional three-leg, four-wire architecture, this one has shown to be more controllable. This research demonstrates that a three-phase, four-wire system can nevertheless be effectively controlled.

Wind Turbine

The energy from the wind may be transformed into electricity by means of wind turbines. Within the turbine, there is an electric generator that transforms mechanical energy into electrical power. There are wind turbine systems available with power ratings between 50W and 2-3 MW. Wind turbines can only generate electricity at certain wind speeds. Transmission lines in rural regions, as well as energy generation and consumption, are powered by wind power.

Dimensions, axis, number of blades, produced power, and other physical characteristics allow for the categorization of wind turbines. Here are three types of turbines: three-blade, two-blade, and one-blade.

Voltage Source Converter (VSC)

Voltage source converters (VSCs) are electronic power devices that may be connected in either a shunt or a parallel configuration to the system. The generation of a sinusoidal voltage allows one to get any magnitude, frequency, and phase angle that one desires. Aside from that, it splits the DC voltage across the storage devices into three AC voltages. On top of that, it may generate or consume reactive power. In capacitive mode, the VSC is defined as one whose output voltage exceeds the voltages at the AC bus terminals. As a result, the AC system will counteract the reactive power. To activate it, just connect an IGBT in anti-parallel to a diode. The three-phase, four-leg VSI may be modelled in Simulink with the help of an IGBT.

Controller for Active Power Filter

At regular intervals, the reference voltage Vdc* is monitored and compared to the dc link voltage Vdc. A PI-controller handles the erroneous signal. The output of the pi controller is known as Im. In order to get the reference current templates (Ia*, Ib*, and Ic*), we multiply the maximum value (Im) by the three-unit sine vectors (Ua, Ub, and Uc) that are in phase with the three source voltages. These unit sine vectors are created by adding the three line-to-neutral voltages that were measured. When all balanced grid currents have been added together, the reference grid neutral current (In*) becomes zero. Multiplying the magnitude of Im with the phases (Ua, Ub, and Uc) yields the three phase reference supply currents (Ia*, Ib*, and Ic*).
To create a unity vector template, the phase locked loop (PLL) yields the grid synchronizing angle (θ).

$U_a = \mathrm{Sin}(\theta)$

$U_b = \mathrm{Sin}\,(\theta-\frac{2\pi}{3})$

$U_c = \mathrm{Sin}\,(\theta+\frac{2\pi}{3})$

The reference three-phase grid currents' instantaneous values are calculated as

$I_a^* = I_m . U_a$

$I_b^* = I_m . U_b$

$I_c^* = I_m . U_c$

The neutral current is considered as

$I_n^* = 0$

D-Statcom

Reactive power generation and absorption are also within D-STATCOM's capabilities. The D-STATCOM is considered to be in capacitive mode if the VSC output voltage is higher than the terminal voltages of the AC bus. Consequently, it controls voltage drops and compensates reactive power via the AC system. These voltages are in phase and connected to the AC system via coupling transformers' reactance.
The active and reactive power exchanges between the D-STATCOM and AC system may be successfully managed by adjusting the phase and amplitude of the DSTATCOM output voltages. Energy storage also frequently supplies the converter with a DC voltage.

IV. SIMULINK CIRCUIT

A MATLAB-based computer simulation is used to evaluate the proposed structure's performance.

