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A hybrid harmonic mitigation strategy for smart grid integration of solar PV systems in developing power networks

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ABSTRACT

The world shift to renewable energy has drastically changed the power syster models due to climate concerns and decarbonization efforts. Solar PV has emerge as one of the renewable technologies because of its cost that is falling steadily scale, and negligible environmental impact. Nonetheless, the consideration of sola PV in ageing grid systems, especially in developing countries presents technica issues, the most prominent of which, the harmonic distortion by power electroni converters in full interaction with the nonlinear loads. This causes instability c voltages, decreases equipment longevity and system performance. However, smai grid technologies provide advanced control and sensing capabilities, however, th implementation of smart grids in resource-constrained environments is minimal a the moment. This paper puts forward a hybrid harmonic mitigation approach whic is weak grid specific and involves a combination of optimized Maximum Powe Point Tracking (MPPT), Proportional-Integral (PI) control as well as a two-stag passive-active filtering system. It has been proven with simulations i MATLAB/Simulink that inverter synchronization, dynamic response and uniforr Total Harmonic Distortion (THD) reduction to 5% or below, require better inverte synchronization, better inverter operation and constant simulation results, a indicated by Fast Fourier Transform (FFT) analysis under different load condition and all of these are within the standards of IEEE 519. This contributes to the reaso why the proposed system is a cost-effective and scalable solution to the utilities i the emerging economies, especially due to its modular nature that enables it implementation to happen in phases. The publication adds a viable platform t improve the level of power and stability during the shift toward cleaner and smarte energy systems.

1. Introduction

Today, as part of a global call for cleaner energy alternatives, Solar PV systems have been thrust into the centre of gravity in electricity generation systems of almost all countries. Making renewable integration paramount in energy policy worldwide is the result of the international climate agreements and decarbonization targets. The factors, declining costs of installation, modular design, and enhanced reliability across geography and climatic conditions, have not failed to show the strong potential of PV systems [1,2]. However, the integration of PV systems into the conventional power distribution networks with old or poorly maintained grid infrastructures poses several technical challenges. Most existing grid networks were not designed to handle the intermittency of distributed generation, leading to inefficiencies in impulsive use. One of the significant impacts of harmonic distortions is due to the interaction between the nonlinear loads and the PV inverters, which

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destabilize voltage profiles, increase the rate of degradation of equipment, and decrease the overall system efficiency [3]. Although smart grid technologies lend themselves for easily implementing real-time monitoring and adaptive control capabilities, their implementation in many developing economies is limited by the continued presence of financial and technical constraints [4]. These constraints highlight the importance of transitional measures that effectively control the current issues of poor power quality as well as establish the basis for more extensive smart grid implementation in the future.

1.1 Background

Solar PV systems have become one of the main avenues for entry into national and international energy policies, considering the possibilities projected by the International Energy Agency (IEA) for the solar to be able to cover the majority of the electricity generation in the years to come [5]. Smart grid technologies are coming to be acknowledged as necessary for the accommodation of solar variability through different mechanisms such as real-time energy management, flexible demand response and two-way power exchange. Despite improvements, power quality issues remain, as harmonic distortions by inverter-based systems are still an issue at some times. More specifically, these distortions are being exacerbated by the growing dominance of nonlinear loads associated with growing numbers of residential to commercial and industrial consumers. It is challenging to cover this evolving complexity with conventional filtering techniques [6]. Passive filters are a very cheap, but inflexible solution and only generally work in dynamic conditions. On the other hand active filtering offers adjustable control but they are expensive and complex. Hence, an optimum solution will be a synergy between reliable hardware and intelligent control's solutions to maintain high quality and stable power supply especially in developing network scenarios.

1.2 Motivation

The meteoric introduction of solar PV systems in Pakistan is one aspect of an overall trend developing in other developing countries that are moving towards cleaner forms of energy. The power grid of Pakistan has been degrading and inflexible with limited infrastructure needed to overcome the harmful disturbances inflicted by the inverters [7]. Field assessments reveal a recurring situation of violating the limits of the parameters of the secretion of the values at the circuit breaker for the standard (IEEE 519) for the values of harmonic currents "THD", observed when operating automated systems of variable load [8]. It is an unfortunate fact that mitigation solutions tend to ignore the specific needs of such changing systems, especially in low-resource environments. Moreover, in the actual layout, the use of harmonic analysis tool such as FFT is also little exploited. The robustness of the waveform already in place becomes essential not only for how long such systems last, but by extension, the stability of the grid as the amount of solar penetration grows. This research focuses on this task by developing a cost-effective and context compatible harmonic mitigation framework that is resilient to real-world constraints in a variable environment and has a strong technical support, without the need of a complete refurbishment of the existing infrastructure.

1.3 Research Problem

Mitigation tactics are rarely implemented together for both inverter-level control and hardware filtering; instead, they are more or less instituted in isolated systems. Most of these have been designed around ideal operating conditions, such as stable irradiance or balanced load profiles, which in reality occur intermittently over the lifetime of grid-connected systems [9-10]. In practice, grid dynamics include load switching, unbalanced conditions caused by faults, and sudden irradiance fluctuations due to the weather. The gap between the simulation model and real operation limits the conventional solutions. Thus, under typical but variable power conditions, it becomes helpful to understand how integrated control systems like real-time power point tracking with adaptive inverter response and hybrid filtering can be coupled to achieve better harmonic performance.

1.4 Proposed Solution

In this research, a hybrid harmonic reduction model for a solar-integrated distribution network in a transition grid status is developed. The system consists of an optimized MPPT strategy for solar generation, a PI-controlled inverter system and a coordinated filtering stage that combines passive and active components to provide a trade-off among price, control complexities, and real-time adaptability. This system is subjected to severe tests for different operating conditions using MATLAB/Simulink simulations with pure resistive loads, combined resistive-Inductance-Capacitance (RLC) loads and nonlinear (semiconductor and Power electronics devices) loading conditions. FFT spectral analysis enables to capture the dynamic behaviour and assure performance improvements in harmonic distortion analysis. This framework offers better power conversion efficiency and stability of voltage waveforms in irregular environments that is suitable for developing grid conditions with limited smart grid infrastructure.

