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Using Active Filter Controlled by Imperialist Competitive Algorithm ICA for Harmonic Mitigation in Grid-Connected PV Systems

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ABSTRACT

Solar energy has been gaining momentum recently, with a focus on maximizing its investment potential due to its reputation as the most sustainable and efficient energy source. This shift towards solar power could potentially reduce the reliance on oil-based fuels in the future. As a result of the integration of photovoltaic (PV) energy sources into the grid, the reliability of power distribution and maintaining its quality in these systems has become increasingly important. The presence of non-linear loads in these grids causes distortion of both voltage and current waves on the grid side, so it is necessary to implement effective reduction techniques to reduce the distortions in these waves. The research contribution is TO introduce the integration of an active filter on the dc side of grid-connected PV systems, along with a control circuit for the filter switches. The control switches were operated using a Sinusoidal Pulse Width Modulation (SPWM) control scheme, while the controller parameters were tuned using the Imperialist Competitive Algorithm (ICA). The proposed system was simulated in the MATLAB/Simulink environment with variations in solar radiation and temperature. The simulation results demonstrated a reduction in the total harmonic distortion factor (THD) for voltage and current waveforms on the grid side, which are within the permissible limits. This confirms the effectiveness of the proposed filter and the efficiency of the control strategy and algorithm for parameter adjustment.

1. Introduction

Renewable energy sources are favoured for electricity production due to the rising demand for eco-friendly power and the decline of traditional sources like natural gas, oil, coal, and nuclear. Solar PV stands out for its lack of pollution and waste, as well as its efficient production process.

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Currently, solar PV seamlessly transitions between low and high-power grid systems. Transmission lines are used to manage the increasing electricity demand and integrate multiple energy sources, reducing the need for power banks and replacing traditional sources with green, renewable ones. However, distributed systems face more power quality issues compared to centralized grids [1].

The reason for causing imbalance is the unequal distribution of voltage in either single-phase load or uneven voltage level in generation or distribution. Any unbalanced load at a junction in a grid will impact different load parameters in the related node. To achieve grid integration, a control approach is necessary. Adjustments must be made to both the active and reactive components in order to address the imbalanced demand load [2].

The focus on smart grid advancements as a pressing research topic has been driven by the increasing severity of power shortages and environmental concerns. Integrating unconventional renewable sources like wind, PV, or fuel cells into the power distribution system guarantees a reliable and sustainable energy supply. However, the intermittent nature of these sources and the increasing use of electrical machines and unbalanced loads present hidden challenges to power quality [1], [2].

LC filters, also called inductor-capacitor filters, are employed in grid-connected PV systems to improve power quality by reducing electrical noise and enhancing the power factor. These filters work by filtering out unwanted high frequencies and reducing harmonics, using inductance coils (L) and capacitors (C) to create a resonant circuit that selectively allows certain frequencies to pass through while blocking others. LC filters can be used for power conditioning to reduce ripples [3]. However, they are costly due to the need for high-value inductance for average to large energy demands [4]. Therefore, an LCL filter is used. The design trait of lymphoblastoid cell lines (LCL) plays a crucial role in the overall system and is essential for system stability [5]. The LCL filter scheme must consider cost concerns, higher capacitance value, cost-effectiveness, and lower inductance value, which is large and expensive. Additionally, the impedance of the LCL filter affects grid stability, so careful consideration is necessary during the design process [6].

LCL filters are a type of electrical filter employed to enhance the power quality in grid-connected photovoltaic systems. These filters are utilized to mitigate harmonic distortion that can be generated by inverters used within these systems. An LCL filter consists of an inductor (L), followed by a capacitor (C), and another inductor (L) [3]. The first inductor (L) is placed in series with the inverter and functions to smooth voltage and current waveforms. The capacitor (C) is connected between the terminals of the first inductor and the second inductor, acting to filter out undesirable high frequencies and reduce harmonics. The second inductor (L), positioned between the capacitor and the grid, enhances the filtering effectiveness by providing additional impedance to high frequencies [4].

LCL filters are characterized by their ability to present a high impedance to harmonics over a broad frequency range, resulting in a more effective reduction than traditional LC filters. However, these filters may require precise tuning and attention to conditions that could cause high-frequency resonance, which can lead to equipment damage or reduced filtering efficacy. Therefore, advanced control systems are implemented to maintain stability and optimal performance of the LCL filters [5].

The grid's stiffness is determined by the LCL filters' resonant frequency, which adjusts as the grid's impedance changes. Therefore, in order for the solar PV system and the grid to function properly, synchronization and control strategy are crucial. To achieve frequency synchronization, a phase-locked loop (PLL) is used to control the synchronous reference frame [6].

Phase-Locked Loops (PLLs) are electronic control systems utilized in a broad range of applications, including the enhancement of power quality in grid-connected PV systems. A PLL's function is to synchronize the frequency generator's output signal (typically an inverter) with a reference signal, which can be the voltage signal from the electrical grid. The PLL adjusts the frequency and phase of the output signal to match that of the grid voltage, allowing for efficient energy transfer from the solar power system to the electrical grid with minimal disturbance and loss [5].

The rise in concern for power electronic devices in recent trends is due to their utilization in real-time applications. Various types of controllers are commonly used to address different power quality issues [7]. The substantial growth of photovoltaic (PV) systems heavily depends on advancements in global radiation and power quality. Inverters, which convert DC to AC power, are often connected to distribution systems. When connected to the grid, voltage and current distortion can negatively impact system performance. The performance of the system and power network, in terms of power quality, is also influenced by highly volatile devices, non-linear loads, and renewable energy sources (RES). The unique functions of power quality affect both consumers and utility equipment. The integration of renewable energy sources into the grid can contribute to improving power quality [8].

Numerous renewable energy sources have been integrated into the grid with the aim of enhancing its power quality (PQ), and several technologies have been proposed to be incorporated into these systems to improve their power quality characteristics. According to [9], by incorporating the enhanced Dynamic Voltage Restorer (DVR) and RLC link filter into the injection transformers with voltage source inverter, the PQ experiences an improvement. The performance of the DVR is further enhanced through the utilization of the 7-level H-bridge connected inverter. Additionally, the RLC filter effectively eliminates switching harmonics. Even though, the using of seven-level H-bridge has led to an improvement in power quality, it has also resulted in the occurrence of failures in the filtering capacitors on the dc side of the system under study. In the context of a three-phase medium-voltage network, as [10] introduce, the hybrid PV-Wind system benefits from improved PQ and Low Voltage Ride Through (LVRT) capability through the implementation of DVR control. Fig. 1 shows the block diagram of the hybrid photovoltaic–thermoelectric generator (PV-TEG) integrated photovoltaic–thermoelectric generator (DVR) system.

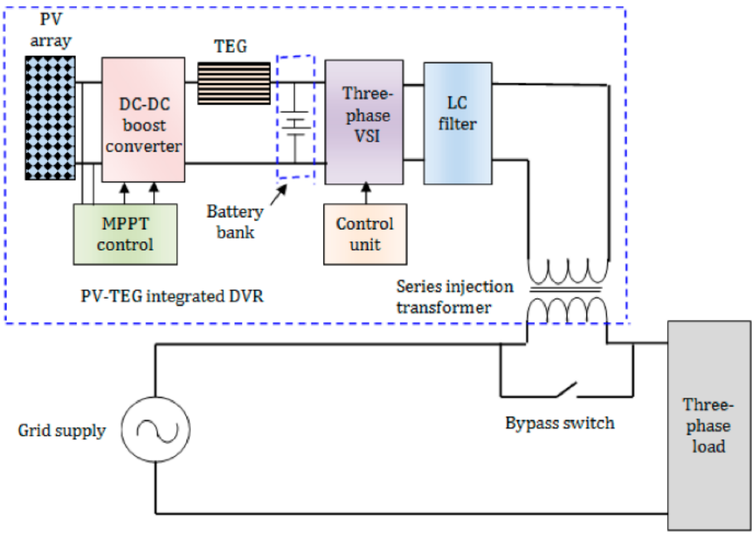

Fig. 1. The block diagram of the hybrid photovoltaic–thermoelectric generator (PV-TEG) integrated photovoltaic–thermoelectric generator (DVR) system [10]

A novel control strategy for multi-functional grid-connected inverters MFGCI that enhances power quality PQ to some degree is introduced in [11]. The proposed system consists of four IGBT/DIODE pairs with a filter on the DC side consisting of two diodes, a switch, a coil, and a capacitor. The capacitor transistors were controlled by comparing the voltages and currents at the inverter output. This approach offers several benefits in terms of PQ characteristics as it tailors the capacity margin and consumer requirements. However, assessing the complexity of PQ before and after compensation was challenging. Fig. 2 shows the typical configuration of a single-phase full-bridge MFGCI.