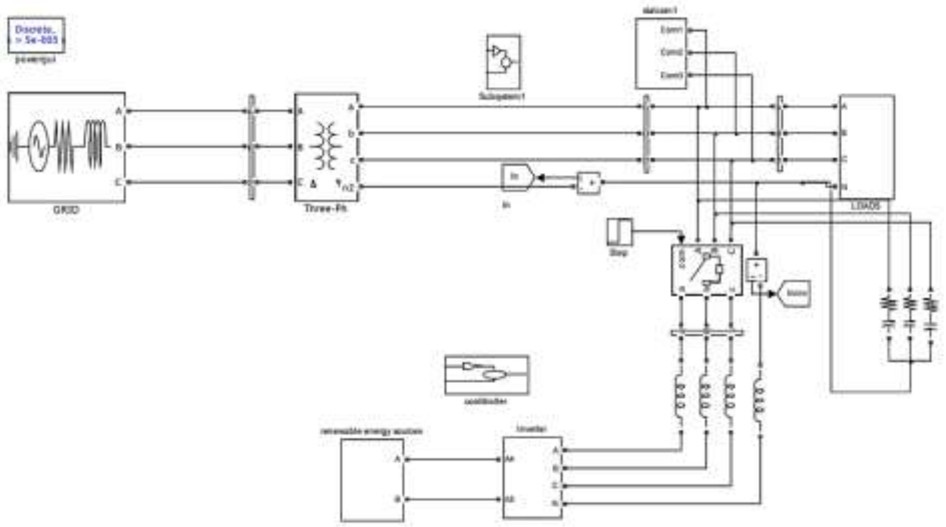

Figure 1: Simulation Diagram of proposed circuit

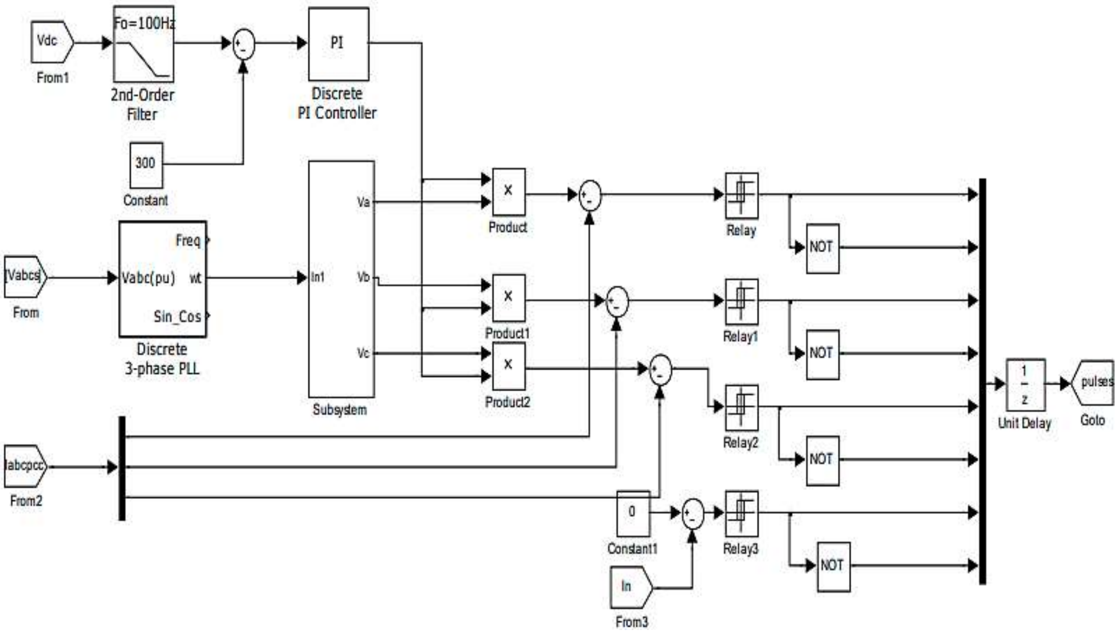

Figure 2: Simulation Diagram of Control circuit

In order to achieve several objectives, a comprehensive simulation study is carried out using MATLAB/Simulink to test the proposed control method for grid-interfaced DG systems connected to a 3-phase 4-wire network. An active 4-leg current-controlled voltage source inverter is used to supply balanced sinusoidal grid currents at unity power factor (UPF) in situations where the amount of renewable energy produced varies. Even though the nonlinear demand at PCC is very uneven, this is still done. A renewable energy source (RES) with a variable output power can be connected to the grid-interfacing inverter through its dc-link. Reactive power, harmonics, and unbalance compensation are needed by the unbalanced, three-phase, and four-wire nonlinear load that is attached to PCC. Figure 3 shows the waveforms of the following: grid voltage, grid currents, and unbalanced load current, and inverter currents. The inverter, the load, and the grid all have active and reactive powers denoted as ($Plnad$, $Qload$).