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1.5 Research Objectives

This research is organized on the following specific objectives:

1. Develop a model for PV-grid interaction in real world using dynamic load conditions with MATLAB/Simulink tool.
2. Use of MPPT algorithms and PI controlled inverters with dual stage filtering scheme.
3. Analyse harmonic distortions with FFT analyser and validate the harmonics with IEEE 519 standards.

The structure in the remaining sections is as follows: Section 2 gives literature review of harmonic mitigation techniques; Section 3 presents modelling and simulation methodology; Section 4 presents results and discussion from the study; and Section 5 concludes the paper with important findings and recommendations for future study.

2. Related Work

Harmonic mitigation in PV systems has recently been pointed out. The need has taken on greater relevance as a result of the rising penetration of renewable energy within smart grid systems. The efficiency and reliability of such systems primarily depend on power quality maintenance as harmonic distortions have now become an important concern.

Mahapatra and Panda have handled the concerns of adaptive harmonic filtering of PV systems under loading conditions in [11]. The on-line estimation of reference currents and hysteresis control are used in the proposed methodology which responds effectively for the changes in load. Although the results show a decrease in harmonic distortion, applicability under ideal conditions makes it impossible to use in most variable and real-world environments. Notwithstanding this shortcoming, the current work provides some very interesting insights in terms of the degree of adaptability required to be achieved from moderate control strategies.

In a related study, Abdelaziz et al. [12] presented a machine learning based approach for harmonic compensation in real time in smart grids. The model uses decision trees and support vector machines (SVMs) to predict and analyse the harmonic disturbances with a high level of accuracy. Although this project is on the technically inspiring side, the project is limited by its complexity and high processing requirements, and hence would be less applicable in resource-constrained environments. Unlike this research focuses on the simplified way to hybrid, and in this research, the other aspect will be explored, which also addresses the growing potential of artificial intelligence for solving the power quality issue.

Ali *et al.* [13] presented the multilevel inverters using sinusoidal pulse width modulation (PWM) and voltage balancing to alleviate THD. However, since assumptions were made on fixed irradiance and uniform loads, the application of this methodology is further limited in adaptability despite demonstrating effective performance in steady-state conditions. Hence, this study resonates with hardware optimization features but does not carry out hybrid or intelligent controls.

Rashid *et al.* [14] developed a passive LC filter design aspect to improve the quality of the power supplied by PV systems. The simulation proved the economics of a cost-effective harmonic suppression under a developed static condition. The approach lacks acuteness for dynamic loads, in any case. The study would thus serve as an initial reference for passive filtering within adaptive control.

Refaat and Massoud [15] gave a full review of the hybrid filtering methods that comprise passive, active, and mixed approaches. However, it did not yield any original experiments; such a review defines the general working strength of each method. Such a synthesis would help frame the current study's hybrid design approach.

Aamir *et al.* [16] analyzed the effect of partial shading on THD in PV systems through obtaining simulations in MATLAB. No mitigation solution was proposed in the study, but it presented a perspective on how environmental elements modify the behaviour of harmonics. It helps provide a more accurate setting for the challenges of designing responsive harmonic control for real-world conditions.

Dhillon and Sinha [17] gave a comparative theoretical study of harmonics synchronization techniques for renewable energy systems. This study sought to compare signal match and frequency coupling model, neither of which had been proven to be valid in the experiment. While not exactly the active mitigation, it provides some conceptual addition to understanding the harmonics behaviour in renewable integrated grids.

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Table 1

Summary of Key Literature on Harmonic Mitigation in PV Systems

Reference	Primary Technique	Strengths	Limitation
[11]	Adaptive harmonic filtering	Real-time adaptability	Ideal grid assumption
[12]	Machine learning compensation	High prediction accuracy	Computationally intensive
[13]	Multilevel inverter control	Effective steady-state THD reduction	Static conditions only
[14]	Passive LC filter	Cost-effective, simple	No adaptability
[15]	Hybrid filtering review	Broad technical overview	No experimental proof
[16]	Control under partial shading	Environmental focus	No filtering solution
[17]	Synchronization comparison	Conceptual clarity	Lacks practical validation
[18]	LCL filter for inverters	Strong filter-inverter synergy	Static grid assumptions
[22]	Unified Power Quality Conditioner	Simultaneous voltage and current compensation	High cost and complex control
[23]	Fractional Order Notch Filter	Precise harmonic suppression	Limited to selected harmonics
[24]	Grid-Forming Active Power Filter	Stable and integrated harmonic control	Performance depends on grid impedance
[25]	Adaptive Harmonic Control	Real-time adaptability under weak grids	Requires high computational effort

Minh and Smith [18] discussed LCL filter based inverter designing for improved grid integration. Their simulations validated filter parameter optimisation and THD reduction although this belongs to static conditions. It complements the current study concerning the emphasis on optimal filter-inverter coordination that is necessary for harmonic distortion minimization.

Reguieg et al. [22] devised an integrated photovoltaic-based Power Quality Optimizer based on Unified Power Quality Conditioner (PV-PO-UPQC) in order to improve grid stability and impedance of voltage and current. The method is efficient to make up for voltage sags, harmonic distortions and reactive power and keep the supply steady in the face of renewable energy fluctuations. However, implementation of the system has a high cost as well as increased complexity of control and limited scalability for small distributed networks.

Ech-cherki et al. [23] proposed a high order Sliding Mode Control (SMC) to control the grid integration of photovoltaic systems. The proposed controller can efficiently decrease the harmonic distortion and the improvement in the transient response and stable the DC-link voltage with different irradiance levels. Despite its robustness and fairly high dynamic performance, the complexity and need for accurate parameter tuning of the technique have been shown to limit its adaptation to real-time embedded applications.

