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Intelligence Based Controlling Models for Effective Power Tracking and Voltage Enhancement in Grid-PV Systems

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Abstract

The underlying research work is focused on enhancement in the efficiency and voltage gain for solar PV systems with the help of designing a novel regulating framework that includes advanced converter topologies integrated with intelligent control techniques. Optimization in extracting energy from the solar panel at different climatic conditions, voltage gain with minimum losses, and enhancing overall system efficiency and power quality are major tasks to be undertaken. The proposed control architecture presents a new Fractional Order Proportional-Integral-Derivative Control (FOPTC) technique and its adaptation mechanism for correct MPPT under dynamic variations of meteorological conditions. Consequently, it offers improved energy harvesting because it is able to identify the global maximum power point with higher speed and precision than traditional control techniques that apply hybrid approaches. The improved topological structure will ensure a substantial rise in voltage gain and efficiency with reduced voltage and current stresses upon the circuit components. In addition, the idea of a Neuro Feed Quadratic Controller (NFQC) is introduced to generate the regulating pulses for switching components of the converter for optimizing the voltage conversion process. Simulation and analytical studies confirm the higher efficiency, improved voltage gain, and reduced total harmonic distortion in the proposed framework over conventional systems.

Keywords:

Grid System; Photovoltaic (PV) Panels;

Maximum Power Point Tracking (MPPT);

Fox Optimized Power Tracking Controller (FOPTC);

Non-Isolated High Voltage Converter (Non-IHVC); Power Quality;

Voltage Gain and Neuro Feed Quadratic Controller (NFQC).

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1- Introduction

The demand for electricity increases in tandem with population growth and industrial development. The reduction of fossil fuels and the effect of carbon dioxide emissions allow Renewable Energy Sources (RES) to meet the demand for energy [1, 2]. According to the recent reports of the country's power industry, in the year 2022, India ranks third among consumers of energy produced, with a current power generation capacity of 404.13 GW. The most popular use of RES is solar Photovoltaic (PV) systems [3, 4], which offer advantages including fuel-free generating, low upkeep, pollution-free, and free of noise production. PV modules are made up of an array of solar or photovoltaic cells arranged in series as well as in parallel to meet the demands for the production of electricity. The temperature, radiation from the sun, and the rapidly changing environment all affect how much power the solar panels can produce. PV power exhibits a non-linear characteristics curve. Maximum Power Point (MPP) of PV modules must be reached in order to get the most power. Maximal Power Point Tracking (MPPT) [5-7] is a term used to describe MPP tracking. MPPT is often one ideal point on a dynamic curve that is extracted from solar cells using the DC–DC converter of the PV system. MPPT controllers are an essential part of a solar energy system since they optimize power generation and, consequently, the PV module's overall efficiency. An MPPT device is composed of an embedded electrical system with a control algorithm

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and a DC/DC converter [8]. Every PV installation is designed to extract as much energy as possible in real time, under every imaginable operating and environmental scenario. The most used MPPT control algorithms in PV systems are Perturb and Observation (P&O), Incremental Conductance (InC), Constant Current, and Constant Voltage. One of their advantages is that they work incredibly well in areas with homogeneous temperature and radiation, and they are reasonably easy to use. But all methods have shortcomings; thus they can't respond to continuous changes in the environment and can't recognize MPP [9].

Through the use of the constant procedure in steps and the derivative value and scaling factor, the existing works provide many methods for optimizing the MPP computation, including identifying the area under the MPP curve [10, 11]. One advantage of machine learning algorithms is that they are predicated on an understanding of the PV system and its environment. One drawback is that their effectiveness is largely dependent on their knowledge in creating regulations and membership requirements. Among the other disadvantages stated by them is the challenge of responding quickly when solar irradiation changes. The array's heterogeneous PV panels and the existence of one or more hot spots could impair system performance [12, 13]. Recently, there has been consideration of meta-heuristic algorithms, which are mainly intended to handle difficult situations with several variables and yield the optimal values. These were put forward due to the fact they can determine the global MPP by combining possible solutions or using random variables [14, 15]. During each iteration, these algorithms employ a number of particles to look for a possible solution. Having a lot of particles might increase the accuracy or speed. It can, however, also lead to tracking that requires less energy. Inappropriate energy fluctuation is also a result of the random variables that are employed in the solution's combination and selection [16-18]. This paper's primary goal is to apply an original and innovative optimization strategy for MPPT controlling along with a unique DC-DC converter design and its AI-based controlling technique.

Such interventions have generated a very high necessity and interest in the development and application of solar photovoltaic systems as one of the dependable sources of energy harnessed in sustainable ways. However, the traditional solar photovoltaic system is bedeviled with critical issues that result in reduced efficiency and performance. These problems include suboptimal maximum power point tracking in changing climatic conditions, low voltage gain, poor efficiency in voltage converters, and inefficient mechanisms of control for the operation of converters. More specifically, conventional MPPT techniques cannot handle dynamic weather variations and hence cannot track the global maximum power point, resulting in reduced energy extraction. The conventional DC-DC converters used by a PV system also have low voltage gain and efficiency that limits the overall performance of the system. Besides, most of the existing control strategies of converters are associated with complex mathematical operations and have not been efficient in handling the voltage conversion process, creating unnecessary energy losses and reducing the overall reliability of the system.

The present article therefore introduces a new framework by combining three original elements: the Fox Optimized Power Tracking Controller, the Non-Isolated High Voltage Converter, and the Neuro Feed Quadratic Controller. It is designed to accurately determine the global MPPs under changing climatic conditions so as to extract maximum electrical energy from the solar PV system. The Non-IHVC proposed a new converter topology that offers extreme voltage gain and efficiency, solving the limitations of conventional converters. In effect, the NFQC enhances the voltage conversion ability of the converter by generating the required regulating pulses accurately to keep proper operation of switching devices. The proposed framework has been tested through detailed simulation and performance comparison with traditional models using different parameters that prove its superiority in enhancing the efficiency and effectiveness of the solar PV systems. The following are this work's main contributions:

- To begin with, the Fox Optimized Power Tracking Controller (FOPTC), a cutting-edge controlling approach that can determine the global MPP in the face of changing climatic conditions, is used to extract the greatest amount of electrical energy from the solar system.
- As a result, Non-Isolated High Voltage Converter (Non-IHVC), a new converter topology, are used to improve PV output with higher voltage gain and efficiency.

Then, because it produces the regulating pulses needed to correctly operate the converter's switching devices, the Neuro Feed Quadratic Controller (NFQC) is designed to enhance the voltage conversion performance of the converter.

- Using a variety of parameters, the simulation results and performance of the suggested framework are verified and contrasted with the traditional models.

It advocates the integration of a set of advanced techniques toward some identified drawbacks of conventional solar photovoltaic systems. Among those will be the introduction of what it referred to as the FOPTD-Fractional Order Proportional-Integral-Derivative Controller. Unlike other conventional techniques prone to inefficient use of time, poor performances over varying environmental conditions, and harmonic generation, this newly integrated algorithm with adaptive characteristics fits just right for these. The novelty is that FOPTC can achieve the goal of optimizing the MPP tracking from the solar PV system, especially under fluctuating meteorological conditions. Unlike the classical MPPT techniques that may turn out to be less efficient with changing climatic conditions, the technique of FOPTC regulates its control parameters dynamically such that operation at or around the global maximum power point of the system is ensured. This leads to a substantial improvement in the energy extraction efficiency, which is of vital importance in order to maximize output from solar systems, in general, and particularly under changing solar radiation and temperature regimes. Such adaptability in FOPTC can ensure that solar PV operates at optimum through the day irrespective of ruling environmental conditions. The invention of Non-Isolated High Voltage Converter, Non-IHVC, topology is another novelty that has been introduced in this approach. The Non-IHVC significantly improves voltage gain and overall efficiency compared to other traditional converters. Traditional converters, such as DC-DC converters, usually have insufficient voltage gain and suffer from losses owing to the dependency on only single-stage or isolated topologies. The topology of a Non-IHVC topology is integrated with an interleaved boost converter, coupled-inductor substrates, and output-lift capacitors. This configuration improves the voltage gain and efficiency of the converter by reducing the losses normally encountered in the magnetic component and capacitive elements of the circuit. The interleaved nature also reduces the ripple in the output voltage, leading to smoother operation with less stress on the components of the system. Also, the coupled inductors will permit this converter to store and transfer energy more effectively to achieve higher overall performance, especially with the high voltage requirements of modern solar PV systems. This indeed leads to much better control while the energy losses are way lower than in conventional controllers, which experience inefficiency due to lagged response to changes in system conditions. This allows NFQC to generate the regulating pulses in real-time with regard to the actual operation state of the converter. With this, the system can work with a high input power factor and minimum energy loss.

The structure of the article is as follows: Background information, an overview of the topic, and the purpose of this page are all covered in Section 1. Section 2 presents a comprehensive review of the literature on MPPT controlling and grid-PV system power quality enhancement. In Section 3, the proposed framework is elucidated, and its operational mechanism is demonstrated. In Section 4, a range of metrics are used to validate the simulation and comparison findings of the proposed controlling techniques. In Section 5, the conclusions of this study are summarized together with recommendations for additional research.

2- Related Works

The comprehensive literature review of the models currently in use for maximizing power extraction from solar PV systems is provided in this section. It also looks into some of the most modern converter and controller topologies utilized in grid-PV systems, along with their advantages and disadvantages [19-22]. Some of the literature now in publication uses MPPT analysis techniques to reach the maximum operating point without utilizing machine learning algorithms, which come with a number of drawbacks due to the constantly shifting conditions of radiation exposure. Nevertheless, some other studies [23] tracked MPPT in PV systems using machine learning techniques. Siwakoti & Blaabjerg [24] used a flying capacitor transformer-less inverter to increase the single-stage PV systems' efficiency. Additionally, it reduced current output ripples, flipping loss, and distortions by utilizing a Pulse Width Modulation (PWM) technique [25, 26]. Here, three distinct operating modes have been employed: zero state, positive cycle, and negative cycle. The principal benefits of this method were enhanced compensating capacity and no leakage current. A single-stage DC-to-DC converter had been developed by Lakshmi & Hemamalini [27] to adjust the DC voltage using MPPT. Here, it was shown that reactive power required a significant amount of inverter current to be supported. Then, in order to guarantee that the necessary standards of power quality had been fulfilled, the LCL filtering technique was put into effect in conjunction with the controlling strategy. Throughout the simulation investigation, the active and reactive power modifications had been determined with a constant load state. In order to maximize the power produced by solar PV panels, the P&O MPPT algorithm had been applied. In this instance, the boost DC-DC converter topology caused an increase in the PV system's output voltage. The SRF can operate in both steady and reactive modes in real-time application systems. This method had the advantages of a large voltage gain and simple calculations. It does not, however, address the primary problem of increased harmonic contents in output power resulting from nonlinear load.

An Advanced Universal Power Quality Conditioning System (AUPQS) has been put forward by Rahmani et al. [28] in order to deal with the effects of distortion and harmonic problems that plague electrical grid systems. Here, uneven load conditions have been utilized to obtain the voltages that emerged by the use of the series active filtering technique. PV systems may operate successfully if MPPT is used, which increases the grid systems' overall performance. A dynamic golden search-based MPPT controlling technique for PEMFCs that has been demonstrated by Bahri & Harrag [29]. The golden search is a technique for finding the absolute highest or lowest value of a curve within a specified range of values, or for a unimodal function, by progressively limiting the range of values that a known parameter point is present inside. The golden search method is used in the research suggestion to find the MPP in the PEMFC curve. PV systems may operate more efficiently if MPPT is used, which increases the grid systems' general efficiency. Yang et al. [30] created the P&O with SMC to capture solar energy from PV systems under a wide range of different environmental situations. In this instance, the granularity of the input and output linearization could be guaranteed by creating the control gain matrix. Benefits of this regulating strategy included reduced unmodeled dynamics, increased stability, and randomized fluctuations.