Assuming both the grid and inverter active-reactive powers are positive, power is transmitted from the grid side to the PCC. The load is absorbing both reactive and active energy if the indication is positive. Since the grid-interfacing inverter is not yet connected to the network, all of the load power requirements are met by the grid when the system starts up.

V. RESULTS AND DISCUSSION

As seen in Figure 3, there are three currents: the source current, the load current, and the inverter compensating current. When the timer hits 0.7 seconds, the inverter starts working. Figure 3 (a) indicates that a nonlinear load is responsible for the source current's non-sinusoidal behavior from zero to seventy-seven seconds. After 0.7 seconds, the inverter balanced the non-sinusoidal wave, and the waveform became sinusoidal. The load current waveform is shown in Figure 3 (c). Figure 3 (d) shows the compensating current, which is supplied by the inverter.

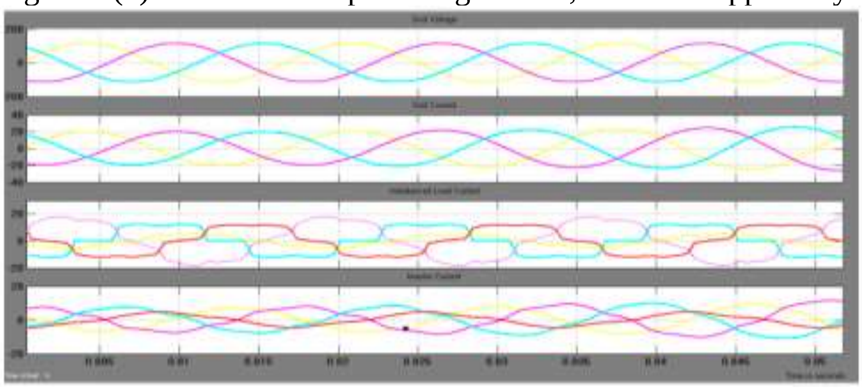

Figure 3: Simulation results: (a) Grid voltages, (b) Grid Currents Unbalanced load currents, (d) Inverter Currents

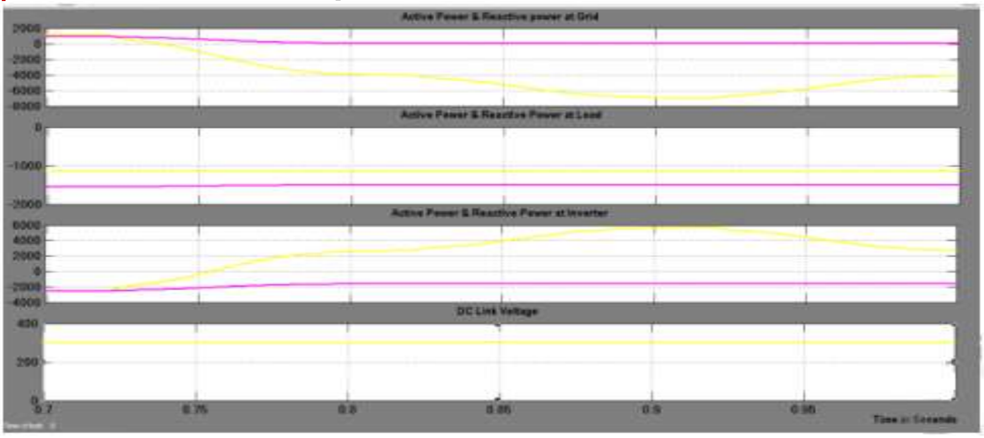

Figure 4: Simulation results: (a) PQ-Grid, (b) PQ-Load, (c) PQ-Inverter, dc-link voltage

VI. CONCLUSION

The system efficiently controls reactive power, makes ensuring the grid currents are balanced and sinusoidal, and correct for harmonic distortions by integrating renewable energy sources like wind turbines with voltage source inverters and shunt active power filters. By demonstrating effective harmonic correction and enhanced power quality in the face of variable renewable energy production, the simulation findings indicate the practicability of the control technique. The system's capacity to regulate grid voltages and preserve unity power factor is additional evidence of its promise in contemporary power distribution systems. By improving the stability and dependability of networks with different generation and load profiles, this strategy helps optimize energy use and might be a great option for future smart grid applications.

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