Kaur and Bath [24] presented a detailed review on harmonic distortion in power systems caused by electronic converters and integrating renewable energy. The study revealed the main sources of harmonic pollution, comparative techniques for mitigation and their performance under a variety of grid conditions. While the review gives strong theoretical insight and the classification of the mitigation strategies, there is a lack of experimental validation and a quantitative benchmarking of the discussed techniques.

Qaisar et al. [25] introduced a Grid-Forming Active Power Filter (GFMC-APF) model to improve and upgrade the power quality by simultaneously control voltage, frequency, and harmonic content. The approach enhances the system inertness and dampening while decreasing the harmonic distortion. However, there is limited experimental validation in the study and the performance of the proposed filter is affected by grid impedance variations, especially under the condition of weak grid.

3. Methodology

This section describes the detailed methodology that is designed in order to deal with the management

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of power generation in grids of PV installation, with optimization of the energy and with the maintenance of excellent power quality. Each component and control strategies are well described to illustrate how they contribute to the enhanced performance of the system and commensurate with the integration with the grid. It begins with a PV array which is connected with a boost converter and is controlled with a maximum power point tracking (MPPT) algorithm which ensures to extract the maximum energy.

3.1 System Overview

The proposed system is aimed at providing a better power quality of solar PV energy injected to the grid. The system is initially started using the PV array linked with boost converter control using MPPT algorithm initializes to make sure that maximum energy is extracted from the PV array. After that the output is fed to Voltage Source Inverter (VSI) with the dc to ac conversion being performed under the control of a carefully tuned PI controller. The inverter output is passed through the harmonics mitigation stage, which is the combination of passive-active filters in order to improve the quality of waveforms. The cleaned output is then fed into the grid even in the varying load conditions [19]. A well-oriented schematic of the system is given in figure 1.

A PV grid connected system has a set of dedicated and sophisticated components, which are arranged in a particular order for achieving efficiency, stability, and compatibility of grid standards. The sunlight is transferred into electrical energy by PV arrays and directed towards the MPPT controller that handles the power in an efficient way. The controller is used to dynamically change the operating parameters for maximum power under different environmental conditions. Afterwards, the output voltage is converted by high voltage dc/dc boost converters to a suitable level for inverter operations. The inverter transforms the DC into AC which is synchronized with the frequency and voltage values of the grid system. Tidal installation by clients: A harmonic filter is put in place on the inverter output to combat the harmonic distortions and meet the requirements for the operation to meet the standards of the electricity industry (IEC) 61000-3-2. Finally the filtered AC power is injected in the utility grid. Such a system is illustrated in figure 2 to enlighten the reader about the specific detail about each of the components and the interaction among them in order to highlight the cohesive design required for an effective operation [20].

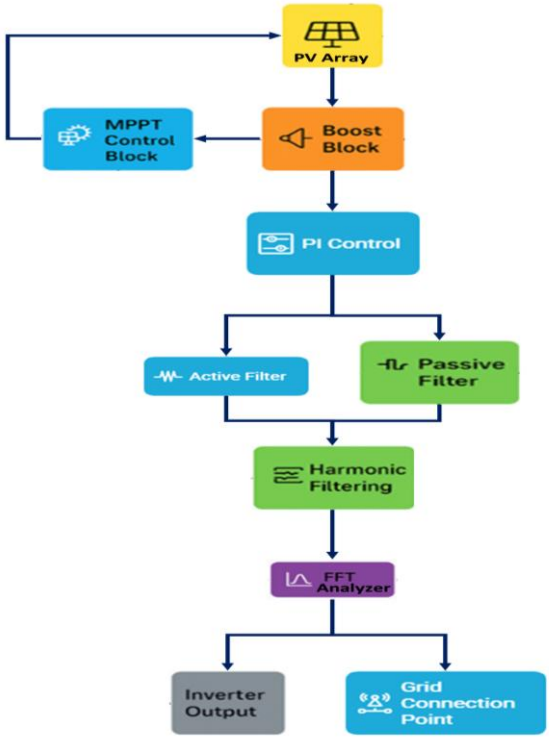

Fig. 1. A grid-connected PV system with a boost converter controlled by MPPT

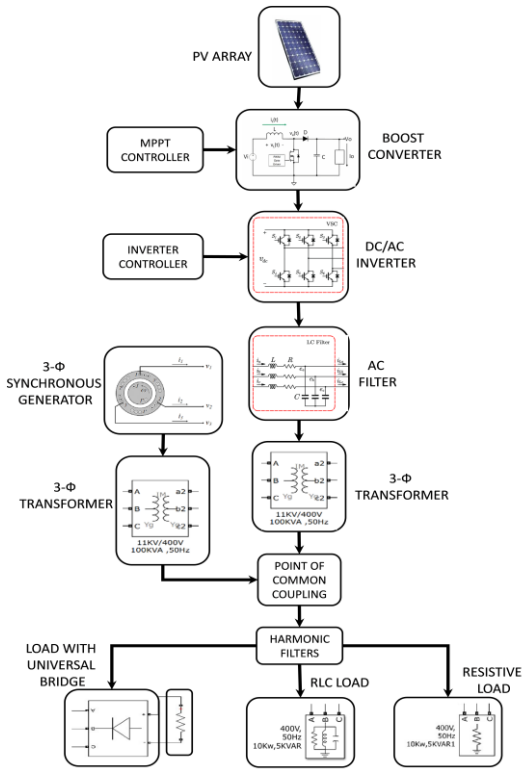

Fig. 2. Grid connected PV system with components.