Despite all the efforts toward research in the area of solar PV systems, there exist a number of critical gaps in making these systems efficient with regard to maximum power extraction and overall system efficiency. One important research gap relates to the inadequacy of MPPT techniques that are in use today. Most of the previous works implement conventional MPPT methods without machine learning algorithms; thus, they cannot adapt to radiation variability. These conventional methods normally cannot work at their maximum under different environmental conditions, which results in less-than-optimal energy extraction from solar PV systems. Further, to a limited extent, a number of studies have been done to extend the use of machine learning approaches in MPPT tracking. However, such implementation is yet to be considerably wide, and the possible benefits that such advanced algorithms can offer remain largely unexplored. This calls for much more innovative and adaptive MPPT solutions that would respond to changes in solar conditions on a dynamic basis to assure maximum power extraction.

Few converter topologies are able to deliver both efficiency and simplicity. The traditional DC-DC converters developed for grid-PV applications generally suffer from low voltage gain, poor efficiency, and increased circuit complexity. Although some of the modern designs of converters, like the flying capacitor transformer-less inverter proposed by Siwakoti & Blaabjerg [24], have been successful in improving efficiency and reducing the ripples in the current output, they are still not at their optimum design. Many converter architectures that have been proposed so far either lack in promising their required performance over a wide range of operating conditions or pose other problems like increased component stress and higher costs. Therefore, new converter topologies that can offer high voltage gain without compromising on simplicity and reliability are in urgent need.

The other prominent gap exists in the topologies of controllers used to control the operation of these converters. Most of the existing controller strategies are found to be inefficient and have complex mathematics involved in them. These conventional controllers often result in a lack of control precision that should be optimum for the performance of converters and usually increase energy losses, reducing system reliability. Some research works have introduced neural network-based controllers and other advanced techniques for control, but these are still not yet mainstream, their full potential having not been realized. This, therefore, calls forth the need to develop more efficient and robust control strategies that can integrate with such advanced converter designs for improved system performance.

Finally, there is a deficiency in full validation and comparison of new frameworks against pre-existing models. While individual parts of PV systems, like MPPT algorithms, converters, or controllers, have been studied in detail, there is hardly any general framework integrating those parts and validating their performance jointly against traditional models. These gaps suggest deeper studies not only to propose new techniques but also to test and compare them vigorously for various parameters in order to prove the superiority and practicality of the results in real-world applications. Addressing these gaps will move the field of solar PV systems very far ahead toward efficient, reliable, and cost-effective solutions for renewable energy harvesting.

The survey results show that there are benefits and drawbacks to the current converter and controller architectures. When it comes to issues with rising voltage drop, fluctuations, and speed of response, it typically fails. To solve these problems, the proposed investigation intends to design a new controller using MPPT and a DC to DC converter layout.

Most of the challenges with solar PV systems are power-efficiency-simplicity-reliability tradeoffs; for instance, DC-DC converters and their control mechanism designs are major areas where many of the challenging problems need to be overcome. Traditional DC-DC converters applied to grid-connected PV systems fail to satisfy high voltage gain, effective energy conversion, and low circuit complexity simultaneously. Most of these designs are plagued by a multitude of limitations in the form of poor efficiency, low voltage gain, and electrical component stresses that lead to increased maintenance costs and risks in operation. However, they also do not present the optimal solution. In general, such converters face a tradeoff between complexity and performance, hence they are not feasible for wide-range applications. It follows that there is an immediate need for new-generation converter topologies capable of ensuring high voltage gain, efficiency, and simplicity on both counts. In fact, available solutions meet the above requirements comprehensively for a narrow range of operation conditions.

Besides the converter architecture, control strategies for converters present another significant gap. In most converters, traditional controllers involve complex mathematical formulations that cannot easily provide the desired precision and reliability, given their limited adaptability. Most of the conventional techniques have resulted in increased energy losses, deteriorated system stability, and reduced operational efficiency. While application of neural network-based controllers and other innovative mechanisms of control has given promising results to enhance the precision of control with a minimum of energy losses, practical implementation and integration in mainstream applications remain rather limited. This calls for more robust, efficient, and adaptive control strategies that will go hand-in-hand with advanced converter topologies. Such controllers should address the deficiencies of the existing methodologies and also be up to the modern technological developments to harness and generate energy effectively with guaranteed system performance.

3- Proposed Methodology

The overall block diagram, circuit model, and mathematical renderings are included in this part along with a comprehensive discussion of the suggested grid-PV system. The goal of this research is to create new and distinctive regulating strategies using converter topology to enhance grid systems' overall power tracking performance and voltage conversion efficiency. The three main goals of this work are to maximize electrical energy generation by utilizing innovative MPPT controlling, improve high voltage gain output by utilizing a special DC-DC converter model, and support voltage regulation with an efficient converter controlling model. Figure 1 depicts the flow of the suggested structure, which includes the following operational modules:

- PV modeling;
- Fox Optimized Power Tracking Controller (FOPTC) for energy generation;
- Non-Isolated High Voltage Converter (Non-IHVC);
- Neuro Feed Quadratic Controller (NFQC) for converter;
- DC-AC inverter;
- Grid system.

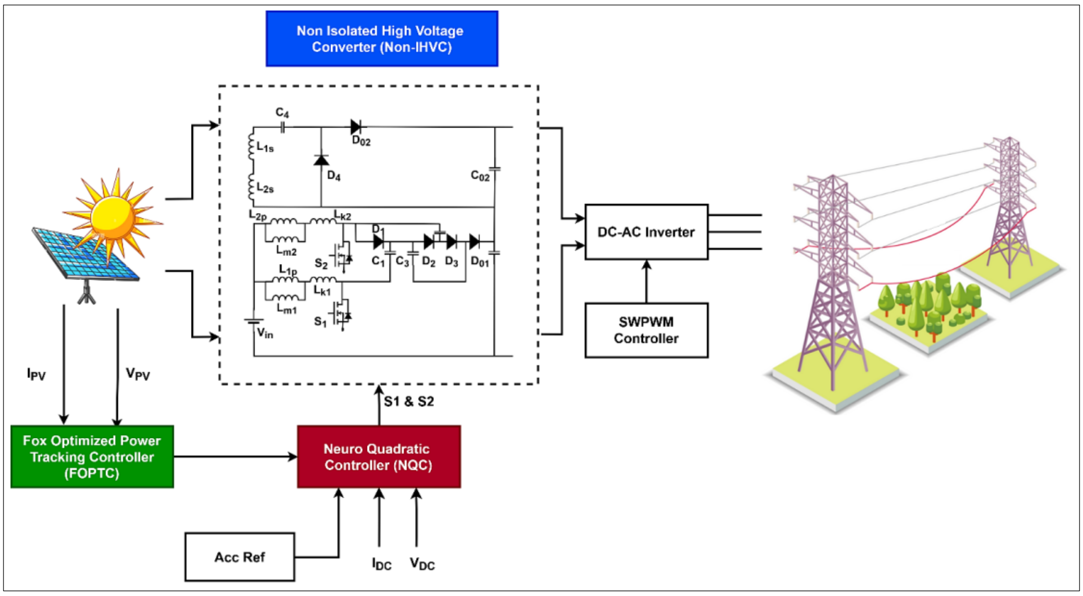


Figure 1. Block diagram of the proposed work

Supplying energy to the many resources that nature provides is one of the most significant tasks in the modern world. There has been a lot of discussion about the benefits that renewable sources of energy have for various application industries. Most grid-based businesses utilize Solar Photovoltaic (PV) systems to harvest sunshine as a dependable source of energy. Solar PV finds applications in many application scenarios due to the easy accessibility and efficient design of the panel. The PV modules normally work at maximum efficiency to draw out the maximum amount of power from the solar system with the help of the MPPT technique. Some traditional solar PV systems apply part of the hybrid control techniques, which have limited scope on issues of more time consumption, lower efficiency, and high harmonics.

Firstly, Fox Optimized Power Tracking Controller (FOPTC) is a state-of-the-art technique in controlling, able to identify the global MPP with meteorological conditions. This extracts the maximum quantity of electrical energy from the solar system. What is unique about FOPTC is its adaptive algorithm, making the proper functioning of the tracker under all climatic conditions optimal in performance. Increasing energy extraction efficiency thus depends on new converter architecture—the Non-Isolated High Voltage Converter—for boosting the output voltage and efficiency of PV output. The Non-IHVC proposes a special interleaved boost converter with a coupled-inductor substrate along with output-lift capacitors that greatly increase the voltage gain and efficiency compared with traditional converters.

The NFQC is then designed to ensure that the converter works at an optimum voltage conversion efficiency by coming up with the regulating pulses that drive its electronic switches to work in order. What is novel about the NFQC is the integration of a neural network-based feed-forward mechanism that helps in precision control with reduced energy losses, way above that which has been attained by conventional control methods. The outcomes and simulation results of the proposed framework were compared with traditional models and validated against a variety of parameters that turned out to be more efficient, offering higher voltage gain with lesser operational complexity.

Following the PV panel model, the new FOPTC model is used to maximize solar energy yield in response to changing climate conditions. Based on the recently created Fox Optimization (FO) algorithm, which provides the best way to determine the MPP for tracking solar energy, this controlling technique was created. Consequently, the novel Non-IHVC topology is used to improve and raise the voltage level of high-gain output photovoltaic systems. With minimal complexity, this converter efficiently reduces the voltage and current stress on the circuit's electrical components. This study employs an intelligent NFQC technique to enhance the converter's performance by producing the regulating pulses needed to operate the switching components of the converter. The proposed framework's voltage conversion efficiency and voltage gain are significantly increased by using this controlling model. After that, the DC-AC conversion is carried out using a standard SVPWM regulating model, which provides the grid with high-quality power that has fewer harmonics.

The proposed work involves various innovative and new contributions relating to the sociology of solar PV energy systems, especially in regard to improving the methods of power extraction and conversion processes. One of the exciting novelties of the described deliverables is the implementation of the Fox Optimized Power Tracking Controller (FOPTC). Compared with conventional MPPT methods, FOPTC has better efficiency in searching for the global MPP in the condition of different meteorological factors. This helps in maximizing electrical energy being produced by the solar PV system within the fluctuating environmental conditions like temperature and irradiance. The FOPTC’s abilities to track and follow through on elaborate changes in the condition of the system when implemented can be seen as a major improvement compared to other hybrid control strategies since they come with higher time consumption, lower efficiency, and elevated harmonic distortion.

This is another innovation in the context of this work, as the project integrates new converter architecture known as the Non-Isolated High Voltage Converter (Non-IHVC). Specifically, for increasing the voltage gain and efficiency of the PV output, this converter is the most suitable one. This makes the Non-IHVC have a better design than the ordinary converters that makes it act as a better solution in voltage conversion, hence enhancing the efficiency of the PV system in energy harvesting. The Non-IHVC structure is designed for low energy losses and maintaining its stability at high voltages, and thus, the authors’ proposed system can be considered as a valuable contribution to the advancement in the use of power electronics in renewable energies. Moreover, one can identify another major contribution concerning the Neuro Feed Quadratic Controller (NFQC). The NFQC is designed to ensure that the Non-IHVC has an enhanced voltage conversion efficiency by providing the correct regulating pulses that affect the functioning of the converter’s switching devices. This controller applies neuro-fuzzy algorithms to control the conversion process with high efficiency and reliability because the controller adapts to the changes in parameters. The high flexibility of adjusting the control parameters in real-time offers a better efficiency of the PV system through the improvement of the NFQC, which establishes a new standard in voltage conversion methods of renewable energy systems.