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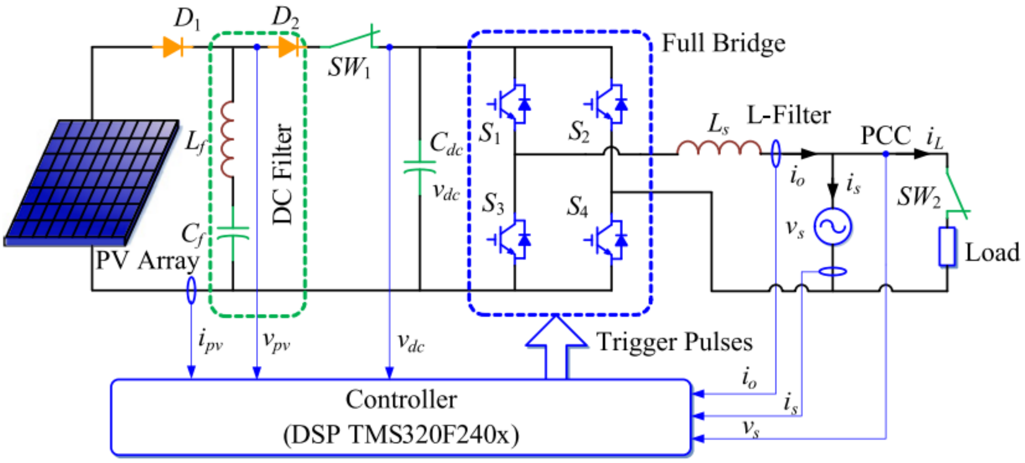

Fig. 2. Typical configuration of a single-phase full-bridge MFGCI [11]

In [12], a single-phase grid connected PV system uses the incremental conductance (INC) based MPPT algorithm. The neutral point achieves appropriate voltage balancing through the use of the Carrier Based Pulse Width Modulation (CBPWM) technique. The results showed that injecting the PV power to the grid helps to reduce the grid current harmonics. The CBPWM technique is chosen for this system due to its advantages of low harmonic outputs and reduced switching losses. The most common drawback of this system was that the PV array current decreases when there is a change in solar irradiance.

A novel approach is introduced in [13] to enhance PQ at the Point of Common Coupling (PCC) by using a composite filter. This method effectively eliminates the unpredictable flickering that is commonly observed with other filter types. Various parameters are assessed based on the intensity of flickering. However, in cases where the flickering level is high, it leads to additional PQ problems. The Adaptive Neuro Fuzzy Inference System (ANFIS) for addressing PQ issues and improving the THD in the power system is introduced in [14]. This technique ensures uninterrupted power supply while significantly reducing THD. The disadvantages of this technique were that it's limited in its ability to handle large power quantities as it operates within moderate frequency ranges.

In [15], the improvement of system PQ is demonstrated through the utilization of a Scott-transformer-based power factor correction (PFC) rectifier for a 3-level neutral point-clamped (NPC) inverter-fed induction motor drive (IMD). Additionally, the Scott-transformer-based PFC rectifier is controlled using current feed forward control. The implementation of a three-level NPC Voltage Source Inverter (VSI) results in reduced stator current ripple and stator voltage. Furthermore, the addition of the dc bus reference current to the torque component of the stator current reference enhances dynamic performance. The DC link voltage is affected by sudden changes in the motor drive's load variation.

A hybrid control scheme is suggested in [16] to enhance the performance of grid connected PV systems. The main goal of this method is to predict the gain parameters for both normal and abnormal scenarios in micro grids. Despite the challenges faced by PV systems, they remain a crucial renewable technology with potential impacts on the system. An approach is suggested in [17] to enhance the performance of grid-connected PV systems by combining DC supply with a compact switch multi-level inverter MLI configuration. This configuration requires fewer power electronic devices compared to existing MLI topologies, resulting in a more refined output voltage with reduced THD. However, the drawback of all these topologies is the presence of numerous independent fluctuating DC sources, which can pose challenges in practical applications.

In [18], a novel approach is introduced for controlling harmonics caused by a fast-growing nonlinear load (NL) using a synchronous reference frame (SRF) control combined with a PV-based shunt active power filter (SAPF). This method also addresses reactive power compensation in distribution systems. The THD of the source current is reduced below IEEE standards for both balanced and unbalanced load conditions, while also maintaining a constant DC-link voltage. The traditional PI controller doesn't perform well under varying load conditions. By implementing this control strategy [18]. The main power quality challenges for grid-connected PV systems include [19]:

- Fluctuations: Rapid changes in power production due to weather changes, such as clouds passing over solar panels.
- Voltage interference: These are transient changes in the quality of the grid voltage that affect sensitive equipment and can lead to data loss or equipment damage.
- Harmonics: Electronic devices in PV systems can cause harmonic distortion on the grid, resulting in distortion of the electrical signal.
- Load management: The challenge of electrical load management is due to the variability of power production from PV systems.
- Voltage redistribution: Some PV systems can cause fluctuations in voltage levels on the grid, affecting stability and power quality for users.
- Transmission and distribution system capacity: Increasing PV loads may require upgrading of transmission and distribution system infrastructure to meet quality requirements.

These challenges require technical and regulatory solutions to ensure that PV systems are effectively integrated into the electricity grid without negatively affecting its quality.

This paper delves into the main issues surrounding power quality in on-grid PV systems and the significance of analyzing the harmonics generated by PV inverters. The primary emphasis has consistently been on voltage and current harmonics due to their potential impact on vital components and technology in on-grid PV systems. Furthermore, this paper provides insight into the importance of power quality as a significant concern, the sources of harmonic generation, and the different mitigation strategies explored in current literature.

The future of power quality and conflict reduction in grid-connected PV systems lies in the development of advanced technologies such as internet of things (IOT) applications, smart grid management systems, energy storage systems and microgrids. These technologies have the potential to improve the efficiency, reliability and sustainability of the grid, while reducing the environmental impact of energy production.

Despite the various methods currently used to improve power quality and stability of electrical grids, there are still many negative effects that have not been controlled, the most important of which are changes in voltage and frequency, instability, and increasing the harmonic content of the voltage and current waves provided by these systems when changes occur in the intensity of solar radiation. This affects the performance of electrical devices and deteriorates the quality of service. Therefore, these systems must be carefully designed to deal with these fluctuations and ensure stable operation. This paper presents the use of an active filter in the DC side of a grid-connected PV system using the ICA algorithm to adjust the controllers parameters used in the sine pulse width modulation SPWM control scheme in order to minimize the THD values at the grid side, inverter output, to improve the power quality of these systems.

The objective of this paper is to designing a power electronic device for reducing THD in the grid waves. An efficient control strategy is developed by using imperialist competitive algorithm ICA to adjusting the parameters of the controllers. The importance of this device with a PV source is to meet grid load demand providing adequate power to the grid through a multi-level inverter, which ensure effective use by end users, maintaining constant voltage magnitude to avoid power quality issues, compensating reactive power to enhance overall system power factor, and minimizing total harmonic distortion to improve power quality. The contributions of this paper are:

- Improving the power quality and increasing the energy conversion efficiency of grid-connected PV systems.
- Using an active filter on the DC side of grid-connected PV systems by reducing the THD of grid voltages and currents.
- Using the Imperialistic Competitive Algorithm ICA to adjust the parameters of the controller used to control the active filter switches to improve the performance of grid-connected PV systems and reduce harmonic interference in the grid.

ICA is utilized in this paper to tuning the controller parameters in SPWM control method for regulating the active filter integrated on the DC side of a grid-connected PV system. The Section 2 conducts a review of existing harmonic mitigation techniques in the grid-connected PV systems. In the Section 3, the proposed system with its control scheme is introduced. Section 4 and Section 5 highlights the imperialist competitive algorithm ICA and the simulation results, respectively. Conclusions and recommendations are presented in the Section 6, and references are listed in the last section.

2. Harmonic Mitigation Techniques in the Grid-Connected PV Systems

The PV power systems are gaining popularity as a renewable source of power. They are in high demand in the power sector and are being used to reduce environmental pollution caused by non-renewable sources of power. Grid connected PV systems have different configurations, including centralized inverters, string inverters, multi-string inverters, and module integrated inverters [20]. The advantages of using grid-connected PV systems include low environmental impact, proximity to consumers, reduced transmission line losses, lower maintenance costs due to no moving parts, expandable installed capacity, and no emission of carbon dioxide gases [21].

2.1. Source of Harmonics Generation in Grid-Connected PV Systems

The main way to convert power in grid systems is by using an inverter to transfer DC power from various sources to the grid. These sources can be batteries, super-capacitors, and photovoltaic arrays, all operating at different voltages and power levels. However, this study specifically focuses on the combination of PV arrays and inverters. Regrettably, inverters inherently generate undesired harmonics in voltage and current when supplying power to the grid. The following are the causes of these harmonics from PV inverters [22].

The emission of harmonics at the inverter output is significant due to the requirement of relatively high switching frequency for Pulse Width Modulation (PWM) approaches to operate inverter switches (e.g., IGBTs).

PWM is a method utilized for regulating the power of inverters within grid-connected systems. This method entails toggling the inverter's output on and off rapidly, generating a sequence of pulses with different widths to manage the power output. Nevertheless, the rapid fluctuations in power output and the existence of harmonics in the waveform can potentially cause issues within the system [23].