3.2 PV Module Modeling

The PV module is modelled using the single diode equivalent circuit, as shown in Figure 3, which is considered a robust and most accurate representation of the real-world characteristics of the PV panels. This model considers very crucial environmental factors,

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such as solar irradiance (S) and ambient temperature (T), to change the efficiency and performance of the module. The PV current (I_L) produced in the module is represented in equation (1) and varies with changes in the sunlight intensity and temperature:

$$I_L = (I_{SC} + K_i(T - T_{ref})) \times \frac{S}{S_{ref}}; \quad (1)$$

Where; I_{sc} indicates the short circuit current, K_i indicates the temperature coefficient of I_{sc}, T_{ref} indicates the reference temperature and S_{ref} indicates the reference value of irradiance. This current is fed to a diode based circuit which is responsible for the recombination losses and leakage current in PV cell. The model takes the standard representation of a diode with non-ideal conditions taking R_s (as series resistance) and R_{sh} (as shunt resistance) of internal resistance and leakage pathways, respectively. The output current (I_{PV}) is imposed as:

$$I = I_L - I_D - \frac{V}{R_{sh}}; \quad (2)$$

Where I_D is the diode current, expressed as:

$$I_D = I_s\left(e^{\frac{qV}{AkT}} - 1\right); \quad (3)$$

In this equation, I_s is the diabetic reverse saturation current charge mass q is the electron charge ideality factor A k is Boltzmann's constant and T is the absolute temperature in Kelvin degree. The voltage (V_{PV}) and the current (I_{PV}) of the PV module is measured and filtered to remove noise. In addition, the diode voltage (V_{diode}) is used as an output parameter of the circuit.

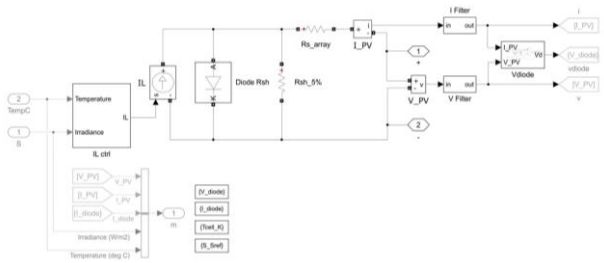

Fig. 3. Equivalent circuit of PV Solar System

The PV module parameters have the critical role in determining the electrical characteristics of the module. The module has max power (P_{max}) of 120 kW with corresponding voltage (V_{mp}) of 48 Volt & Current (I_{mp}) of 2500 Amp. The open circuit voltage (V_{oc}) and short circuit current (I_{sc}) are 50V and 2600A respectively. The module is made of 60 series connected cells with a temperature coefficient of short circuit current (K_i) being 0.10199/°C and open circuit voltage temperature coefficient (K_v) of -0.36101/°C. The ideality factor of the diode (A) measures 0.95 and has a great influence on the recombination characteristics of the PV module.

This model is suitable for the study of the performance of PV systems under different environmental conditions. It can also be embedded with MPPT algorithms and grid-tied inverters to improve the energy extraction and stability of the grid. The temperature and irradiance-dependent parameters give enough flexibility in the model to simulate the actual characteristics of the PV system and thus make it a valuable tool for research and optimization in the area of renewable energy.

Table 2

Photovoltaic Module Parameters

Parameter	Value
Maximum power (Pmax)	120 kW
Maximum voltage (Vmp)	48 V
Maximum current (Imp)	2500 A
Open-circuit voltage (Voc)	50 V
Short-circuit current (Isc)	2600 A
Number of cells (Ns)	60
Temperature coefficient of Isc (Ki)	0.10199/°C
Temperature coefficient of Voc (Kv)	-0.36101/°C
Diode ideality factor (A)	0.95

The parameters of the PV module used for performance simulation are provided in Table 2. These parameters allow for accurate characterization of the module and enable reliable prediction of its behavior under varying operating conditions.

3.3 MPPT and Inverter Control

The state-of-the-art Perturb & Observe (P&O) maximum power point tracking (MPPT) algorithm is used to maximize the power extraction from the PV array. The method involves slightly displacing the system from the operating point of the PV module and observing changes in power output to track and optimize the operating point instantly. Through this mechanism, the maximum power point is automatically determined and maintained with varying irradiance and temperature conditions. In particular, the P&O method is claimed to be the simplest, robust and efficient under dynamic conditions. Implementing MPPT, a PI controller is used to govern the operations of the inverter. It

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stabilized the AC voltage levels and output frequency with appropriate integration with grid requirements. The schematic flowchart illustrating the MPPT and inverter control system is shown in Figure 4. It clearly shows how the control loop dynamics interact with the other components of the system. This strategy enables the system to operate efficiently and simultaneously deliver quality power to the grid.

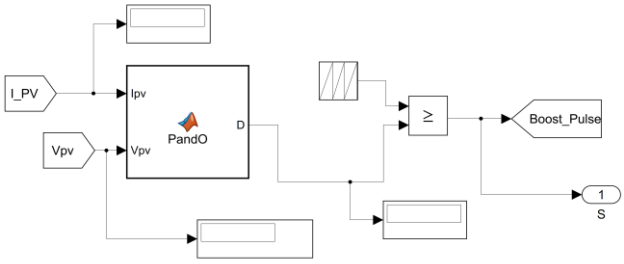

Fig. 4. MPPT and inverter control illustrating boost converter and control dynamics.

3.4 Harmonic Mitigation Strategy

Harmonics, the unwanted frequency components mainly introduced by nonlinear loads and switching by the inverter, end up largely tarnishing the power quality. The suggested scheme uses a combined strategy of passive and active filtering for proper mitigation of these harmonics. Through the use of LC and LCL configurations, passive filtering can provide a low-cost solution for particular dominant harmonics with clearance at a fixed frequency. When installed at the right junctions, these filters greatly dissipate the overall harmonic content. An active filter strategy acts as a counterpart within the inverter control system to dynamically vary with fluctuating harmonic profile conditions. It continuously monitors the harmonic levels and injects compensating signals to nullify transient and variable harmonic disturbances, thereby enhancing the system's adaptability and efficiency. Thus, this strategy ensures compliance with strict IEEE harmonic standards to reduce harmonic distortions while delivering stable and high-quality power to the grid.

3.5 Simulation Platform

Rigorous validation of the system performance was done through extensive simulations using MATLAB/Simulink and SimScape Electrical for dynamic modelling and accurate electrical simulations. The simulation framework thus provided the opportunity to assess system components, control strategies, and harmonic mitigation performance in various operating conditions. The Fast Fourier Transform (FFT) analysis tool is used to evaluate and quantify the harmonic distortions with precise information on the spectrum. This capability serves as an important means of verifying compliance with IEEE 519 harmonic standards. Thus, it allows complete validation of harmonic reduction methods and fine-tuning of filter configurations. Simulation results provided insights into the transient and steady-state behaviour of the system, which in turn guided improvements to ensure its robustness and reliability [21].