3-1- Fox Optimized Power Tracking Controller (FOPTC)

The novel MPPT controlling model, FOPTC, is developed in the proposed study and used to maximize PV panel electricity under varying environmental conditions. A range of optimization techniques are used in the earlier literature works [31-33] to maximize the amount of electricity produced by the solar panels. However, the traditional controlling algorithms have a number of issues related to imprecise power tracking, inefficiency, and a lengthy search time for the optimal solution. In order to maximize the energy yield from the solar systems, the suggested research study intends to apply a unique optimization-based controlling technique. This controller is developed based on the process of Fox Optimization (FO) technique; it differs from other models in that it mimics the ways of a red fox in the snow for foraging and exploring. In order to plunge into a blanket of snow and chase its food, it also imitates the jumping technique. During the exploitation stage, the prey evaluates the red fox's geographical separation, after which the fox determines the jump technique needed to descend and pursue the prey. For Foxes to jump in the other direction and towards the northeast, an impostor fox is also recommended. Consequently, the distance to the prey, the jump value, and the direction range value are used to figure out the new location. Additionally, the avoidance of local optima is supported by lowering a particular value. One important way to avoid becoming trapped in local optima is to base the exploration phase on the average time variable and the optimal position. Making use of a random variable in conjunction with a condition, the exploration and exploitation stages are controlled. The objective of this variable is to evenly distribute the amount of iterations among the stages equally. When it comes to maintaining equilibrium and avoiding local optima, the proposed strategy is crucial. In order to split the iterations properly between exploration and exploitation, a condition statement is used. Every iteration, the value of the variable is reduced, indicating that the agent continues to pursue the prey more effectively. This parameter is used to lower the effectiveness of searching based on the optimal position. The fitness value influences the search agents in order to prevent local optima as well as to serve as the condition for updating the position. If the updated position remains unchanged, the exploration phase disables to clear the way for future phases to function.

PV voltage, PV current, and duty cycle are the input parameters used in this controlling model. These parameters are initialized along with the particular optimization parameters, such as population size, fitness value, and maximum number of iterations. The prerequisite for killing the prey has been established for the exploitation stage. The fox measures how far away from the prey it is in order to calculate its new position based on how far sound travels. It is represented mathematically as follows:

$$\mathcal{DS}_i = \mathfrak{S} \times \varsigma \tag{1}$$

$$\mathfrak{S} = \frac{\beta_i}{\varsigma} \tag{2}$$

where, $\mathcal{DS}_i$ indicates the distance of sound, $\mathfrak{S}$ denotes the sound speed in the air, β_i is the best position of fox, and ς represents the random value ranging from 0 to 1. The red fox must locate a new location once it has determined how far away from the prey it must jump in order to grab it. The fox must therefore determine the jump height $\mathfrak{U}$. It is determined using the equation that follows:

$$\mathfrak{U}_i = 0.5 \times G \times \mathscr{s}^2 \tag{3}$$

where, G indicates the acceleration gravity that is valued as 9.81, and $\mathscr{s}$ represents the average time that the sound consumes to travel. As a consequence, the new position of fox is determined according to the following model:

$$F_{(i+1)} = \mathcal{DP}_i \times \mathfrak{U}_i \times x \tag{4}$$

where, $F_{(i+1)}$ indicates the updated new position of fox, $\mathcal{DP}_i$ represents the distance of prey, and x is a random value ranging from 0 to 0.18. In the exploration phase, the fox uses its best location thus far to guide its random walk by doing random searches. In order to investigate prey in the search area, the fox must wander erratically, hence it lacks a jumping technique during this phase. A minimum time factor and the value of the variable are used to manage the search to make sure the fox moves randomly in the direction of the best place. The time transition value $\mathcal{T}$ is estimated according to the minimum time variable as shown in below:

$$\mathcal{T} = \frac{Sum(\varsigma(j,:))}{D}, \mathscr{mt} = Minimum(\mathcal{T}) \tag{5}$$

where, ς is the time of sound travel, D is the dimensionality, and $\mathscr{mt}$ represents the minimum time variable. Moreover, the best optimum solution is identified according to the new position update of fox in the searching space as mathematically represented in below:

$$F_{(i+1)} = \mathcal{B}F_i \times r(1,D) \times \mathscr{mt} \times k \tag{6}$$

where, $F_{(i+1)}$ indicates the new position, $\mathcal{B}F_i$ denotes the best searching agent, and k is the optimization parameter computed as shown in below:

$$k = 2 \times \left(i - \frac{1}{Mx_i}\right) \tag{7}$$

where, i is the current iteration and M_i is the maximum number of iterations. The global optimal value, which is utilised to locate the MPP for obtaining maximum energy yield, is computed based on the updated position using the best searching agent.

In particular, the Fractional Order Proportional-Integral-Derivative Control technique results in higher efficiency in the Solar Photovoltaic systems than any other traditional hybrid control technique. The first and major advantage of the FOPTC technique is that it handles the intrinsic nonlinearity and dynamic nature of solar PV systems more aptly than conventional PID controllers. Classic PID controllers, based on integer-order calculus, even tuned with some assumptions about system behavior, have poor performance if environmental conditions change-such as temperature, irradiance, or shading. In fact, such sudden changes will lead to sudden variations in the operating point of the PV system, for which classic controllers have quite a problem acting effectively in MPPT. By contrast, the fractional-order calculus utilized in FOPTC allows for more flexibility regarding the tuning of the proportional, integral, and derivative terms within a wider range of frequencies. It is this fractional approach that indeed enables FOPTC to fit better into the dynamic response of the system, in particular when the variations are smooth functions of time-the most frequent case for a solar PV generator. The fractional-order terms enable the controller to give more smooth and precise control signals that guarantee faster convergence to the maximum power point with fewer oscillations in the output power. Therefore, FOPTC will ensure operation of solar photovoltaic systems at the maximum power point with overall efficiency even when the environmental variations are fast. The FOPCTC method could bring in such fractional-order terms having potential responses resulting in stability and, importantly, better performance during long-term operation. Greater efficiency and reliability of a solar photovoltaic system mean improved energy harvesting and further reduction of energy losses associated with suboptimal tracking conditions. Figure 2 shows the flowchart of the research methodology through which the objectives of this study were achieved.

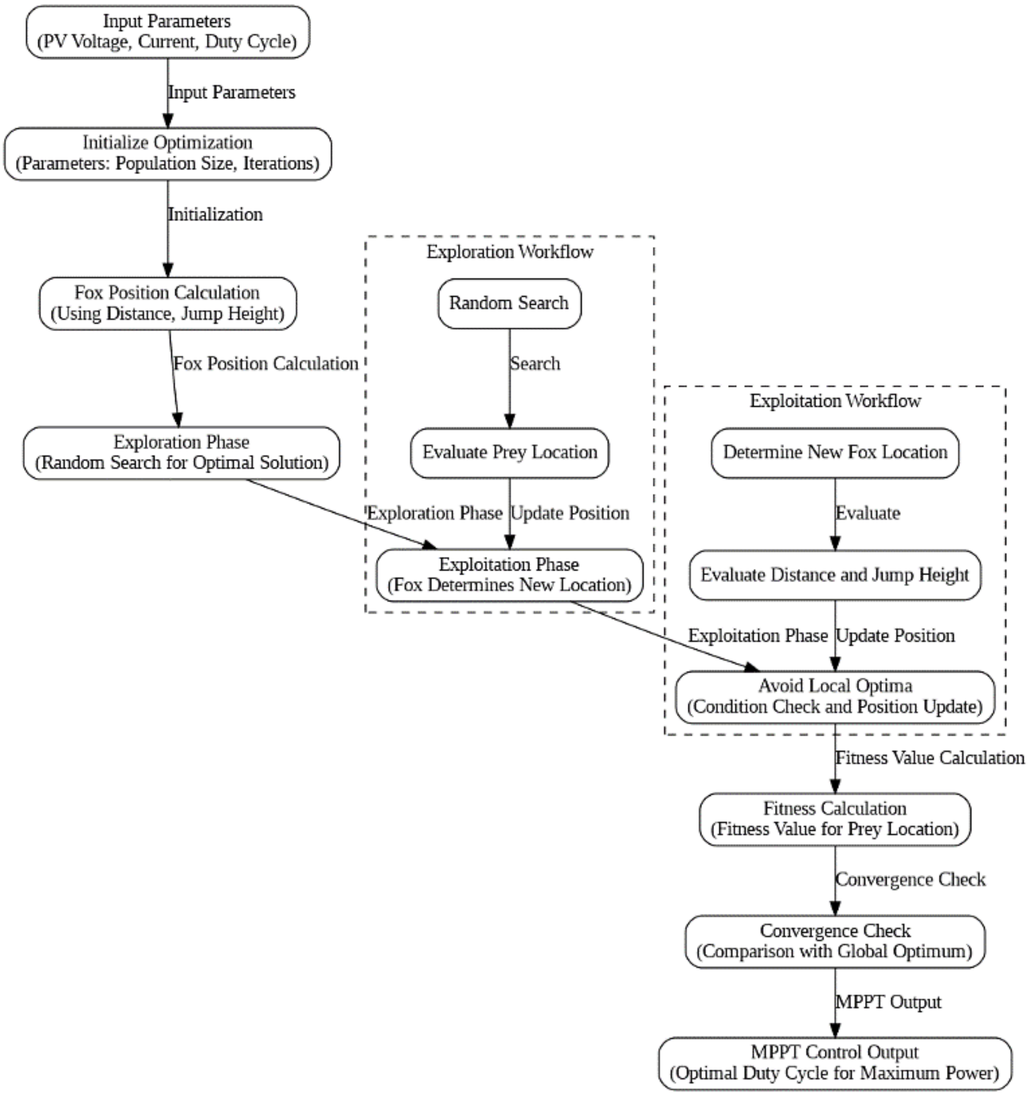


Figure 2. **Flowchart of the proposed FOPTC**

3-2- Non-Isolated High Voltage Converter (Non-IHVC)

The Non-IHVC converter model is an innovative way to increase PV voltage with high-gain voltage output and efficiency in the proposed grid-PV system. A range of DC-DC converters are used for voltage regulation and boosting in the literature. However, they have three main issues: low gain output, poor efficiency, and increased circuit complexity [34-36]. Therefore, for grid-PV applications, the proposed work develops a novel and distinctive converter architecture called Non-IHVC. An interleaved boost converter with a coupled-inductor substrate serves as the model for the proposed converter. At both the primary and secondary ends of the coupled inductor, output-lift capacitors and diode-capacitor coefficient units are used to improve their peak voltage capacity.

The Non-IHVC is a new prospect in the field of DC-DC converters for grid-PV systems. Traditional converters often encounter three critical issues: lower gain output, comparatively poor efficiency, and higher diffusion of complexity of the circuit. The shortcomings mentioned above are to be resolved in the proposed Non-IHVC that features a considerably improved architecture that would increase the voltage gain and efficiency of the converter while retaining a fairly simple design. The interleaved boost converter with a coupled-inductor substrate as the basic model is one of the new features of this study. This design also makes it possible to achieve better performance and stability in operations, especially in high voltages. Although the Non-IHVC has been derived from the IHVC at a primary-secondary coupled inductor connection, a number of new aspects have been introduced throughout the converter: output-lift capacitors and diode-capacitor coefficient units are placed at both ends of the coupled inductor. This configuration increases the maximum voltage output capability and therefore increases the voltage gain compared to usual models of converters. This is a significant advancement because in the imperative grid-connected PV systems, the competency of traditional converters in achieving real-voltage gain is generally elusive due to issues with the regulation of voltage gradients, which is an essential feature for efficient electrical power transmission and promotion. It also has its own operational mode that boosts the performance of the Non-IHVC. In mode 1, the switch S1 is turned ON and S2 is OFF; the leaking inductor Lk1 and the magnetizing inductor Lm1 charged exponentially towards the input voltage Vin. Such an energy storage system causes minimal discharge of energy and the right charging of the inductor's voltage. Besides, diode D2 remains in the reverse-biased state during this operation due to the electrical voltage across the capacitors C2 and C3 that helps in reducing power loss during the operation and increases the efficiency. Since S2 is off, it resulted in the movement and storage of energy from the magnetizing inductance Lm2, leaking inductor Lk2, and C2 to C3 across S1. The conversion process that takes place in this case is efficient, and they alleviated the problem of energy wastage, which is prevalent in converters. A further advantage of the Non-IHVC is in the ability to amplify the power level further with increased efficiency. The energy transferred to the secondary windings and capacitors is well regulated and used to supply the load through diodes and the second set of windings, thus making the converter highly efficient, even when there are several changes in load. The control of current through the primary and secondary windings of the coupled inductor is done efficiently, which reduces losses and improves the performance of the converter.