The presence of a large inductance or capacitance on the DC side of the PV inverter can have significant effects. When an inductance is used, it acts as a current-type harmonic source, smoothing the DC current. On the other hand, when a capacitance is used, it behaves like a voltage-type harmonic source, smoothing the DC voltage. As a result, the inverter, depending on whether it has an inductor or capacitor, can function as either a current source or a voltage source, affecting the harmonic components [24].

Continuous current connections, may result in system conflicts as well. These connections are utilized in certain electrical systems, like those employing transformer less inverters, to streamline the design and lower expenses. Nevertheless, they can trigger harmonics because of the elevated current levels that may pass through the system, potentially leading to overheating and other complications [23], [24].

The fluctuations in solar irradiation throughout the day result in notable variations in the DC-link voltage, leading to the generation of harmonics on the AC side of the inverter [25]. The investigation into the different sources of harmonics caused by PV inverters is still ongoing, but these are the primary reasons for PV inverter harmonic emission [26].

2.2. Power Quality Concerns in Grid-Connected PV Systems

Power quality issues in grid-connected PV systems are of paramount importance as they can affect the overall performance and reliability of the system. Problems such as voltage dips, swells, harmonics and power fluctuations can lead to increased equipment failures, reduced efficiency and even safety hazards. Grid-connected PV systems rely on a stable and reliable grid connection to operate effectively, and any variations in power quality can disrupt the operation of the system [27].

It is essential for operators and designers of grid-connected PV systems to implement measures such as proper voltage regulation, harmonic filtering and monitoring of power quality parameters to ensure optimal performance and long-term sustainability of the system. Addressing power quality issues in grid-connected PV systems is critical to realizing the full potential of solar energy and promoting a more sustainable and efficient energy grid [28].

The increasing use of sensitive loads on electrical grids, new operating practices and the radical growth of non-linear and single-phase loads have led to power quality issues for these systems. As a result of the high penetration of DERs, there has been a significant increase in the number of grid-connected inverters, which are one of the main sources of harmonics in these networks [28], [29].

As a result of the continuous promotion of grid-connected photovoltaic systems to achieve a more sustainable society, PV inverters will increase and continue to operate under different situations including fluctuating and low solar radiation, thus generating voltages and currents with high harmonic components [30]. This leads to power distortion at the POC, creating a new challenge for electrical distribution networks because the high harmonics generated by these inverters lead to power loss, reduced system capacity, degradation of network components, failure of protection components, etc.

2.3. Harmonic Mitigation Techniques in Grid-Connected PV Systems

PV inverters play a significant role in introducing harmonics into grid-connected PV systems. These harmonics are generated during the conversion of direct current (DC) to alternating current (AC) by the inverter and affect the overall power quality of the grid. The level of harmonics generated by these inverters is influenced by various factors such as inverter type, system configuration and component quality. Various strategies are used to mitigate harmonics in these systems, each with its own advantages and disadvantages. The aim is to strike a balance between maximizing PV power generation and safeguarding grid power quality. Selecting the appropriate approach requires a thorough evaluation of the system and grid specifications, there are several factors to consider when selecting a harmonic mitigation technique, including simplicity, compactness, cost effectiveness, efficiency and harmonic mitigation. Some of the commonly used technologies are [31], [32]:

- Advanced inverters: The use of inverters that use advanced control techniques in accordance with international standards that minimise harmonics through their efficient design, thereby reducing the harmonic impact on the grid. Fig. 3 shows the spider diagram of advanced inverter. The spider diagram illustrates the specifications of each technique [33].
- Passive filters: Designed to be compatible with specific harmonic frequencies, they absorb and minimise harmonics from the system. Fig. 4 shows the spider diagram of passive filters [34].
- Active filters: Semiconductors and powerful electronic technologies are used to create signals that counteract and eliminate harmonics. They generate a current that opposes the harmonics in the system and minimises their effect. Fig. 5 shows the spider diagram of active filters [35].
- Power management and control systems: Using the sensing and intelligent control techniques to calibrate system output and minimise harmonics [36].
- Energy storage: The use of batteries and other storage solutions can help smooth out rapid changes in PV output, minimising harmonics [37].
- Isolation transformers: Can limit the transfer of harmonics between PV systems and the grid [38].
- System design: Optimising the distribution of components and wiring, and optimising grounding strategies can reduce harmonic transmission paths [39].

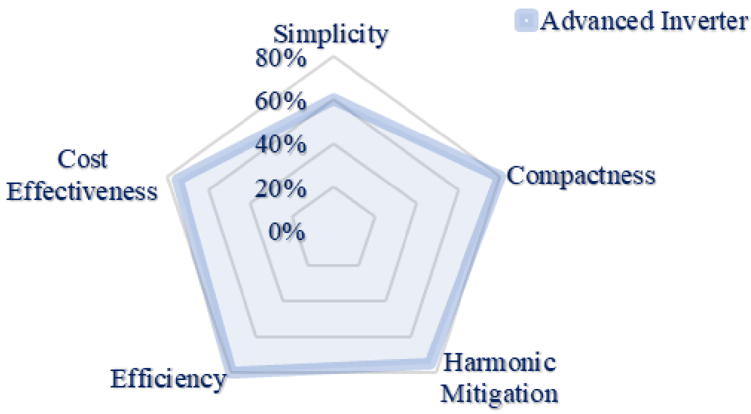

Fig. 3. Spider diagram of advanced inverter

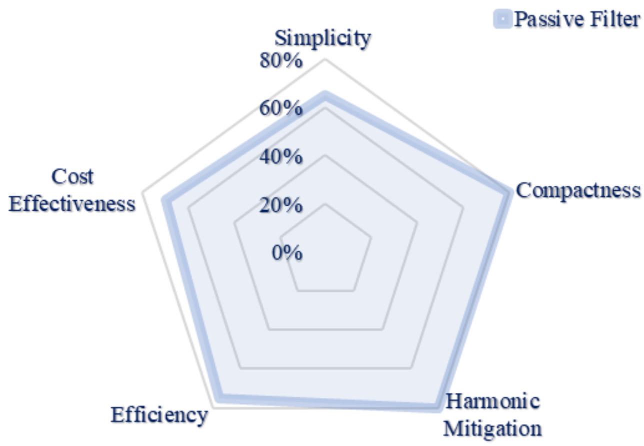

Fig. 4. Spider diagram of passive filters

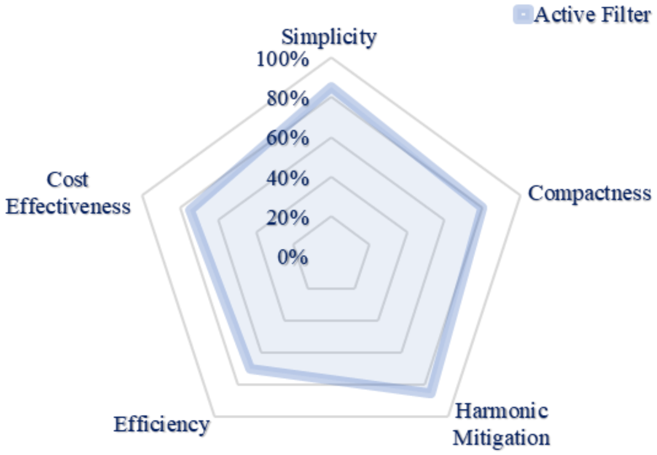

Fig. 5. Spider diagram of active filters

2.4. Modern Techniques Using in Harmonic Mitigation of Grid-Connected PV Systems

Several technologies are used to reduce harmonics in grid-connected PV systems, the most important of which is Voltage Vector Control VVC focuses on regulating voltage and reactive power to maintain grid stability [40]. The spider diagram of VVC is shown in Fig. 6.

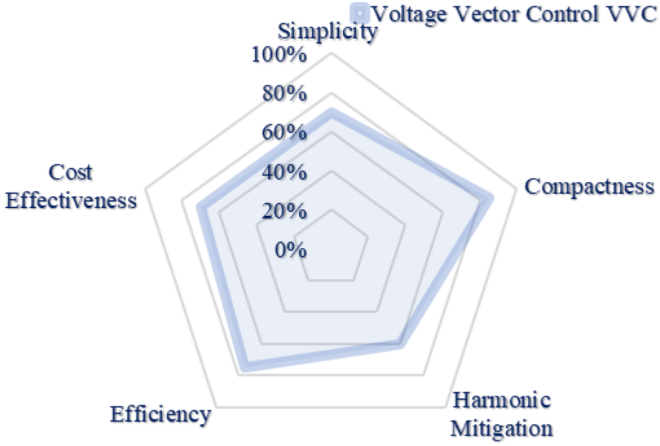

Fig. 6. Spider diagram of voltage vector control vvc

Static Var Compensator SVC manages voltage and reactive power by rapidly injecting or absorbing reactive power [41]. The SVC spider diagram is shown in Fig. 7.