4. Results and Discussion

This section evaluates the operation performance of the defined grid connected PV system. Various considerations such as load depending behaviour of system, waveform integrity of system, harmonic distortion, power quality, effectiveness of harmonic mitigation measures applied are considered.

4.1 Scenario Analysis

In this research the system was put to test under various load conditions of resistive, reactive (RLC) and nonlinear of kinds in testing for its performance in different operational scenarios. Under pure resistive loads the voltage and current waveforms were maintained by the system as stable and near sinusoidal, a build-up of high quality power and efficiency. On the other hand, the occurrence of the disturbances, the sources of which were RLC loads, consisted of the resistance, inductor, and capacitor was observed. Phase imbalances and reactive power flow are the two conditions that contributed to these disruptions and these cases highlight the need for proactive efforts to be carried out to contain the harmonics. Diode rectifiers and power electronic converters created new diversionary loads, which injected harmonic loads and this increased the waveform irregularities and abrupt transient responses when they were supplied with un-linear loads. These vibrations placed further load on the system and this brings more about the underlying fact of undertaking viable harmonic control practices. The results of the simulation as depicted in Figure 5(a) and Figure 5(b) give a good picture of the effects of various types of load on electrical parameters at point of common coupling (PCC), including the experienced variation in harmonic distortion and waveform deterioration.

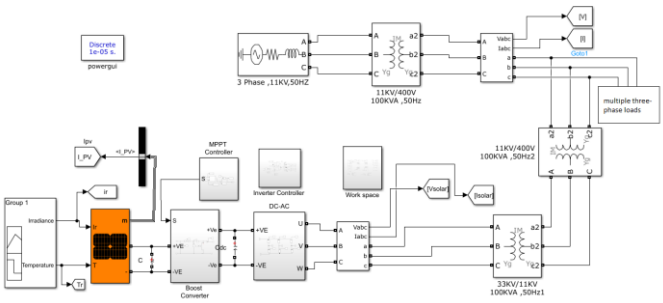

Fig. 5 (a). Solar System and 3-phase Synchronous Generator connected to the Point of Common coupling.

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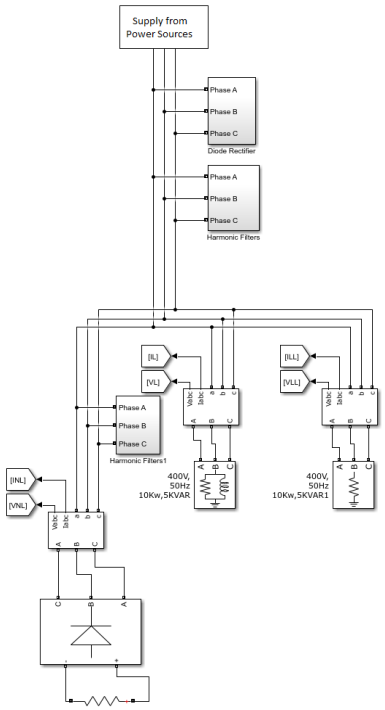

Fig. 5(b). Resistive, RLC, and Nonlinear Loads connected to the point of common coupling (Power Source).

4.2 Waveform Analysis

Figure 6 shows the dynamic interaction between solar power and the grid. The waveform of the grid voltage looks sinusoidal, which means that the power supply is clean. However, the grid current waveforms reveal a strikingly distorted waveform with spikes and levelled areas, indicating a large amount of contribution by the harmonics. The distortion is mainly a result of the interaction between the grid, nonlinear loads, and the inverter interface of the PV system. The voltage and currents of the PV system are also non-sinusoidal, having choppy and step shapes. It is due to direct distortion resulting from the use of power electronic conversion in PV inverters.

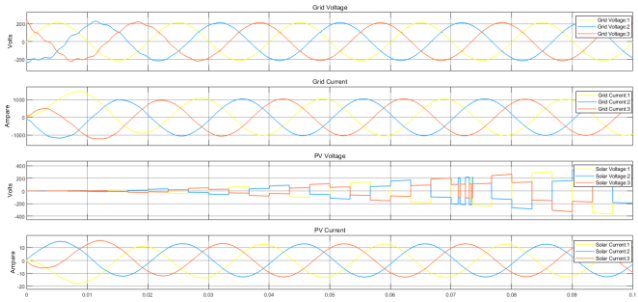

Fig. 6. Output Waveform of Grid and Solar Power

The comparison of the behavior of a linear and an RLC load is given in Figure 7. The voltage and current waveforms of the linear load are mainly of a sinusoidal type, indicating that they perform optimally since these loads do not cause harmonic distortion. To the contrary, the voltage and current waveforms of the RLC load exhibit mostly sinusoidal waveforms with minor distortions, implying there is harmonic content present. One may deduce that RLC loads do not create significant harmonics but are subject to them and indicate existing harmonics in a system.

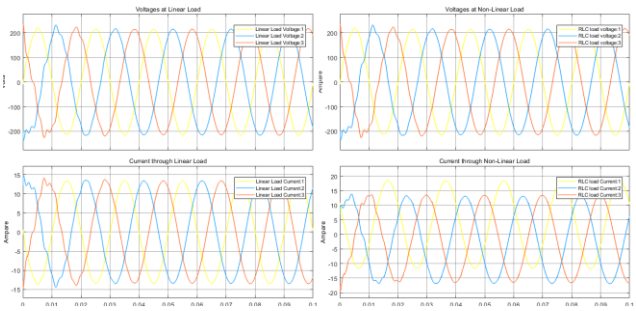

Fig. 7. Output Waveform of Linear and RLC Loads

Analysis of Figure 8 reveals a striking difference between the actual pattern and the anticipated sinusoidal behavior, which is typically characteristic of nonlinear load conditions. Although the voltage waveforms are fairly sinusoidal, there is a noticeable distortion referred to the peak, which means that harmonic components are present. The most remarkable finding is in the current waveforms, which present a radical stance in the sinusoid manner and represent a special look of being a rectangular or stepped shape. Such frequent distortions prove the high number of harmonics produced by the bridge rectifier, which is the most hallmark feature of nonlinear loads.