In general, the parameters of Non-IHVC need to be cautiously selected according to the required performance objectives of high voltage gain, efficiency, and also the capability of operating under various input conditions, including solar irradiance and temperature. Major parameters of the converter—that is, duty cycle, inductance, capacitance, and switching frequency—are chosen to optimize the efficiency with the required voltage conversion ratio. At this point, the duty cycle is optimized in order to have maximum voltage gain with minimum losses due to switching and conduction. The values of inductance and capacitance are chosen to minimize ripple, provide stable operation for different load conditions, and enhance the efficiency of the converter. Additionally, the switching frequency is adjusted to reduce the losses due to switching since the high rate of converted power has to be provided. All these parameters should be optimized through simulations and theoretical studies in such a way that operating conditions under which the entire system will work would point to a good efficiency of the converter, with the expected output to be derived from the solar panel and grid connection requirements.

The circuit model of the proposed Non-IHVC is shown in Figure 3, and its appropriate modes of operation are illustrated in Figures 4-a to 4-f. When S1 is switched ON and S2 is turned OFF, mode 1 commences. The leaking inductor Lk1 and the magnetizing inductor Lm1 start being charged exponentially towards V_{in} by S1 as soon as S1 is turned on. Because of the orientation of the electrical voltage spanning capacitors C2 and C3, the diode D2 remains reverse biased throughout this CI1 energy storage operation. Due to S2's deactivation, the energy that has been stored in the magnetizing inductance Lm2, leaking inductor Lk2, and C2 becomes backwards biased, flows to C3, and charges across S1. The secondary windings of L1s and L2s drain and control at their ends, respectively, based on the current conditions of L1p and L2p. By D02, the energy held in the secondary winding and C4 gets delivered to C02. When the current via L2s almost hits zero, Mode 1 comes to its end. The following model represents the mode 1 operation:

$$I_{L1p}(\mathrm{t}) = I_{S1}(\mathrm{t}) - I_{C1}(\mathrm{t}) \tag{8}$$

$$I_{L2p}(\mathrm{t}) = \frac{V_{in} - V_{C1}(\mathrm{t})}{L_{2p}} \times \mathrm{t} \tag{9}$$

$$I_{L2s}(\mathrm{t}) = I_{D4}(\mathrm{t}) = \frac{1}{n} I_{L2p}(\mathrm{t}) \tag{10}$$

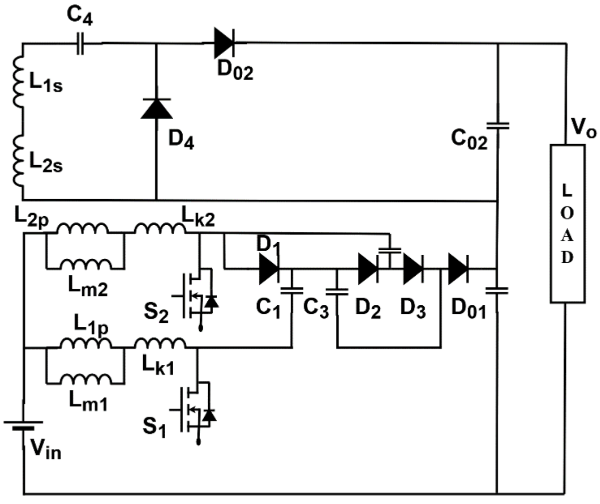
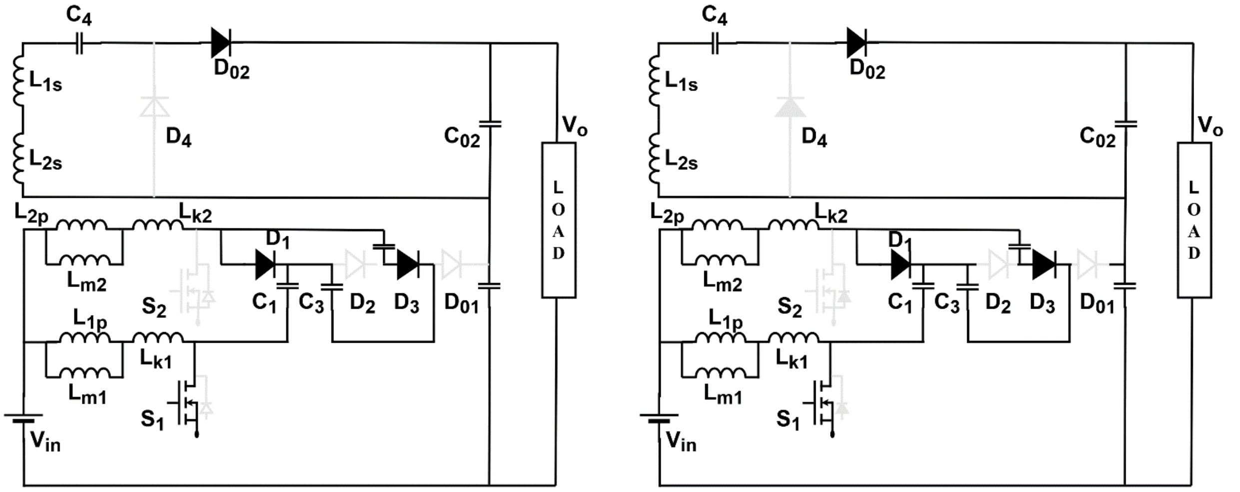
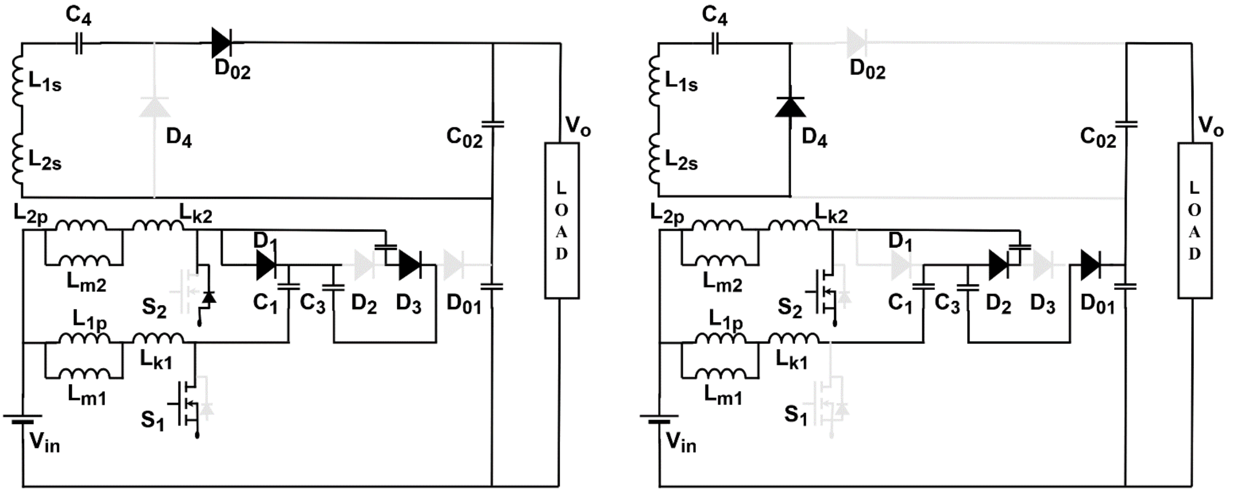


Figure 3. Circuit model of Non-IHVC



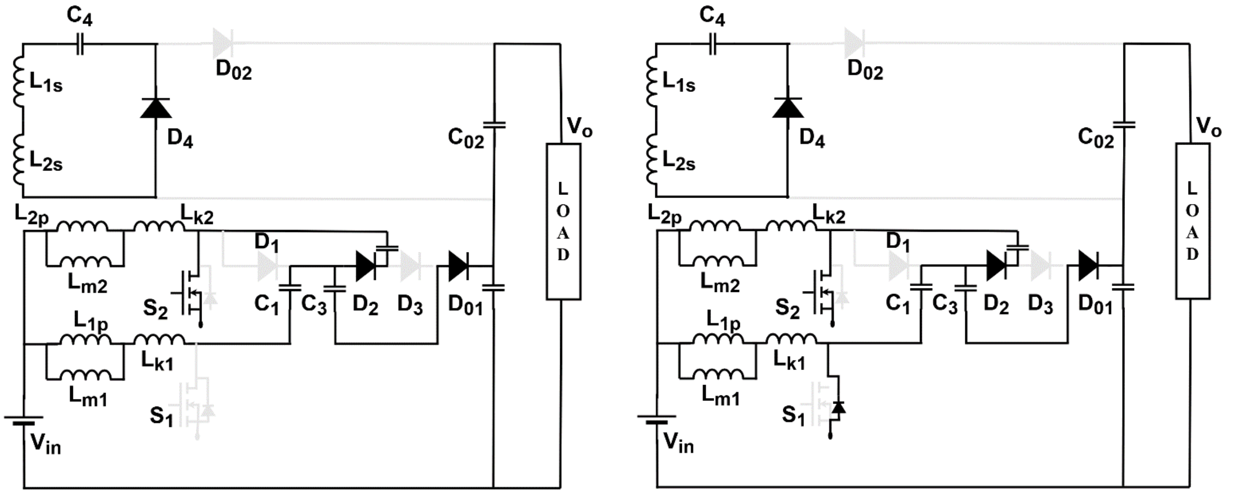
(a) Mode 1

(b) Mode 2



(c) Mode 3

(d) Mode 4



(e) Mode 5

(f) Mode 6

Figure 4. Converter mode of operations

The energy retained by Lm1 increases at Mode 2, as S1 is turned ON, and Lm2, the magnetising inductor, fully transfers to C2 and C3. The energy held in L1s is moved to C02 at the level of the secondary side. When the current through L1s turns negative, the current via L2s begins to increase since it is charging. When S2 is prepared to switch ON, mode 2 comes to a conclusion. Mode 3 is when S2's diode is biassing forward and starts to flow. As a result, S2 experiences a tiny negative current. The diode of S2 is turned off when the current flowing across Lk2 drops to zero, releasing the maximum amount of energy stored in Lk1. Thus, L1p's and L2p's corresponding energy retention and distribution operations come to an end. When switch S2 is activated and switch S1 is deactivated, mode 4 starts.

Magnetising inductor Lm2 begins to charge linearly towards Vin while S2 is turned on and runs in the form of energy storage mode. The electricity stored in the leaking inductor Lk1 and magnetising inductor Lm1 flows to C2 by means of D2 since S1 is deactivated. D1 is biased by the opposite direction of the voltage crossing C1. While L1s stores energy, L2s functions in the energy discharge interval at the second side. D02 continues to be opposite-biased while the total energy kept in the additional windings is passed on to C4 by means of D4. At zero current flowing via L1s, mode 4 comes to an end. In Mode 5, the magnetising inductor Lm1 keeps transferring its stored energy to C1, C3, and C01 while the amount of energy held within Lm2 keeps increasing. The output capacitor C02 releases the energy it holds to the demand, and the device's control capacitor C4 stores energy at the other end of the circuit. When S1 is ready to be turned back on, Mode 5 comes to an end. S2 stays in the ON state during Mode 6. The possible discrepancy between S1's anode as well as cathode endpoints causes the anti-body diode to be forward-biased. Thus, a negative current flows through S1 as a result of current flowing across it from the grounding point through C1. The diode of S1 goes turned off and the current via Lk1 hits zero, signalling the completion of a flipping cycle. The voltage stress among the switching devices and diodes are computed as shown in below:

$$V_{S1} = V_{S2} = \frac{V_{in}}{1-D} \tag{11}$$

$$V_{D1\ to\ D3} = \frac{2}{1-D} \times V_{in} \tag{12}$$

$$V_{D01} = \frac{2+\aleph}{1-D} \times V_{in} \tag{13}$$

Similarly, the current stress of switches and diodes are also estimated according to the following equations:

$$I_{S1} = I_{L1p} + I_{L1s} \tag{14}$$

$$I_{S2} = I_{L2p} + I_{L2s} \tag{15}$$

$$I_{S2} = I_{S1} = \frac{I_{in}}{2} \tag{16}$$

The proposed grid-PV systems have higher overall voltage gain output and efficiency thanks to the use of this converter model.