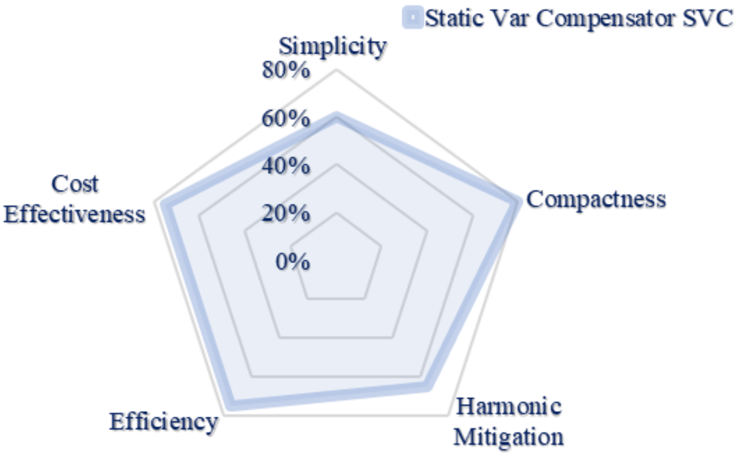

Fig. 7. Spider diagram of static var compensator svc

Dynamic Voltage Vector Control DVVC dynamically adjusts voltage and reactive power in photovoltaic systems to ensure grid stability and improve system efficiency [42]. The DVVC spider diagram is shown in Fig. 8.

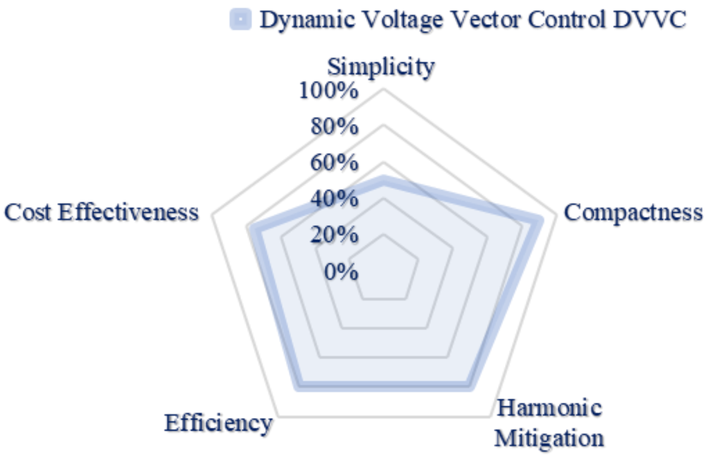

Fig. 8. Spider diagram of dynamic voltage vector control dvvc

Flexible AC Transmission Systems FACTS controls the voltage and reactive power of a power system to increase the capacity and stability of the system. These technologies are used to reduce conflicts in grid-connected PV systems by maintaining the stability of the grid and maximizing the efficiency of the system [43]. The DVVC spider diagram is shown in Fig. 9.

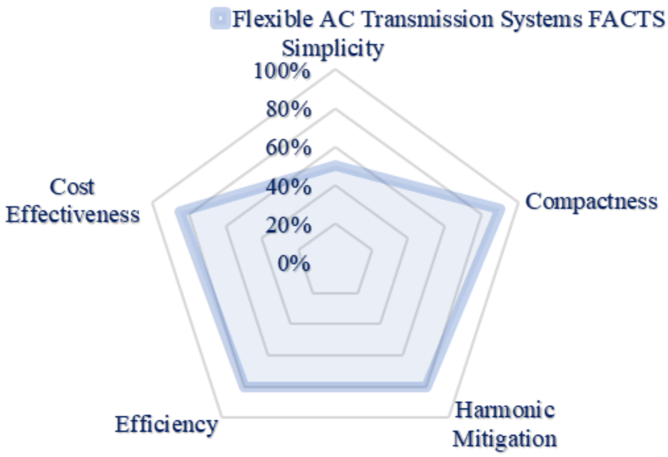

Fig. 9. Spider diagram of flexible ac transmission systems facts

In summary, the simplicity, compactness, efficiency, cost effectiveness and harmonic mitigation of the most active candidates used to reduce harmonics in grid-connected photovoltaic systems are shown in Fig. 6, Fig. 7, Fig. 8 and Fig. 9.

2.5. International Standards of Power Quality in Grid-Connected PV Systems

There are several international standards related to grid-connected PV systems, the most important of which is IEC 61727 “Photovoltaic (PV) systems - Characteristics of the utility interface”, which defines the technical requirements for the safe and efficient connection of photovoltaic systems to the electrical grid. The standard includes specifications related to power quality, including both voltage requirements, which are concerned with the acceptable limits of voltage levels generated and transmitted to the grid, and frequency requirements, which are concerned with the acceptable limits of voltage levels generated and transmitted to the grid. Frequency requirements specify acceptable frequency ranges and how the system should respond to changes in grid frequency. Power quality requirements include requirements to minimize the effects of harmonics, oscillations, voltage flicker and excessive currents that can affect the electrical system and connected equipment [44].

IEC 61853-1 fully characterizes the performance of PV modules under a variety of conditions to optimize power quality and ensure efficient and stable system operation when connected to the grid. The standard describes the performance of PV modules in terms of power over a range of irradiances and temperatures, and provides a complete set of characterization parameters under different irradiance and temperature values. The standard does not deal directly with power quality in terms of voltage, current or harmonics, but relates to power quality in terms of predicting and specifying the efficiency of PV modules and their ability to generate power under different standardized operating conditions. The effect of these characteristics on output power is between the lines - efficient and reliable panels ultimately mean better power quality [45].

IEEE 519 is entirely designed for electrical harmonics in grids, and this includes grid-connected PV electronics. Its specifications cover the harmonic limits of the users, as it determines the maximum flexibility of the harmonic currents that they can feed into the grid, which contributes to the uninterruptable of other equipment as well as the smoothness of the grid. It also includes the range of harmonics of the distribution network, which includes the range of harmonics in the distribution network voltage. It also includes load classification, measurement techniques and harmonic management strategies. For PV systems, this means that they must comply with the standards set out in IEEE 519 to ensure that the harmonic currents that the systems contribute to the grid remain within acceptable limits. This helps maintain power quality on the grid and minimizes problems such as frequency distortion, increased power losses and electrical equipment problems [46], [47].

3. The Studied System

The purpose of this paper is to enhance the quality of electric power supplied to the grid from the PV array by incorporating a conventional controller-operated active filter into the DC bus bar. The system configuration involves a PV array connected to an inverter, with an active filter inserted to minimize voltage and current ripple. Additionally, the system comprises a transmission line, voltage transformers, and the load, as depicted in Fig. 10.

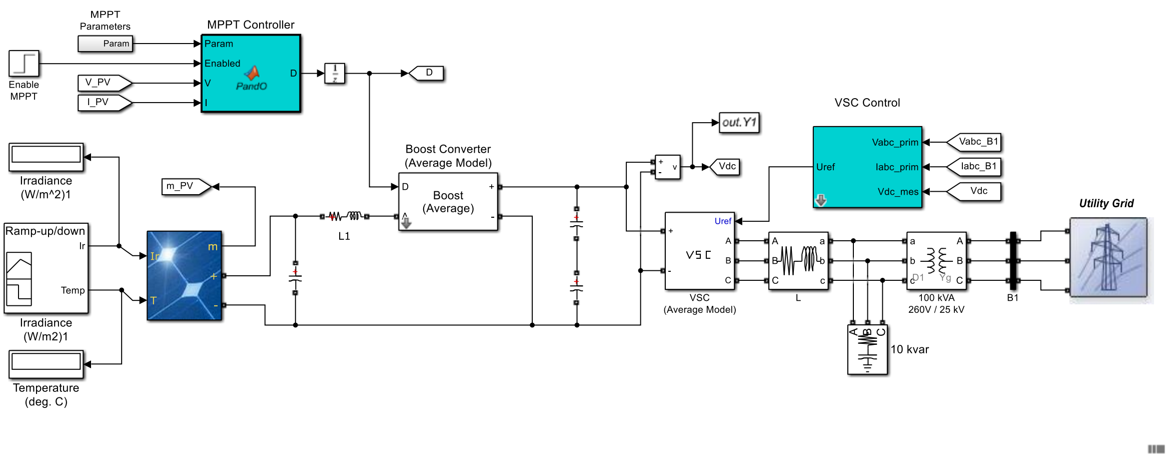

Fig. 10. Proposed system

The Perturb & Observe technique is used in a Simulink model to implement Maximum Power Point Tracking (MPPT) in a boost converter. The DC-DC boost converter is connected to a 25-kV grid via a three-phase three-level Voltage Source Converter (VSC). The PV array has a capacity of 100 kW. The proposed model consists of the following elements: A PV array that can generate up to 100 kW when exposed to 1000 W/m^2 sun irradiance, DC-DC boost converter, 3-level 3-phase VSC, 100-kVA 260V/25kV three-phase coupling transformer, and the utility grid.

The dynamics resulting from the interaction between the control system and power system are represented in this model by equivalent voltage sources that generate the AC voltage averaged over one cycle of the switching frequency. Simulink effectively resolves the algebraic loop within the average model, enabling iterative and precise solutions of the PV model with increased sample times (50 microseconds compared to 1 microsecond). As a result, this model facilitates significantly faster simulations.