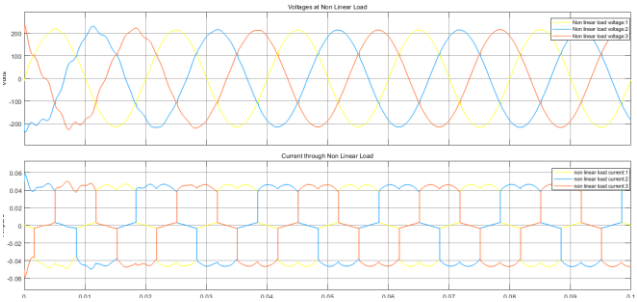

Fig. 8. Output Waveform of Non-Linear Loads (using Bridge Rectifier)

The effects of mitigating harmonics on the grid and solar power integration have been illustrated in Figure 9. The waveform of the grid voltage is clean and sinusoidal, proving compliance with the standards of the grid. Particularly important is that the waveforms of the grid currents are already much smoother and show a much stronger sinusoidal shape, thus demonstrating that an impressive share of the harmonic currents has been mitigated. That implies that the harmonic mitigation equipment has suitably mitigated nonlinear load distortion as well as PV distortion. The PV voltage waveform is significantly improved, closely resembling a sinusoidal signal despite retaining power electronic switching features. In addition, the PV current injected into the grid has demonstrated a significant improvement in its sinusoidal nature, thus a decrease in the harmonic

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content that the solar power supply source contributes. These results confirm the success of the adopted mitigation methods in improving the quality of power exchange between the grid and the solar PV system.

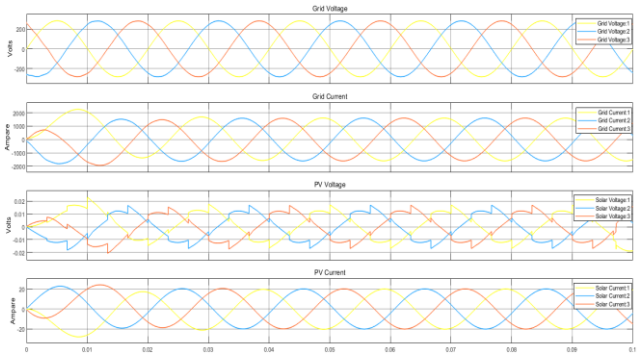

Fig. 9. Grid and PV System Voltage and Current Waveforms After Harmonic Mitigation

As depicted in Figure 10, the addition of harmonic mitigation led to a substantial increase in the sinusoidal quality when comparing the generated waveform under linear and RLC loads. The voltage waveforms of the two loads have become cleaner, with no distortions, and are very close to the ideal fundamental frequency. In the same way, the present waveforms are smooth and sinusoidal in shape, whose magnitude is proportional to the respective voltages. The lack of high-frequency distortions and nonlinearities suggests the use of mitigation techniques that have minimized harmonic content and improved power quality at these loads.

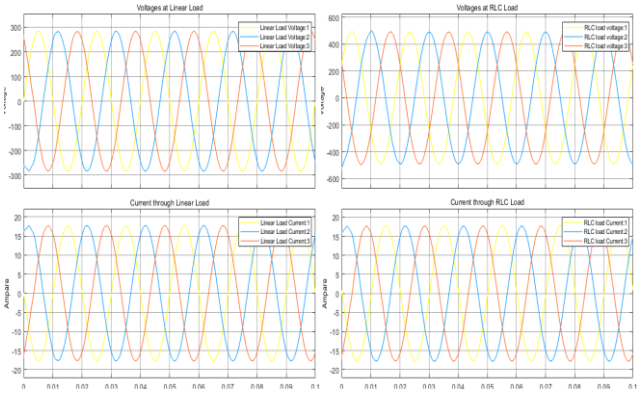

Fig. 10. Voltage and Current Waveforms of Linear and RLC Loads after Harmonic Mitigation

As illustrated in Figure 11, there is a significant improvement in the waveforms of the nonlinear load after harmonic mitigation. The waveform of the voltage is now almost similar to a pure sine wave, having less distortion at the peak. Moreover, the present waveform across the nonlinear load has been considerably enhanced, transitioning from a highly distorted shape to a more sinusoidal one. Whereas slight variations with the perfect sine wave still exist, this mainly affects the given nonlinearity of the load. On the whole, the content of the harmonics decreased considerably.

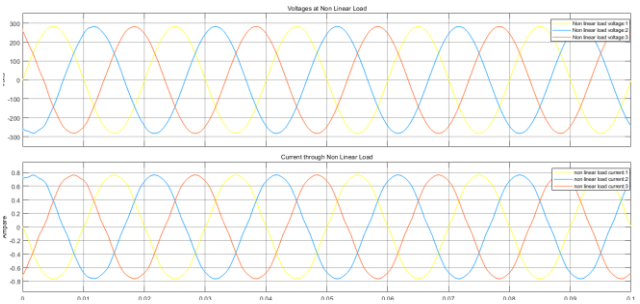

Fig. 11. Waveforms of Non-Linear Load following Harmonic Mitigation

The integrity of the system is strictly tested by performing an analysis of the waveform and inspecting harmonic behaviour in different loading conditions. Under a pure resistive load, the voltage and current waveforms were harmonics-free, properly coordinated, and exhibited minimal interference, indicating efficient and stable energy transfer. The addition of RLC loads resulted in a slight oscillation and phase mismatch of the voltage signals, indicating the occurrence of power quality problems. Low-frequency distortions were more visible with nonlinear loading conditions, where the forms were flat on top and sharp on the edges in the current wave shape, similar to the effects of diode rectification. Such distortions had a massive influence on the harmonic structure at the point of common coupling (PCC), where they caused a rise in Total Harmonic Distortion (THD). While Figure 8 shows the waveform under nominal loads, it also highlights the significant degradation in waveform quality under nonlinear load conditions. It is such an impressive contrast which underlines the great urgency of effective harmonic mitigation methods. It will require a complex solution that incorporates both control contingent and hardware-oriented filtering methods to achieve and maintain waveform compliance and power quality standards.