This design of a power circuit has an unparalleled uniqueness with novelty in its way of application in the domain of power electronics; it is completely different from any other conventional structure, because of the inimitable integration of avant-garde components and techniques. This design introduces newer concepts, along with the modern approach and architecture of the overall design, thus enhancing overall efficiency, performance, and reliability compared to conventional circuits. The proposed circuit integrates new control strategies with optimized topologies, overcoming a number of limitations found in previous models. Some of the limitations typical in older circuits include poor energy conversion rates, inadequate load regulation, and inefficient power management under variable conditions. The proposed circuit is differentiated by carefully selected components working together to enhance system performance in real-world applications. The circuit is designed to implement the latest advances in semiconductor technology, such as wide-bandgap devices, and allows for much higher efficiency than that of previous designs. Additionally, it will be designed to adapt dynamically to changes in load conditions and/or varying input sources, optimizing performance under a wide range of environmental and operational conditions. The above-mentioned dynamic adaptability, in combination with a strong feedback mechanism, increases this capability of the circuit to provide stable power output even under unfavorable conditions-a capability that has often been beyond the reach of traditional designs due to their inability to accommodate such fluctuations.

Furthermore, the design approach embeds modern optimization techniques in the form of intelligent algorithms for power management, which ensure that the circuit operates at peak efficiency across a broad range of operating conditions. These inventions of the proposed circuit not only distinguish from traditional model circuits but also beyond the boundary, which could be attained by power conversion systems. Consequently, it comes out with superior performance power circuit in energy efficiency, compactness, and reliability and at the same time upgrading the defects of the earlier designs. It has thus ensured that the proposed power circuit is not a reproduction of any of the traditional ones but an advanced solution towards satisfying the rising demands of various modern power systems and applications.

3-3- Neuro Feed Quadratic Controller (NFQC) for Converter

This study uses a novel controlling technique called NFQC for the converter in order to measure its overall voltage conversion efficiency. Numerous controlling strategies [37, 38] are used for the converter component in the earlier literature publications. However, the bulk of controlling models are limited by two key problems: inefficient controlling and mathematical operation complexity. The two variables that make up this controller's construction are the controlling input matrix and the value of the definite state. To obtain a suitable response, the closed-loop system's effectiveness has a connection with the eigenvalue generated by these weighting vectors. This process establishes a feedback gain matrix by optimizing the cost function.

The Neuro Feed Quadratic Controller offers revolutionary technology in converter control through its patented, unique, and very effective solution for voltage conversion efficiency. Traditional control methods are normally inefficient and mathematically complex; hence, their performance is degraded. NFQC's innovative design enables it to transcend such traditional inefficiencies through advanced neural network architectures and optimized feedback mechanisms. Probably one of the main novelties brought by the NFQC is the implementation of a feed-forward network technique within neural network architecture. In this respect, it would mean that multiple other additional layers would be added to the neural network, enhancing its ability to model complex relationships or dynamic behaviors of the converter system. By utilizing a deep learning framework, the NFQC can very effectively manage and optimize the control processes to obtain more precise and efficient voltage conversion. This is very different from traditional control strategies that are usually based on simpler, less adaptive models.

The two critical variables used in the construction of the NFQC are the matrix of controlling input and the definite state value. These variables are used to determine how well the closed-loop system performs; this performance is linked directly to these eigenvalues, which are generated by the weighting vectors. The NFQC optimizes these eigenvalues to provide an optimal and very effective feedback gain matrix that ensures the best possible control performance. The cost function is used in conducting optimization, and it is minimized by the NFQC while seeking the best possible control outcomes. This use of the cost function has the advantage of systematizing and objectifying the design of the controller so that high performance is always ensured by NFQC. Another exclusive component of the NFQC is its ability to concoct suitable responses through its sophisticated feedback mechanisms. The controller will continuously be fine-tuning its feedback, gain matrix with real-time data and can adapt to any changes in conditions to maintain optimal performance. Thus, dynamic adaptability offers considerable leverage over traditional controllers, typically fighting for efficiency against changing operational conditions.

Advanced neural network techniques are used in the NFQC, making it novel. Deep learning will enable the controller to deal with complex nonlinear relationships within the converter system that usually are hard to be handled by traditional controllers. Capabilities in handling such complex nonlinear relationships empower the NFQC to achieve higher accuracy and efficiency for modern converter applications.

In order to implement the feed forward network technique, a number of layers have been included to the neural network's architecture. Every consecutive layer is connected to the layer before it, and the highest layer produces the network's output. A feed forward network can be applied to several kinds of mappings between outputs and inputs. A hidden layer in this network possesses sufficient neurons in it to cope with any limiting input-output mapping issue. This neural network has a multi-layer structure and learns the network by employing the back-propagation approach. This method generates the controlling signal for the converter as the output and passes the PV voltage, PV current, accelerated reference, DC output voltage, and DC output current to the inputs. Here, the fully connected feed forward structure $\mathcal{O}_{\mathcal{N}}(a)$ is formulated as shown in the following equation:

$$\mathcal{O}_{\mathcal{N}}(a) = \mathscr{f}_M \circ \mathscr{f}_{M-1} \circ \ldots \circ \mathscr{f}_1(a) \tag{17}$$

$$\mathscr{f}_m(h) = \rho(w_{1h} + b_1) \tag{18}$$

where, $m = 1,2 \ldots M$, ρ denotes the non-linear activation function, w_{1h} is the weight value, b_1 indicates the bias value, $\mathscr{f}_M(.)$ defines the scalar output function, and $\rho_M(.)$ is the identity function. As a consequence, the linear dynamic parameter integrated with the neural network is estimated as represented in the following equation:

$$X^{\mathcal{N}}(a) = \frac{1}{\partial} Log[1 + \partial X^R(a)] + w^{\mathcal{N}}(a) \tag{19}$$

where, ∂ indicates the trainable parameter, R is the linear quadratic function, and $a^{(i)}$ defines the input information. Then, the loss value for the predicted output is mathematically represented as shown in below:

$$\underset{X}{\mathbb{L}(\theta)} := \frac{1}{|\delta|} \sum_{i=1}^{|\delta|} \left[X^{(i)} - X^{\mathcal{N}}(a^{(i)};\theta)\right]^2 \tag{20}$$

$$\underset{Y}{\mathbb{L}(\theta)} := \frac{1}{|\delta|} \sum_{i=1}^{|\delta|} \left[Y^{(i)} - X_a^{\mathcal{N}}(a^{(i)};\theta)\right]^2 \tag{21}$$

where, $X^{(i)}$ and $Y^{(i)}$ are the outputs, $\mathbb{L}()$ is the loss function, and $\mathcal{N}$ denotes the network. This algorithm is used to generate the controlling pulses that drive the converter's switching components.

Obviously, there are many advantages of NFQC over traditional control techniques. First, a neural network-based feed-forward approach significantly enhances modelling and control capability in complex systems. In other words, this provides voltage conversion with higher accuracy and efficiency—quite vital in high-performance converter applications. Traditional controllers have linear models that miss nonlinear dynamics of new converters and hence perform suboptimally. These limitations are overcome by the deep learning framework NFQC, which provides a more robust and adaptable control solution.

It is further guaranteed by the eigenvalue analysis and minimization of a cost function when optimizing the feedback gain matrix, ensuring that the NFQC will work with maximum possible efficiency. Systematic design in this respect overshadows conventional methods that have so far been largely trial-and-error or heuristic tuning. In contrast, NFQC optimizes control parameters in a very structured and objective way, therefore assuring more reliable and consistent performance. It also reduces mathematical complexities usually associated with the control of converters. It is indeed through automation of all optimization and control processes via neural network techniques that the NFQC manages to simplify the implementation and maintenance of the control system. This reduced complexity makes the NFQC more workable and of wider application. This, coupled with dynamic adaptability to changing conditions, gives it a high-performance boost over static control models. Most of the variations in operating conditions which can take place require manual adjustments, or even reconfiguration, with conventional controllers—a very time-consuming, inefficient process. Thereby, this self-adjusting feature of the NFQC assures that it is running at peak performance without human intervention.

The Non-IHVC topology has obvious merits in the improvement of voltage gain and efficiency compared to the classical converters, mainly due to the efficient step-up or step-down of high input voltages without isolation. Traditional converters are buck or boost converters, isolated by an input-to-output transformer that might also introduce some extra losses due to core loss, resistance of winding, or switching losses. On the other hand, Non-IHVC uses the principle of direct coupling between input and output, hence eliminating any transformer and thereby reducing substantial losses associated with the mechanism of isolation. This direct coupling simplifies not only the converter design but also enhances the overall efficiency of the system by minimizing the conversion losses normally arising from magnetic components in isolated converters. Besides, Non-IHVC topologies are often designed with high-voltage capability, enabling them to deliver higher voltage gains at lower switching frequencies, thus enhancing their energy efficiency and minimizing losses due to switching transitions. Further, Non-IHVCs are indeed designed with various advanced control mechanisms, including voltage-mode control or current-mode control, to optimize their performance in the wide range of input and output conditions for higher efficiency and better voltage regulation under varying load conditions.

The Neuro Feed Quadratic Controller has a great contribution to optimizing voltage conversion efficiency by implementing an intelligent and adaptive control mechanism using neural network principles. Unlike the traditional controllers, which employ fixed control parameters set prior to their use, a neural network in NFQC keeps readjusting its control strategy based on instant or real-time feedback from the system. This is possible by the adaptability of NFQC optimally operating the Non-IHVC through continuous learning and readjustment to variations in the input voltage, output load, and environmental factors like temperature. Application of the neural network in NFQC allows predictions with compensation effects that possible disturbances in the system are held-off when running an active Converter at operating-point-optimal for a big bandwidth operation. Besides, the quadratic nature of NFQC allows the converter response to be fine-tuned for better voltage output regulation with minimal ripple and noise, which could degrade system performance. The NFQC, therefore, is especially an ideal complement to Non-IHVCs in that it can operate against dynamic changes in load and input conditions without manual adjustments or recalibration in cases when voltages are fluctuating and power demand is continuously changing. Therefore, a very efficient and robust voltage conversion system within high variations of load and fluctuations of the input voltage is assured with this Non-IHVC topology combined with an NFQC controller because of their synergy

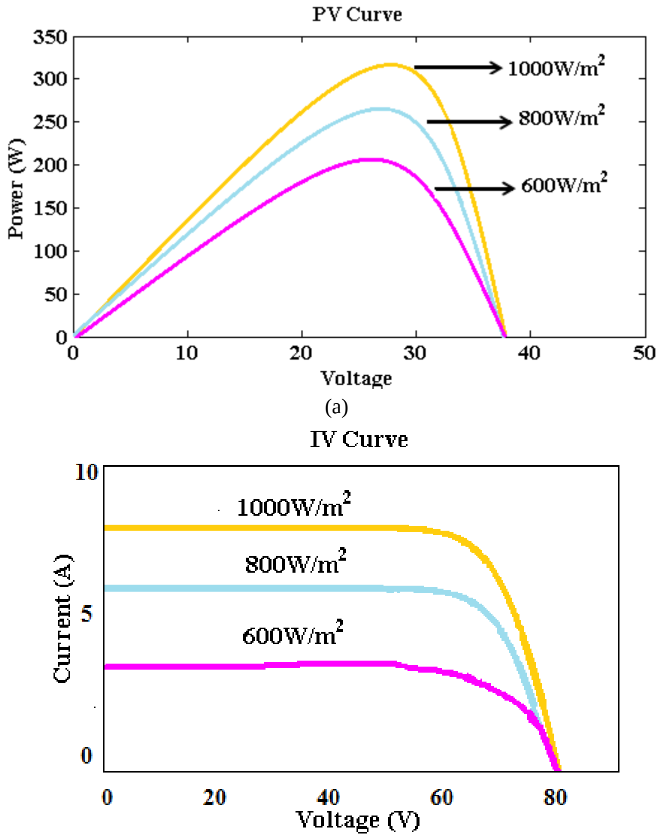
4- Results and Discussion

By using a variety of assessment metrics, this section verifies the proposed framework's simulation performance. Here, the suggested model's results have been implemented and validated using the Matlab/Simulink tool. The parameter settings are given in Table 1.