The MPPT Control MATLAB Function block incorporates the Perturb and Observe MPPT algorithm. The MPPT Control MATLAB Function block incorporates the Perturb and Observe MPPT algorithm. The 100-kW PV array is made up of 66 sets of 5 series-connected 305.2-W modules that are connected in parallel. This results in a total power output of 100.7 kW. The specifications provided by the manufacturer for one module are as follows. There are 96 cells connected in series. The open-circuit voltage is 64.2 V. The short-circuit current is 5.96 A. The voltage and current at maximum power are 54.7 V and 5.58 A, respectively.

The PV array block includes two inputs that allows to customize the sun irradiance (input 1 in W/m^2) and temperature (input 2 in deg. C). The signal builder block, which is linked to the PV array inputs, determines the patterns for irradiance and temperature. The simulated system after adding the suggested filter is shown in Fig. 11.

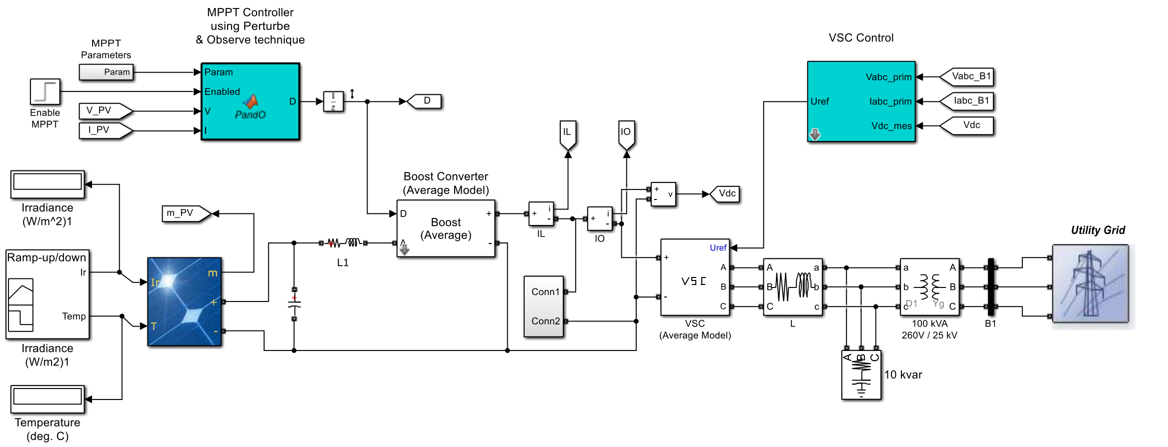

Fig. 11. proposed system after adding dc-link filter

3.1. The Suggested Active Filter

In order to obtain a sinusoidal current at the output of the inverter, a filter is utilized. This filter consists of four transistors, an inductor, and a capacitor, as shown in Fig. 12, The main objective is to remove high-frequency components from the current produced by the PV array and ensure a consistent current level at the input of the inverter. As a result, the filter aids in minimizing harmonics in the waves produced by the inverter.

The current IL of the inductor is maintained at a constant value by utilizing four IGBT transistors. The gate signals for transistors T3 and T4, as well as T1 and T2, are in opposite phases and determined by comparing the control signal with the sinusoidal signal. The duty cycle of the transistors is affected by both the current i_L and the voltage of the DC link.

3.2. The Control Scheme

The control strategy shown in Fig. 13 comprises of a pair of low-pass filters, one high-pass filter, and two controllers - one proportional P and the other proportional-integral PI. By comparing the trigonometric signal with the control signal, the control signals are generated. This approach allows for the control of the DC side voltage and effectively reduces resonance and current fluctuations. The filter input current is controlled to achieve a soft input current in the inverter input.

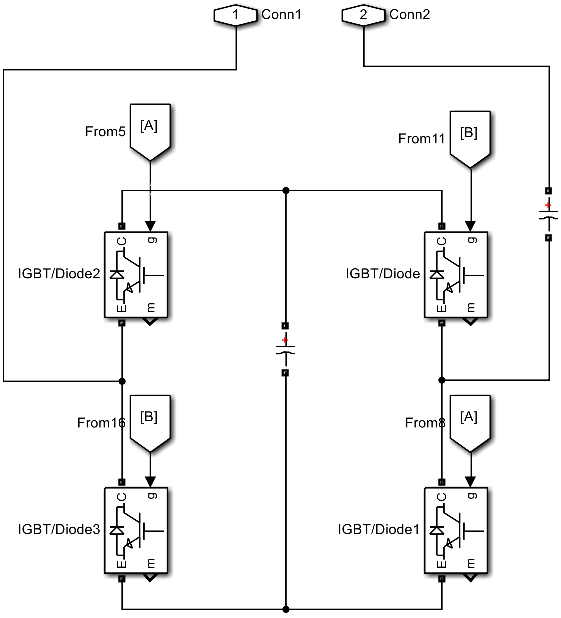

Fig. 12. Structure of the series filter used

The purpose of the low-pass filter LPF1 is to decrease the presence of high-frequency elements in the pulse load currents. Multiple low-pass filters are connected in a series to effectively minimize load current ripples and expedite the detection time of dynamic load change. The current gain, known as the proportional controller P, is employed to counteract losses. Its purpose is to regulate the current ripples IL, as stated before. When P values are high, the current ripples in the DC loop are six times smaller than those in the feeder. To maintain a manageable current and ensure a linear control signal, the proportional gain value P is set at 30.

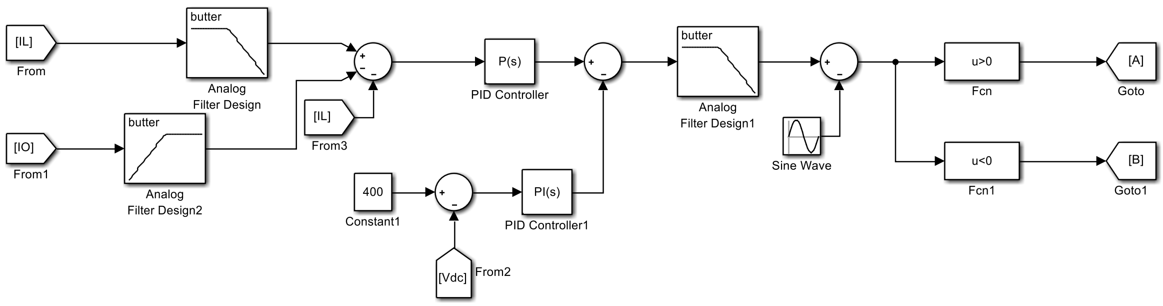

Fig. 13. Filter control circuit

The primary control loop employed a specialized low-pass filter known as LPF2 to minimize the switching ripples of the same frequency. The filter's frequency was configured to be 360 Hz, guaranteeing efficient reduction of the ripples since it is six times greater than the power frequency.

The DC link voltage is regulated using a PI controller, which is connected in parallel to the primary control loop. This setup enables adjustments to the control signal without considering losses in the DC link capacitor. However, due to non-zero losses, the modulation must increase the charging current to the capacitor. To fine-tune this controller, different methods such as manual tuning and optimization algorithms can be utilized. Both of P & PI controllers are adjusted by ICA optimization algorithm.

The resonance currents that occur when diode bridge diodes are connected are detected by the High-pass filter (HPF). These currents are then sent back to the main control loop for prevention. Moreover, the HPF removes the fundamental component and retains only the distorted component. The switching frequency of the filter is configured to 72 Hz. The signals of the gates (T1, T4) and (T2, T3) are determined by interrupting both control and sine waves.

The current IL of the inductor is maintained at a constant value by utilizing four IGBT transistors. The gate signals for transistors T3 and T4, as well as T1 and T2, are in opposite phases and determined by comparing the control signal with the sinusoidal signal. The duty cycle of the transistors is affected by both the current i_L and the voltage of the DC link.

4. Imperialist Competitive Algorithm (ICA)

The Imperialist Competitive Algorithm (ICA) is a unique metaheuristic approach inspired by imperialism and colonization. Its purpose is to tackle complex optimization problems [48]. ICA has the ability to replicate socio-political dynamics. In this algorithm, a solution to the optimization problem is represented by an empire, while imperialists and colonies symbolize specific features or components of the solution. The algorithm involves a process of competition and assimilation in which stronger imperialists capture weaker colonies, ultimately leading to global convergence [49]-[58]. ICA has shown remarkable performance in fields as diverse as engineering, finance and bioinformatics, making it a promising tool for tackling real-world problems [59]-[62]. The flowchart of ICA is shown in Fig. 14.