4.3 Harmonic Analysis using FFT

The Fast Fourier Transform (FFT) was used to analyze harmonic distortions in detail giving a practical knowledge about the harmonic profile of different types of loads. Harmonic analysis of voltage and current waveforms under various load conditions of resistive loads, RLC loads and Nonlinear loads using FFT, each spectrum brings out the dominant harmonic orders particularly the 5th, 7th and 11th components as well as the corresponding Total Harmonic Distortion (THD) values. Consistent axis labelling, units and annotations have been used so as to ensure readability and comparability of the data across all test cases.

Linear loads were found to have very low harmonic contents from the results: where optimum linear loads were held to 0.11% THD for both current and voltage

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as in Figures 12 and 13 respectively. The reactive (RLC) loads had a moderate distortion with value of THD, remained almost constant in last cases for current and voltages i.e. 0.11% and 0.30% respectively, shown in Figures 14 and 15 respectively. On the other hand, nonlinear loads produced a higher level of harmonics, but according to the standards of the International Electro technical Commission (IEC) of 519, which accounts for the highest THD recorded in the cases of currents and voltages (2.14 and 0.11%-respectively, respectively), as shown in figures 16 and 17 respectively. This is an important distortion, which was placed at the disposal of diode rectification and other nonlinear defects. These findings can be summarized in Table 3 and they illustrate, for each type of load, the specific impact on the system, showing the importance of implementing harmonic mitigation measures.