Table 1. Simulation parameters

Parameters	Value
Maximum power	320 W
Maximum voltage	37.1V
Maximum current	8.63A
Short circuit current	9.08A
Open circuit voltage	45V
Duty ratio	0.5

The power voltage (PV) and current voltage (IV) characteristics of the proposed controller design under different temperature and irradiation circumstances are displayed in Figures 5-a and 5-b, respectively. The primary purpose of analyzing and monitoring the IV characteristics is to determine the real power produced by the PV modules under specific operating conditions. These characteristics make it possible to estimate how much power the regulating technique can extract. The study indicates that the suggested controller design provides an identical reproduction of IV and PV properties together with a fast and dynamic response. The MPPT performs much better and has better IV and PV characteristics when the FOPTC is used. As a consequence, the solar irradiation is also depicted in Figure 6.



(a)

(b)

Figure 5. (a) P-V characteristics, (b) I-V characteristics

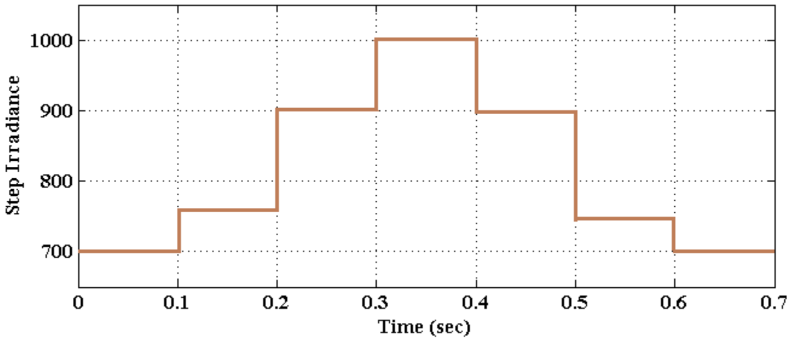


Figure 6. Solar irradiance

In this investigation, the duty cycle was linearly varied to confirm that the PV system was functioning at its peak power. The MPPT algorithms can raise the output power of PV panels by progressively altering the duty cycle of the converter that serves as the interface between the load and the panel. The collected findings showed that the proposed technique may attain the ideal duty cycle faster and with less steady-state oscillations. In this study, the simulated model is used to validate the efficacy of the proposed FOPTC controller and the conventional ANFIS controller with frequent-varying input. To control the duty cycle, periodic perturbations of 0.01 s and a switching frequency of 5 kHz have been chosen. The tracking of speed variability and oscillations are decreased by this performance. Instantaneous power differentiation in the PV for both controllers is shown in Figures 7 and 8. It has been determined that the proposed FOPTC controller has a noticeably superior tracking footpath than the current controller when undergoing uniform radiation.

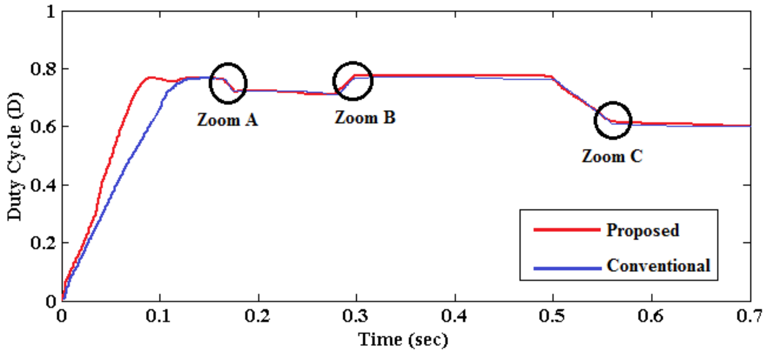


Figure 7. Duty cycle of converter

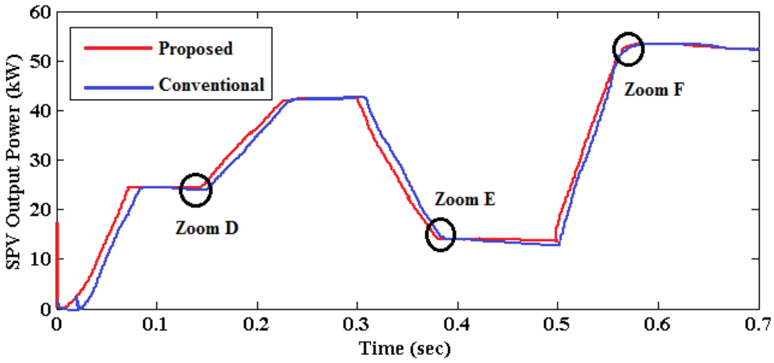
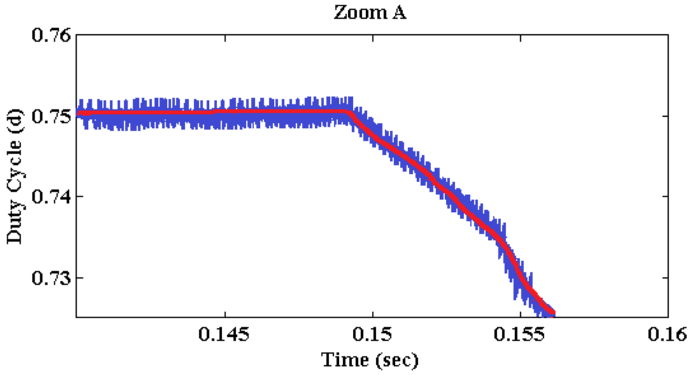
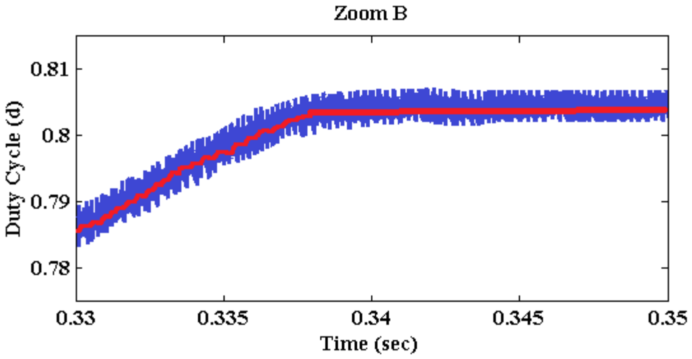


Figure 8. Power tracking performance

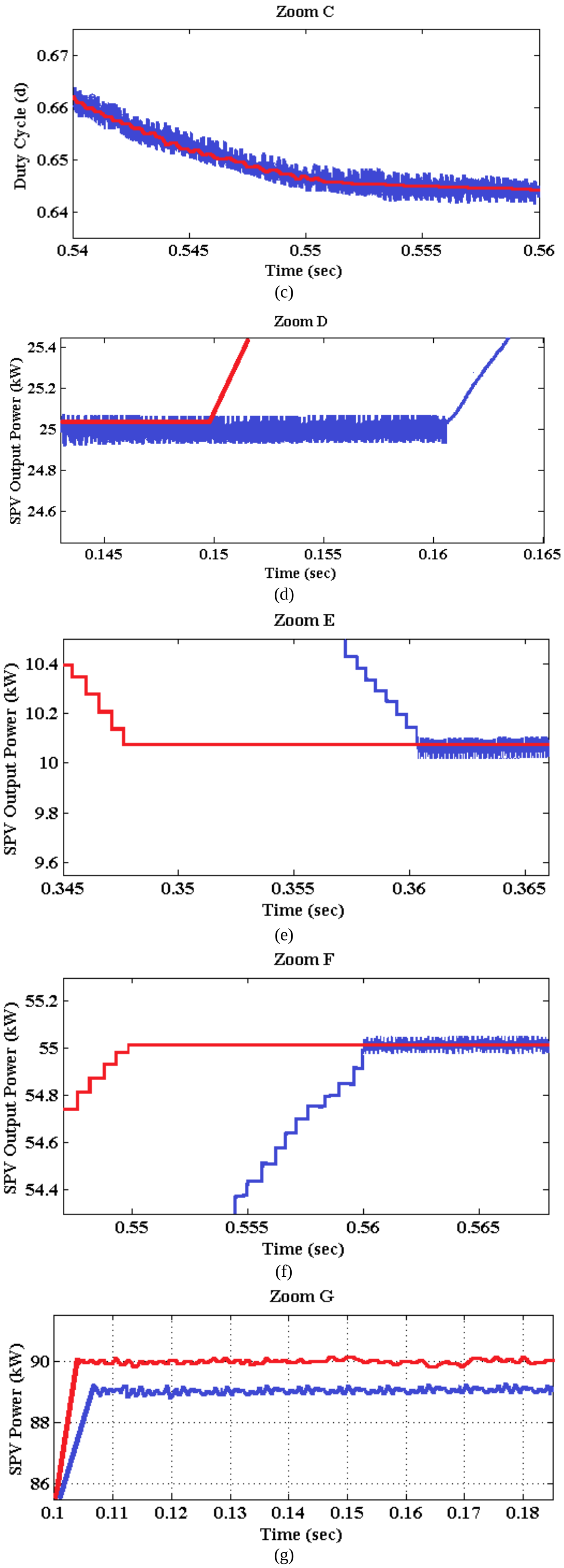
As shown in Figures 9-a to 9-i, the duty cycle's zoomed viewpoint reveals the output's imbalance, which is almost completely eradicated. The simulation demonstration exhibits the FOPTC controller's faster response time compared to the current controller under both steady-state and changing circumstances. With the use of the simulated model, the PV evaluates the performance of the proposed FOPTC controller in comparison to the conventional controller for often variable input. The duty cycle has been chosen to be controlled by steady perturbations of 0.01 s and the switching frequency of 5 kHz. The tracking speed variance and oscillations are decreased with this accuracy. It was observed that the proposed FOPTC controller has a noticeably superior tracking capability than the existing controller while undergoing uneven irradiation.



(a)



(b)


Zoom C
Duty Cycle (d)
0.67
0.66
0.65
0.64
0.54
0.545
0.55
0.555
0.56
Time (sec)
Zoom D
SPV Output Power (kW)
25.4
25.2
25
24.8
24.6
0.145
0.15
0.155
0.16
0.165
Time (sec)
Zoom E
SPV Output Power (kW)
10.4
10.2
10
9.8
9.6
0.345
0.35
0.355
0.36
0.365
Time (sec)
Zoom F
SPV Output Power (kW)
55.2
55
54.8
54.6
54.4
0.55
0.555
0.56
0.565
Time (sec)
Zoom G
SPV Power (kW)
90
88
86
0.1
0.11
0.12
0.13
0.14
0.15
0.16
0.17
0.18
Time (sec)

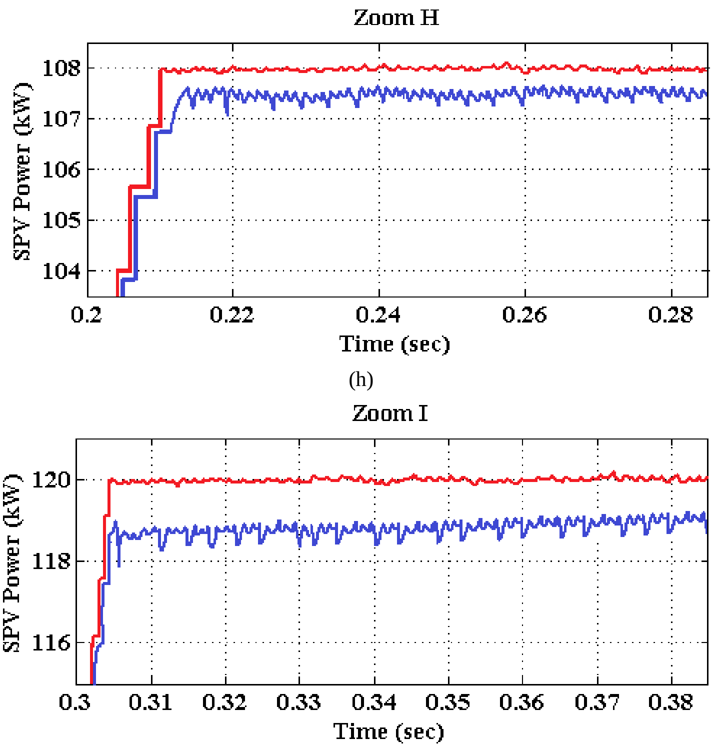
(c)

(d)

(e)

(f)

(g)



(h)

(i)

Figure 9. Zoomed view of duty cycles at changing time sequences

The time variation of the obtained duty cycle reflects the system's efficiency in delivering power to the load. It is varied with respect to the operating condition for the optimum extraction of power from the PV system. Meanwhile, Figure 8 presents the power tracking performance of the system—how well the converter can track and regulate the power due to changes in irradiation and load conditions. Power tracking is very vital in order to maximize energy harvested from the PV system, especially under variable environmental conditions such as changes in sunlight intensity or cloud cover. The proposed converter system, along with the FOPTC controller, demonstrates very good capability of adapting to these variations and maintaining optimum power output to enhance the overall performance of the PV system.