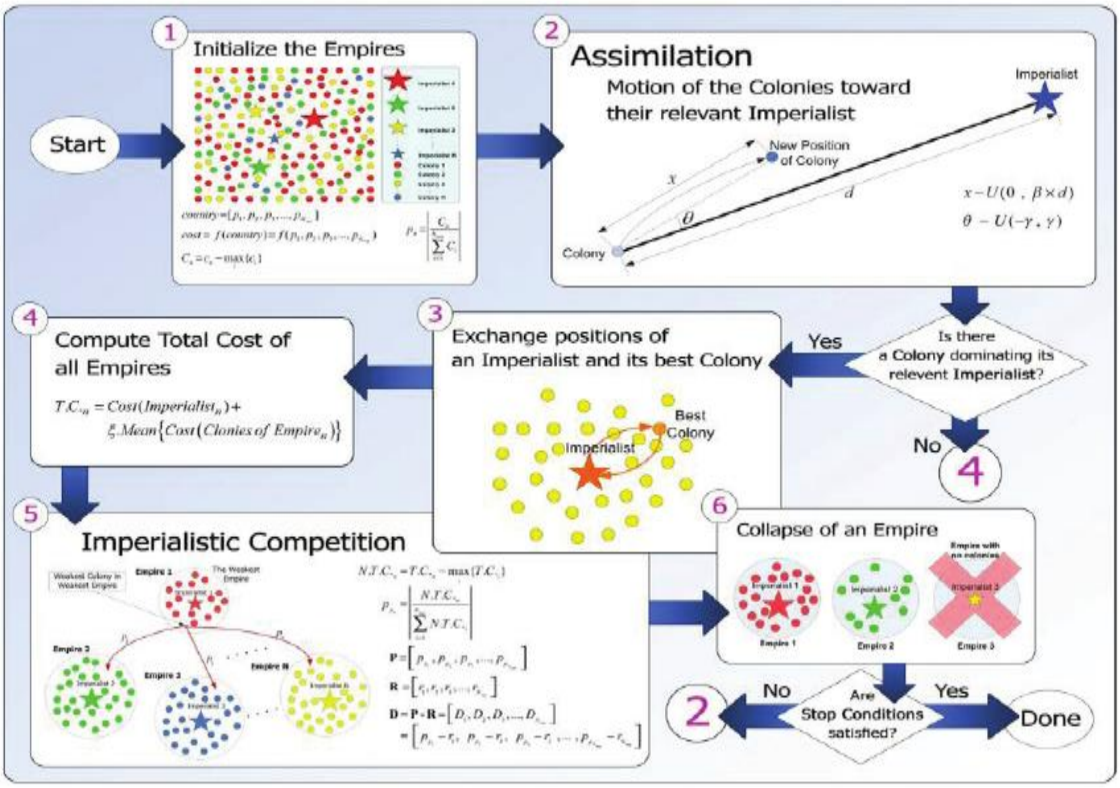

Fig. 14. The flow chart of ICA algorithm

The ICA algorithm is chosen for tuning the controllers' parameters in grid-connected PV systems for several reasons, genetic diversity improves search performance by maintaining good diversity in the population, which prevents the algorithm from converging prematurely on local solutions. In addition to exploration and exploitation, it shows a balanced ability between exploring new solutions and exploiting existing good solutions. This makes it a good tool for finding optimal values for controller parameters.

This algorithm is usually fast in converging to the optimal solution, resulting in a reduction in computation time, which is an important advantage when it comes to controlling PV systems, and it can deal with complex problems. It finds solutions to complex and multivariate problems, and this algorithm has proven its effectiveness in solving control problems in many engineering fields and in tuning parameters, giving confidence to use it in new applications.

By using ICA to adjust controller parameters for an efficient filter, it can improve system performance and power quality by minimizing harmonics and maximizing efficiency. This type of intelligent control is important to ensure that the system responds effectively to changes in electrical load and varying lighting conditions. Table 1 shows the configuration of the ICA, whereas Table 2 shows the ICA parameters.

Table 1. Configuration of the ICA

ICA	Configuration of the ICA
	Values
Number of countries	200
Number of Imperialists	10
Revolution Rate	0.2
β coefficient	1.4
ξ coefficient	0.02
Dimensions	200

Table 2. ICA parameters

Parameter	ICA parameters
	Values
Population size (n)	20
Probability of switching (p)	0.8
Number of iterations	150
Number of variables	3
Maximum limits [kp1, kp2, ki]	[40 30 10]
Minimum limits [kp1, kp2, ki]	[0 0 0]

In this study, the expression of the integration of absolute error ITAE multiplied by time is represented in (1).

$$J(ITAE) = \int_{0}^{\infty} t.\left|e(t).dt\right| \tag{1}$$

Equation (2) shows the error of the studied system is denoted as e(t), where t represents the integration time.

$$e(t) = \left(V_0 - ref(V_0)\right) + (I_L - ref(I_L)) \tag{2}$$

The error e(t) for the objective function's equation is a sum of the errors in DC-link current and DC-link voltage. The ICA algorithm is used in the suggested system to reduce the difference between the reference current and voltage and the actual current and voltage on the DC side of the system after adding a filter. The optimum controller parameter values for the proposed filter switches are presented in Table 3.

Table 3. Optimal values of controllers' parameters

Controller Type	The optimal vales	
	Value	
P controller	$K_P = 30$	
PI controller	$K_P = 4$	$K_i = 6$

5. Results and Discussion

5.1. The Simulation Description

The simulation begins with standard test conditions of 25 ℃ and $1000W/m^2$ solar irradiance. The duty cycle of the boost converter remains fixed at 0.5 from t = 0 sec to t = 0.3 sec. As a result, the PV voltage is calculated as (3).

$$V = (1 - D) * V_{dc} = (1 - 0.5) * 500 = 250\,V. \tag{3}$$

The output power of the PV array is $96\ kW$, while the specified maximum power at $1000W/m^2$ irradiance is $100.7\ kW$.

MPPT is enabled at t=0.3 sec, allowing the MPPT regulator to regulate PV voltage and extract maximum power by adjusting the duty cycle. The duty cycle of D = 0.453 results in obtaining a maximum power of 100.7 kW.

The PV array operates at standard test conditions (25 ℃, $1000W/m^2$) from t=0.3 sec to t=0.5 sec. The duty cycle D ranges from 0.450 to 0.459. The PV voltage is 273.5 V, as calculated in (4), and the mean power is 100.7 kW, which aligns with the PV module specifications.

$$N_{ser} * V_{mp} = 5 * 54.7 = 273.5\,V \tag{4}$$

During the time interval from t=0.5 sec to t=1.0 sec, the sun's irradiance gradually decreases from $1000W/m^2$ to $250W/m^2$. It is evident that this particular MPPT controller is designed to optimize power output only when the irradiance remains unchanged.

During the time interval from t=1.0 sec to t=1.5 sec, while the irradiance remains constant at $250W/m^2$, the duty cycle D fluctuates between 0.466 and 0.474. This variation in duty cycle corresponds to a PV voltage of $V_{PV} = 265$ V and an average power of $P_{mean} = 24.4\ kW$.

Between 1.5 seconds and 6.0 seconds, the sun's irradiance returns to $1000W/m^2$. Following this, the temperature is adjusted between 50 ℃ and 0 ℃ to study its effect. It is worth noting that the highest PV output power of 107.5 kW is achieved at the lowest temperature of 0 ℃.

5.2. Simulation Results

Changes in solar radiation and temperature over the study period are shown in Fig. 15 & Fig. 16, respectively. As shown in Fig. 17, The DC side voltage of the proposed system remains stable even with changes in solar radiation, demonstrating the effectiveness of the active filter and control plan. This is achieved by injecting an opposite and equal current to the harmonic content in the DC side voltages and currents. Fig. 18 & Fig. 19 illustrate the phase current on the grid side and its correlation with variations in solar radiation. It was noted that the current fluctuates in accordance with changes in solar radiation, gradually increasing as the radiation levels change.

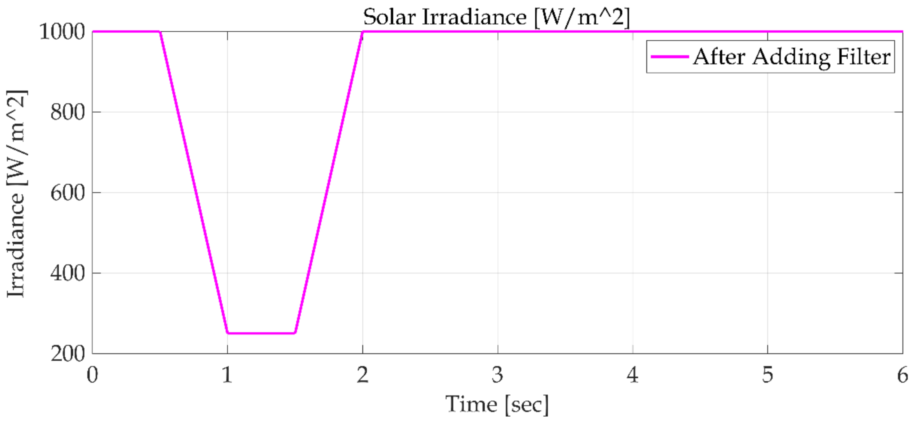

Fig. 15. Solar irradiance

The current variations are not abrupt, indicating that the inverter output current smoothly tracks the changes in solar radiation. This demonstrates the impact of the additional filter circuit in enhancing power quality within these systems. Fig. 20 illustrates that the voltage waveform at the inverter output becomes nearly balanced after the filter is incorporated, differing with the power quality issues typically experienced by PV systems at the inverter output.