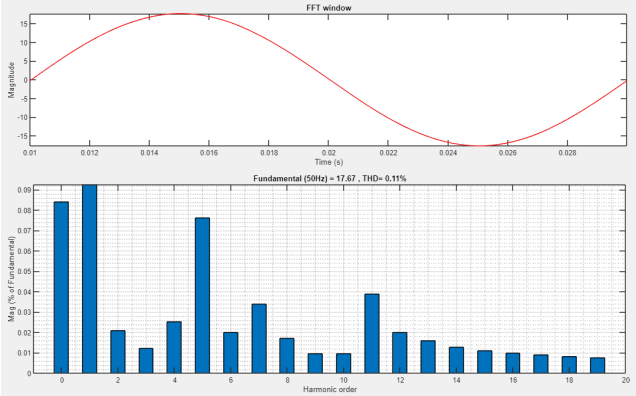

Fig. 12. FFT Analysis of Linear Load Currents

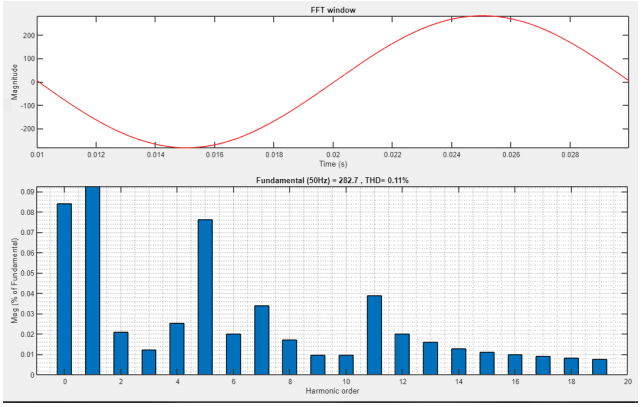

Fig. 13. FFT Analysis of Linear Load Voltages

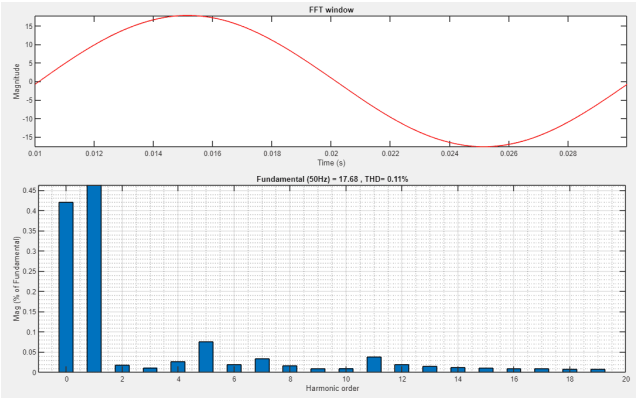

Fig. 14. FFT Analysis of RLC Load Currents

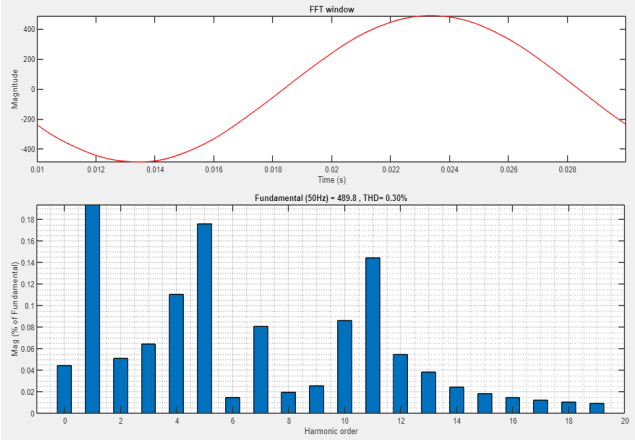

Fig. 15. FFT Analysis of RLC Load Voltages

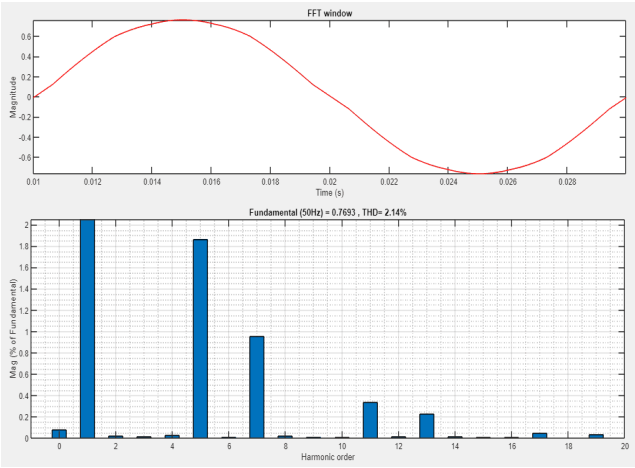

Fig. 16. FFT Analysis of Non-Linear Load Currents

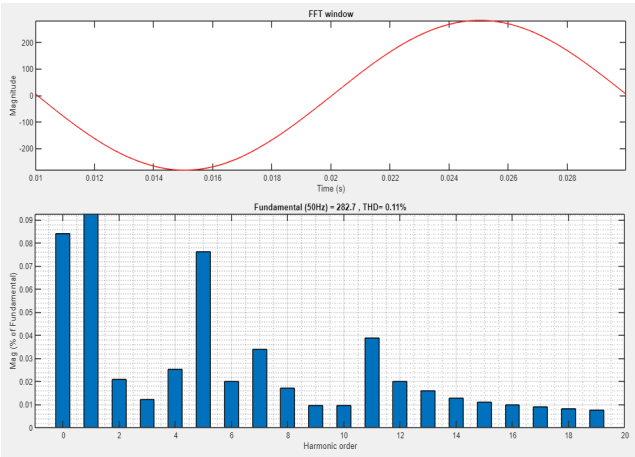

Fig. 17. FFT Analysis of Non-Linear Load Voltages

4.4 Impact of Harmonic Filtering

The initial simulations tests performed without any harmonics-reduction had revealed a highly unstable system level with a very high THD of more than 20%, which is significantly more than the value which will affect the grid. Following the introduction of a hybrid filtering solution, which combines passive LC filters with active-based control inverter, the following simulations showed that the harmonic content was reduced significantly.

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Table 3:

FFT-based harmonic distortion summary for voltage and current under various loads.

Signal	Voltage	Current
Zoom on	FFT Window	FFT Window
No. of Cycles	1	1
Fundamental Freq. (Hz)	50	50
Max Freq. (Hz)	1000	1000
Freq. Axis	Harmonic Order	Harmonic Order
Linear Load THD	0.11%	0.11%
RLC Load THD	0.30%	0.11%
Non-Linear Load THD	0.11%	2.14%

The efficiency and feasibility of this two-tier mitigation strategy was proved as the level of THD was reduced below the 5% mark which is set out in the IEEE 519 standard. The achievement not only fulfilled the regulatory demands, but also created essential achievements in the points of reliability of operations, transient stability and general performance of the system. The increased simulation data, shown in Table 3, attest to the obvious improvements in waveform quality, reduced harmonics. These results suggest that it is essential to make use of both the hardware based and control based approaches for an attempt to address the complex power quality issues in PV grid connected systems.

4.5 Power Quality and Grid Compatibility

Whether pure or impure, technology management methods, considering the versatility of avoiding harmful interactions with the grid is quite strong, the area of importance is reactive power compensation, voltage adjustment and system synchronization. Passive filters are relevant to the impedance of reactive power countering that contributes to improving the power factor at the grid interface. Voltage control systems allow the stability of control of DC-link and AC grid voltages even with variable loads. As greater sophistication is added to synchronization methods, phase-locked loop (PLL) algorithms facilitate smooth transfer of power by synchronizing inverter phases with grid frequencies. Such synchronization of controlling mechanisms promotes the compatibility of the system with the smart grid system, as well as facilitating system adaptation to reliable bidirectional energy transmission and bidirectional adaptation responses, which are inherent features of power systems in the future.

4.6 Implications for Developing Countries

The hybrid photovoltaic solution proposed in this study is a promising solution to the energy challenges facing most of the developing countries. Such countries often face financial constraints, lack of infrastructure and erratic electricity power, making conventional energy practices impractical. The flexibility and scalability of the suggested system also make it possible to implement the idea gradually, so that it is compatible with limited resources in both financial and logistical terms. Combinations of both harmonic suppression and intelligent control mechanisms make systems more resilient and thus reduces the cost of maintenance and increases operational life.

5. Conclusion

The article discusses in detail about a grid-connected photovoltaic (PV) system which pays particular attention to the power quality deterioration and the harmonic distortion issues. The findings suggest simulation-based assessments of performance improvement for validating the strategies of practical employment of the proposed hybrid harmonic mitigation strategy. In particular, the levels of THD, which were initially well above 20% were brought to below the level of 5% as prescribed in the IEEE 519 standard. It emphasizes in a very decisive way the importance of a combination of the passive LC filters and active-controlled inverter techniques for supporting the reliability and general power quality of the system. The Perturb & Observe (P&O) based MPPT algorithm under different ways of environmental conditions made use of the most possible solar energy. On the other hand, the proportional-integral (PI) controllers helped maintain the inverter outputs in position with the grid stable and phase in line. The performance of the system as a whole remained rather intact and it was stable under all load conditions: resistive loads, reactive (RLC) loads and nonlinear load profiles. Furthermore, the success of this implementation at Ziauddin University is a demonstration of the applicability of this technology in the developing world. This implementation had some practical benefits including design modularity, low cost energy provision and greater efficiency and significant reductions in carbon emissions. Together the conclusions offer a workable and scalable strategy towards strengthening energy infrastructures in resource-limited settings and have widespread implications with regards to sustainable development. Future works will focus on investigating on incorporation of artificial intelligence for adaptive harmonic mitigation and evaluation of the role of energy storage systems for promoting further

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resilience to system performance under the condition of variable renewable generation. For future work, experimental validation by pilot-scale experimental implementation is suggested for further validation of findings of simulations. In addition, the integration of artificial intelligence for adaptive harmonic mitigation, and the integration of energy storage systems, may potentially increase resilience of the system and ensure consistency of system performance under dynamic conditions of renewable generation.

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