Figure 9, consisting of sub-figures from (a) to (i), depicts the zoomed view of the duty cycle vs. time to clearly visualize the imbalance in the output, which is almost completely compensated by the proposed control method. It also gives a perfect view of the duty cycle in the changing time sequences, proving that the FOPTC controller has a strong ability for quick tracking changes of input and thus gives it a faster and more steady response than traditional ones. From the simulation results presented, under steady-state as well as dynamic conditions, the FOPTC controller gives a far more stable output with much-reduced oscillations along with quick tracking, especially under changing conditions of irradiance. This improvement in the tracking ability is important in that it gives a minimum ripple in power output, and even when the input energy fluctuates, it means the PV system operates at maximum efficiency. Steady perturbations of 0.01 seconds with a switching frequency of 5 kHz for the control of the duty cycle were chosen to realize fine-tuned regulation for better performance of the system. In this simulation, one can notice that the FOPTC controller gives significantly better performance than a classical controller in terms of achieving higher tracking accuracy with improvement in handling unsmooth variation of irradiation input faced by most real-world PV applications. Moreover, the output voltage and power of PV are validated and compared with the conventional controlling model as shown in Figures 10 and 11, respectively. At a constant temperature of 25°C, the grid efficiency, ramp variations irradiances, and dynamic step irradiances are all considered in the performance evaluation of the PV.

These figures together provide a complete insight into the performance of the proposed converter system to regulate the voltage and power output effectively, even under dynamic and challenging environmental conditions. Comparing the results with traditional controllers, it is deduced that the controller FOPTC offers better power tracking, faster response times, and stability to ensure efficient and optimal operation of a PV system in real-field conditions. It follows that further performance of grid and load current justifies good effectiveness for the proposed converter in integration and deliverability in regard to providing power to a load in view. Such a system turns out to be quite suitable for applications where maximal energy harvesting, together with appropriate interaction in case of power networks, cannot be supported with the least distortion.

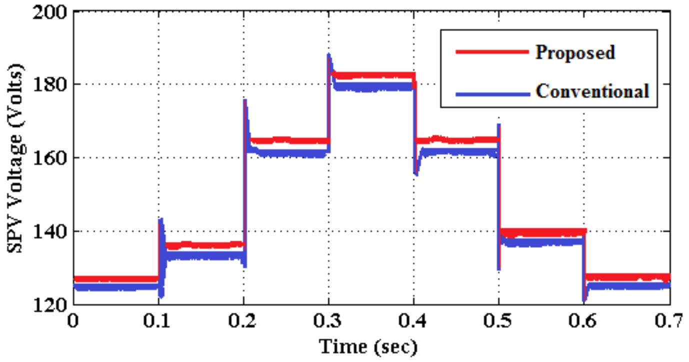


Figure 10. Voltage of PV

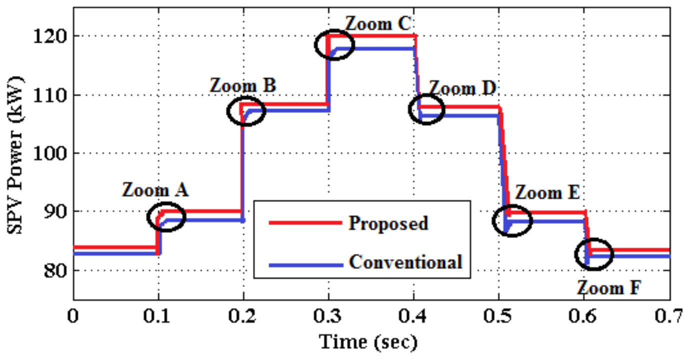


Figure 11. Power of PV

As seen in Figures 12 and 13, the grid system's performance is evaluated using the grid current and voltage characteristics. Because the converter's and the controlling models' voltage regulation and power tracking efficiency are the only factors affecting its performance. Consequently, the load current is also estimated as shown in Figure 14.

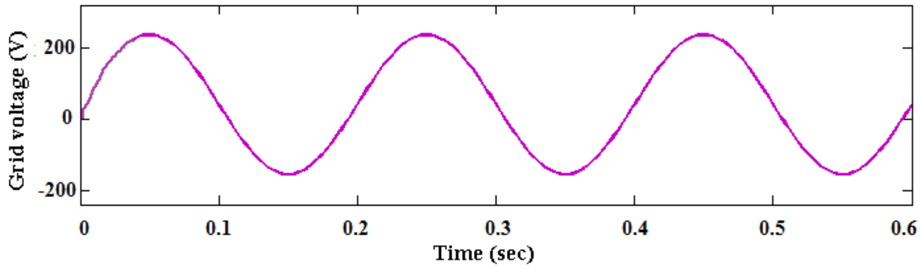


Figure 12. Grid voltage

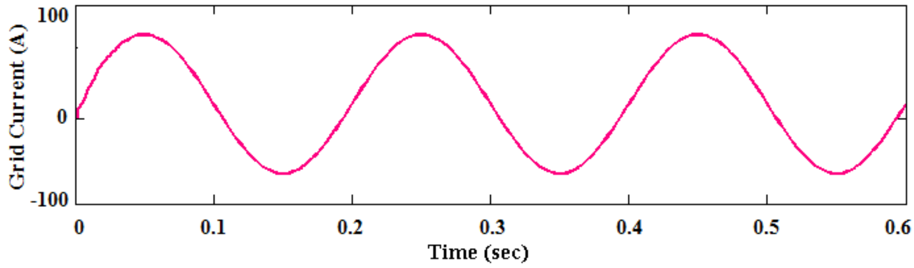


Figure 13. Grid current

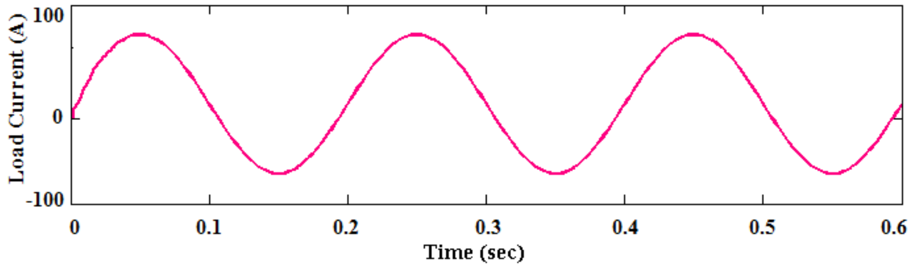


Figure 14. Load current

Furthermore, as Figure 15 illustrates, the Total Harmonics Distortion (THD) of the proposed circuit models is validated. In order to ensure improved system efficiency and performance, the elevated level of harmonic contents must be properly minimized. This is because it can negatively impact the performance of the overall grid-PV system. According to the gathered results, by enhancing the grid system's power quality, the suggested controlling model could successfully lower the THD to 1.06%. Furthermore, the efficiency and loss values of the converter are verified and contrasted, as shown in Figures 16 and 17, respectively. The results of this investigation show that the converter's efficiency has significantly increased, with less loss occurring across the switching components.

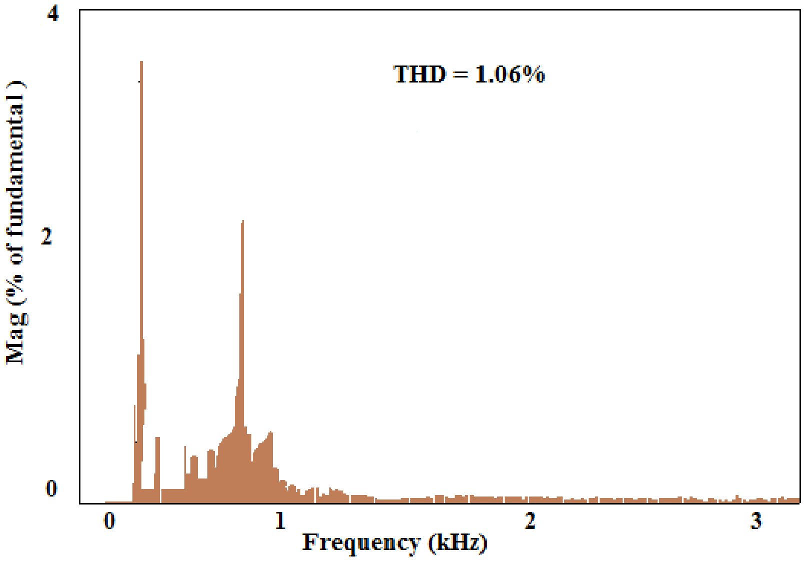


Figure 15. THD value

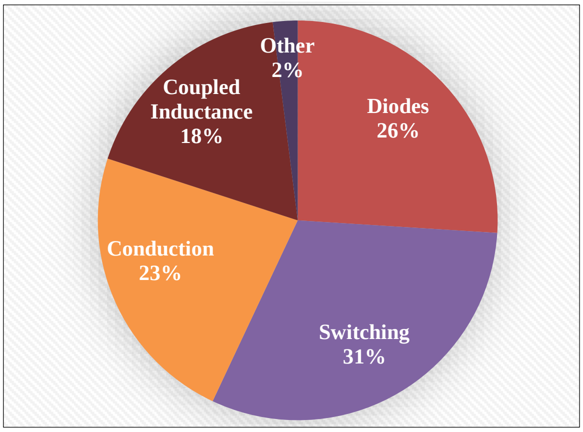


Figure 16. Loss analysis

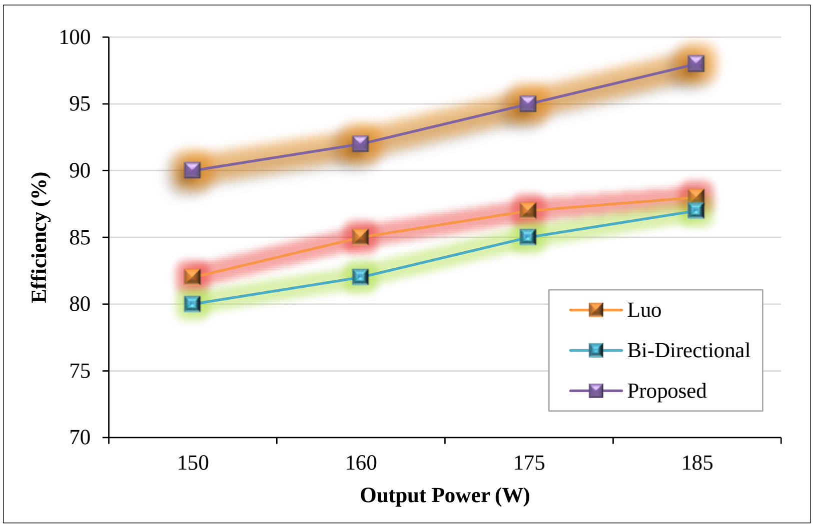


Figure 17. Efficiency

Figure 15 shows the THD value of the proposed power converter system, which is 1.06%. One of the most important parameters that judges the quality of the output waveform is THD. It is, therefore, indispensable to have a very low THD for a system performance enhancement toward ensuring sensitive electronic equipment works effectively. The THD obtained with the proposed converter is 1.06%, which is somewhat small, and it reveals that the quality of power output is good, with limited harmonic distortion. That is something very important for high-performance systems, such as power converters applied in renewable energy applications, where high fidelity in the outputted signal will be necessary for assured and correct power delivery that would prevent losses or damages in connected loads. The value of this low THD evidences that the proposed control technique should involve some advanced modulation strategy or some mechanism of filtering in order to reduce the harmonic content and enhance the purity of the output waveform.