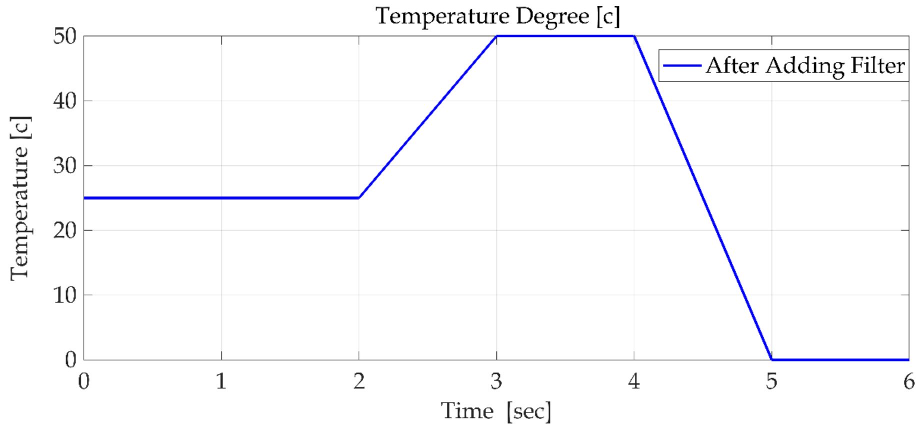

Fig. 16. Temperature

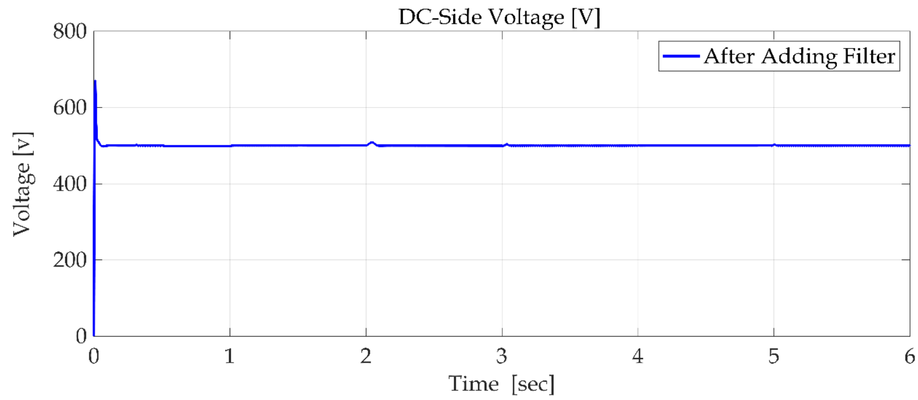

Fig. 17. Dc-link voltage

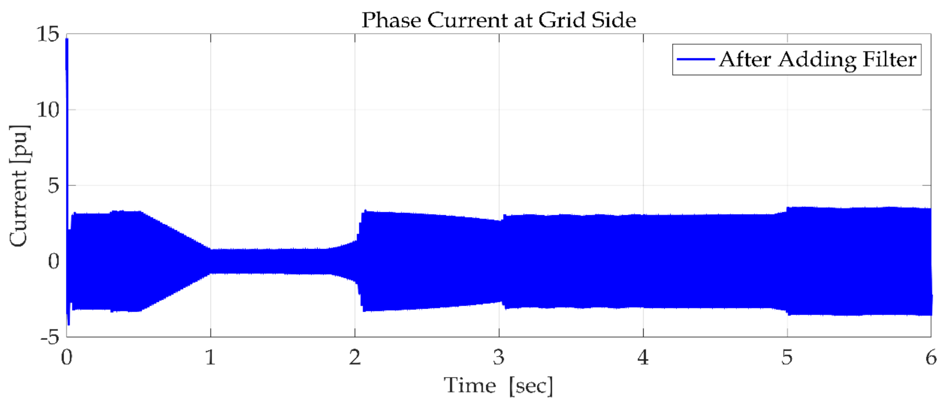

Fig. 18. Grid side current

As for the electrical energy injected into the grid, the Fig. 21 shows that the amount of energy injected into the grid varies smoothly with the variation of solar radiation, confirming the good dynamic performance of the studied system after the addition of the proposed filter. As illustrated in Fig. 22, the slight variations in duty cycle values correspond to fluctuations in solar irradiation, demonstrating the filter's ability to maintain stability amidst changes in solar irradiation intensity. This helps mitigate frequency issues that can compromise power quality in such systems.

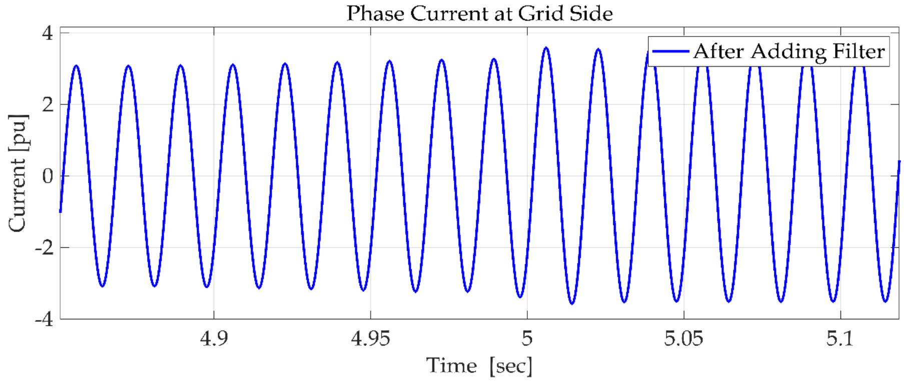

Fig. 19. Grid side current zoom view

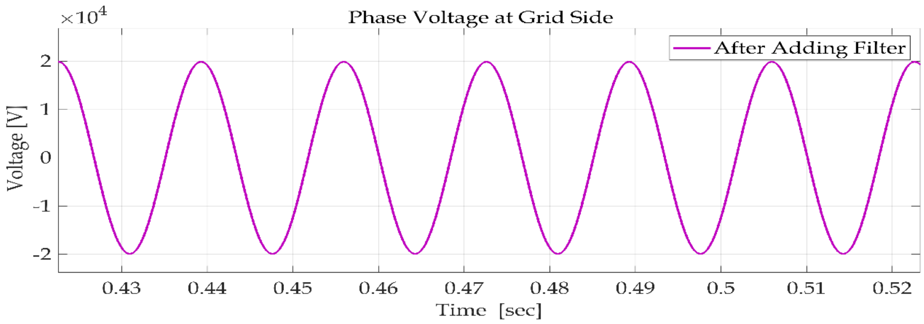

Fig. 20. Phase voltage at grid side

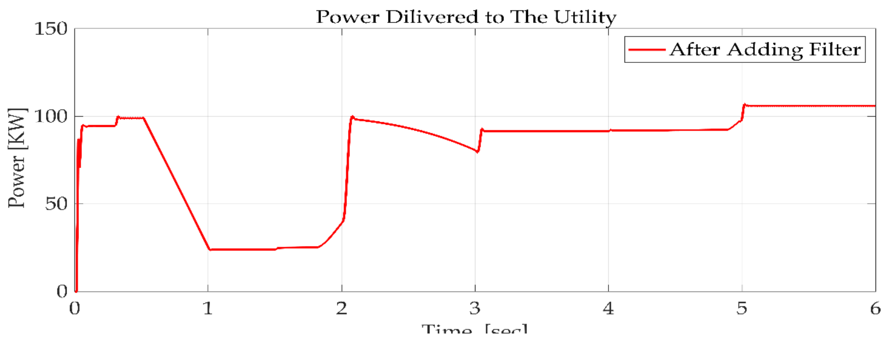

Fig. 21. Power delivered to the utility

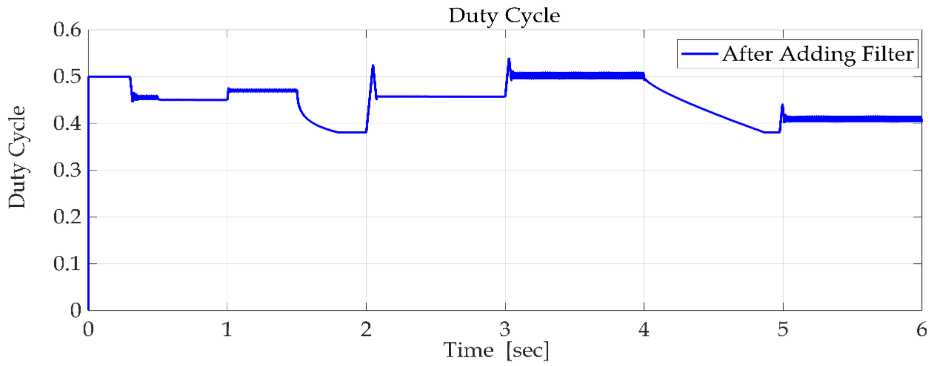

Fig. 22. Duty cycle

As shown in Fig. 23, the voltage produced by PV arrays is influenced by and changes with the level of solar radiation and temperature. As a result, the voltage output from these arrays remains relatively stable despite variations in both solar radiation and temperature. Fig. 24 shows the relationship between the average power fed into the grid and the variations in solar radiation and temperature.

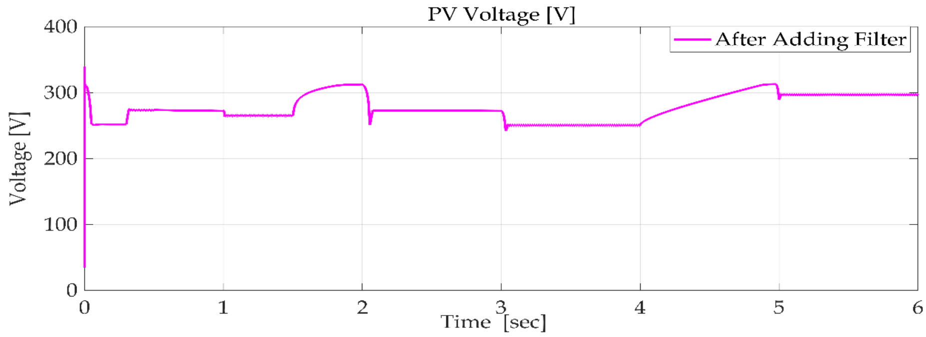

Fig. 23. PV voltage

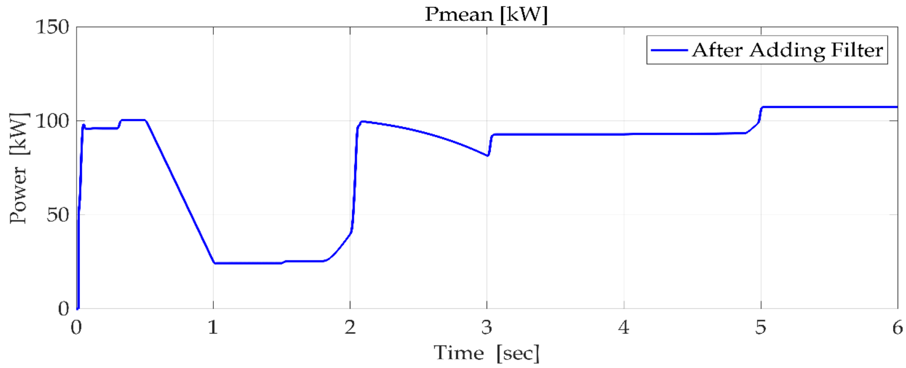

Fig. 24. Pmean

Fig. 25 shows the FFT of the grid current for the studied system during 6 cycles and notice through the figure that the value of the THD is 0.15%, while the value of the THD of the grid voltage is 0.22%, as Fig. 26 shows, which confirms the effect of adding the filter on improving the power quality of this system.

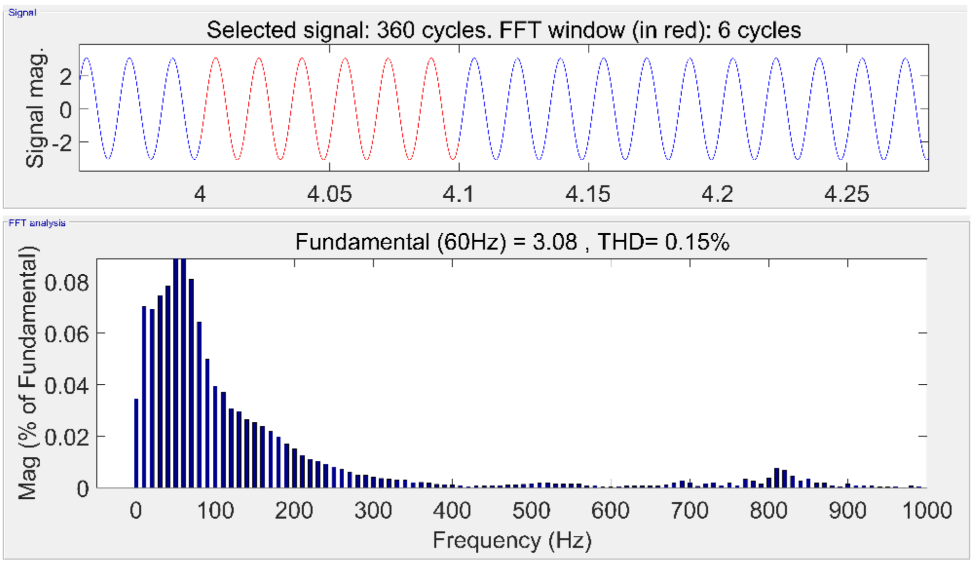

Fig. 25. THD% of grid current

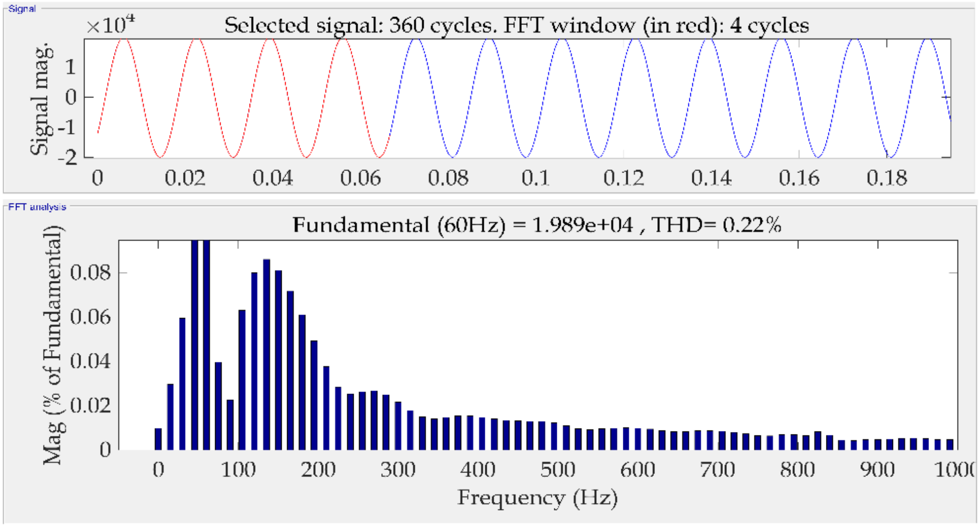

Fig. 26. THD% of grid-voltage

Fig. 27 shows a comparison of the proposed control scheme with some of the most important previous studies carried out in the field of power quality improvement of these systems. It is clear that the proposed candidate outperforms the best and most recent filters in circulation in this field.

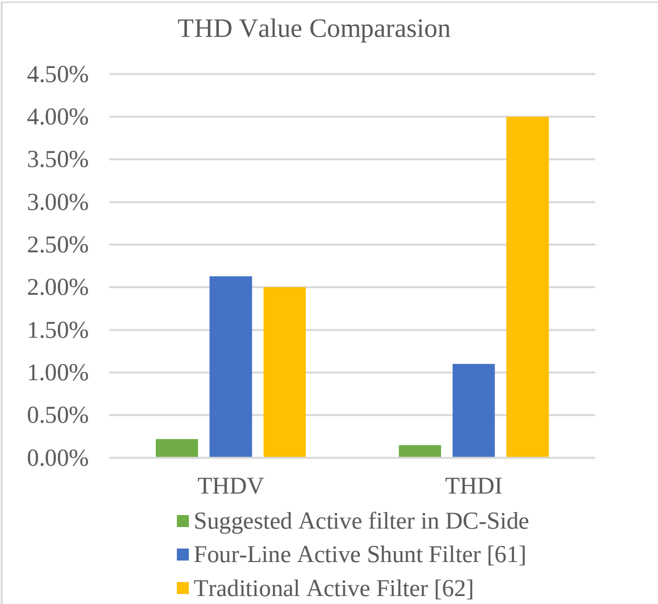

Fig. 27. THD values comparison with previous studies

6. Conclusions and Recommendations

This paper proposes to use ICA for optimal tuning of the controller parameters on the control circuit for controlling the switching operation of the active filter added in the DC side of grid-connected PV systems. The objective function, which is the integral of the absolute value of the error between the setpoint and the actual value for both current and voltage on the DC side, was used to minimize ripple. The effectiveness of active filters in grid-connected PV systems in mitigating harmonics and improving power quality has been demonstrated. These filters have successfully reduced THD in grid-connected systems while maintaining high power efficiency. The voltage distortion factor has been reduced to 0.22% and the current distortion factor to 0.15%. In addition, both voltage and current ripple on the DC side have been reduced significantly. Further research should focus on improving the controllers for controlling the switches operation in each of active power filters, inverters and other power electronic devices using for improving the power quality in grid-connected PV systems. In addition, a control strategy for PV inverters should be designed to address power quality issues at the point of connection (POC). In addition, advanced metering, sensing and control capabilities will be applied to ensure acceptable power quality for customers.

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