Loss distribution is very important for understanding the efficiency and operational characteristics of converters; these losses directly affect the system's overall performance and output. The diodes contribute to 26% of the total loss, meaning the power losses concerning the forward voltage drop and reverse recovery characteristics of the diode are not negligible. About 31% of the switching losses are due to energy dissipation during the switching transitions of the on/off switches in the converter. These losses are significant in high-frequency switching converters, where the events of switching are occurring frequently, hence leading to a higher dissipation. Conduction losses account for 23%, caused by the resistance in components where current flows through, like transistors and inductors. The inductances coupled contribute around 18% and are linked to the energy losses associated with the magnetic components of the converter, such as a transformer or an inductor with possible energy leakage or poor coupling. Other losses contribute only about 2%, including miscellaneous factors like parasitic capacitances, stray inductances, and other less important effects. All these mechanisms' losses should be estimated and understood for the design to optimize them to minimal values. This gives better efficiency of the converter system. These analyses give insight into further improvements that can be carried out either by optimizing the switching strategy or improving the performance of diodes and inductors.

Based on the parameters of settling time (s), rising time (s), and peak overshoot (W), Table 2 compares existing and proposed MPPT regulating strategies. These metrics must be decreased to ensure greater system efficacy because they are primarily used to validate the overall improved performance of the MPPT controlling procedures.

Table 2. Comparative evaluation of the MPPT methods

Performance Measure	MVO-MPPT	GWO-MPPT	PSO-MPPT	P&O MPPT	MBOA-MPPT	Proposed
Settling time (s)	0.0078	0.0082	0.0082	0.1939	0.0069	0.0052
Rise time (s)	0.0016	0.0017	0.0018	0.0028	0.0012	0.0010
Peak overshoot (W)	0.3481	0.4986	0.5308	0.6328	0.2891	0.1692

The proposed framework represents a huge improvement in voltage gain and efficiency within the solar PV system compared to conventional techniques. Most conventional MPPT techniques suffer due to fluctuating environmental conditions, whereas the FOPTC-based approach ensures optimal tracking and energy extraction under varied climates. The Non-IHVC configuration of converters improves the previous topologies in voltage gain and efficiency; thus, they have been able to handle the challenges regarding voltage conversion arising in the high-performance solar systems. Finally, it is in the NFQC controller that optimization is provided for, which cannot be achieved by classic control techniques, enhancing again the efficiency and reliability of the system. Combined, these innovations optimize the performance of not only the solar PV system itself but also the facility's ease of operation while minimizing energy losses and operational complexities over conventional models. That, in turn, allows for more efficiency and wider adaptability for a broad range of modern applications in solar energy.

5- Conclusion

The aim of this research is to improve the overall power tracking performance and voltage conversion efficiency of grid systems by developing novel and unique regulating mechanisms based on converter architecture. The three primary objectives of this work are to enhance high-voltage gain output via the use of a unique DC-DC converter model, optimize electrical energy generation through the use of creative MPPT regulating, and support voltage regulation through the use of an effective converter controlling model. The novel FOPTC model, which is based on the PV panel model, is employed to optimize solar energy yield in response to shifting climatic conditions. This controlling strategy was developed based on the recently developed FO algorithm, which offers the optimal method for determining the MPP for tracking solar energy. Thus, high-gain output solar systems are enhanced and have their voltage level raised by the implementation of the innovative Non-IHVC topology. This converter effectively lowers the voltage and current stress on the electrical components in the circuit with the least amount of complexity. This controlling paradigm leads to a significant increase in the voltage conversion efficiency and voltage gain of the suggested framework. Following that, a typical SVPWM regulating model is used to complete the DC-AC conversion, supplying the grid with high-quality power with fewer harmonics. It was observed that the proposed FOPTC controller has a noticeably superior tracking capability than the existing controller while undergoing uneven irradiation. Numerical results clearly prove the major improvements that can be realized with the proposed system. The tracking capability of the FOPTC controller yielded the best results in a THD of 1.06%, ensuring that this approach ensures significant power quality reduction compared to traditional controllers.

6- Declarations

6-1- Author Contributions

Conceptualization, I.E.S.N., T.P., S.V.P., and B.U.K.; methodology, I.E.S.N. and T.P.; validation, S.V.P. and B.U.K.; formal analysis, T.P., S.V.P., and B.U.K.; data curation, I.E.S.N. and T.P.; writing—original draft preparation, I.E.S.N., T.P., S.V.P., and B.U.K.; writing—review and editing, I.E.S.N., T.P., S.V.P., and B.U.K. All authors have read and agreed to the published version of the manuscript.

6-2- Data Availability Statement

Data sharing is not applicable to this article.

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6-4- Institutional Review Board Statement

Not applicable.

6-5- Informed Consent Statement

Not applicable.

6-6- Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

7- References

[1] Sreedhar, R., Karunanithi, K., & Ramesh, S. (2024). Design, implementation and empirical analysis of a cascaded hybrid MPPT controller for grid tied solar photovoltaic systems under partial shaded conditions. Measurement: Sensors, 31, 100961. doi:10.1016/j.measen.2023.100961.

[2] Boscaino, V., Ditta, V., Marsala, G., Panzavecchia, N., Tinè, G., Cosentino, V., Cataliotti, A., & Di Cara, D. (2024). Grid-connected photovoltaic inverters: Grid codes, topologies and control techniques. Renewable and Sustainable Energy Reviews, 189, 113903. doi:10.1016/j.rser.2023.113903.

[3] Bharathy Priya, D., & Sumathi, A. (2024). Reverse flow transition control mechanism with maximum power point controlling (MPPT) technique for solar PV application. Journal of the Chinese Institute of Engineers, Transactions of the Chinese Institute of Engineers,Series A, 47(1), 37–50. doi:10.1080/02533839.2023.2274084.

[4] Corrêa, H. P., & Vieira, F. H. T. (2024). Analytical estimation of three-phase inverter input impedance applied to MPPT in off-grid variable-voltage photovoltaic systems. International Journal of Electrical Power and Energy Systems, 155, 109482. doi:10.1016/j.ijepes.2023.109482.

[5] Pirashanthiyah, L., Edirisinghe, H. N., De Silva, W. M. P., Bolonne, S. R. A., Logeeshan, V., & Wanigasekara, C. (2024). Design and Analysis of a Three-Phase Interleaved DC-DC Boost Converter with an Energy Storage System for a PV System. Energies, 17(1), 250. doi:10.3390/en17010250.

[6] Refaat, A., Ali, Q. A., Elsakka, M. M., Elhenawy, Y., Majozi, T., Korovkin, N. V., & Elfar, M. H. (2024). Extraction of maximum power from PV system based on horse herd optimization MPPT technique under various weather conditions. Renewable Energy, 220, 119718. doi:10.1016/j.renene.2023.119718.

[7] Gupta, N., Morey, M., Garg, M. M., & Kumar, A. (2024). An experimental investigation of variable-step-size Affine Projection Sign based algorithm for power quality enhanced grid-interactive solar PV system. Electric Power Systems Research, 228, 110036. doi:10.1016/j.epsr.2023.110036.

[8] AL-Wesabi, I., Zhijian, F., Farh, H. M. H., Dagal, I., A. Al-Shamma'a, A., Al-Shaalan, A. M., & kai, Y. (2024). Hybrid SSA-PSO based intelligent direct sliding-mode control for extracting maximum photovoltaic output power and regulating the DC-bus voltage. International Journal of Hydrogen Energy, 51, 348–370. doi:10.1016/j.ijhydene.2023.10.034.

[9] Samundeeswari, S. V., & Irudayaraj, G. C. R. (2024). Interconnection Efficiency in Grid-Connected Photovoltaic (PV) Systems Using Single-Phase Neural Network-Based Neutral Point Clamped and Cascaded H-Bridge Multilevel Inverters. International Journal of Intelligent Systems and Applications in Engineering, 12(11), 188–198.

[10] Zaghba, L., Borni, A., Khennane, M., & Fezzani, A. (2023). Modeling and simulation of novel dynamic control strategy for grid-connected photovoltaic systems under real outdoor weather conditions using Fuzzy–PI MPPT controller. International Journal of Modelling and Simulation, 43(5), 549–558. doi:10.1080/02286203.2022.2094663.

[11] Didi, F., & Chaouche, M. S. (2022). Design and Simulation of Grid-Connected Photovoltaic Systems' Performance Analysis with Optimal Control of Maximum Power Point Tracking Based on Artificial Intelligence. In Review of Computer Engineering Research (Vol. 9, Issue 3, pp. 151–168). doi:10.18488/76.v9i3.3144.

[12] El Mezdi, K., El Magri, A., Watil, A., El Myasse, I., Bahatti, L., Lajouad, R., & Ouabi, H. (2023). Nonlinear control design and stability analysis of hybrid grid-connected photovoltaic-Battery energy storage system with ANN-MPPT method. Journal of Energy Storage, 72, 108747. doi:10.1016/j.est.2023.108747.

[13] Ibrahim, N. F., Mahmoud, M. M., Thaiban, A. M. H. A., Barnawi, A. B., Elbarbary, Z. M. S., Omar, A. I., & Abdelfattah, H. (2023). Operation of Grid-Connected PV System with ANN-Based MPPT and an Optimized LCL Filter Using GRG Algorithm for Enhanced Power Quality. IEEE Access, 11, 106859–106876. doi:10.1109/ACCESS.2023.3317980.

[14] Manas, M., Dakka, O., Sharma, S., Arandhakar, S., Kallelapu, R., & Golla, S. (2023). A novel metaheuristic-based robust unified control MPPT algorithm for grid-connected PV system. Electric Power Systems Research, 221, 109389. doi:10.1016/j.epsr.2023.109389.

[15] Osmani, K., Haddad, A., Lemenand, T., Castanier, B., & Ramadan, M. (2021). An investigation on maximum power extraction algorithms from PV systems with corresponding DC-DC converters. Energy, 224, 120092. doi:10.1016/j.energy.2021.120092.

[16] Ali, M., Ahmad, M., Koondhar, M. A., Akram, M. S., Verma, A., & Khan, B. (2023). Maximum power point tracking for grid-connected photovoltaic system using Adaptive Fuzzy Logic Controller. Computers and Electrical Engineering, 110, 108879. doi:10.1016/j.compeleceng.2023.108879.

[17] Katche, M. L., Makokha, A. B., Zachary, S. O., & Adaramola, M. S. (2023). A Comprehensive Review of Maximum Power Point Tracking (MPPT) Techniques Used in Solar PV Systems. Energies, 16(5), 2206. doi:10.3390/en16052206.

[18] Priyadarshi, N., Maroti, P. K., & Khan, B. (2023). An adaptive grid integrated photovoltaic system with perturb T–S fuzzy based sliding mode controller MPPT tracker: An experimental realization. IET Renewable Power Generation. doi:10.1049/rpg2.12738.

[19] Rashid, M. F., Azhar, A., Khan, S. A., Afzal, S., & Ashraf, I. (2023). Single-Stage & Single-Phase Grid Integrated Solar PV System Fed with MPPT Controller. 2023 International Conference on Power, Instrumentation, Energy and Control (PIECON), 1–6. doi:10.1109/piecon56912.2023.10085751.

[20] Luo, Z., Qin, J., Zhou, F., & Wen, Y. (2023). A decentralized control strategy for single-phase cascaded photovoltaic inverters with MPPT ability. IET Renewable Power Generation, 17(11), 2679–2686. doi:10.1049/rpg2.12796.

[21] Manna, S., Singh, D. K., Alsharif, M. H., & Kim, M. K. (2024). Enhanced MPPT approach for grid-integrated solar PV system: Simulation and experimental study. Energy Reports, 12, 3323–3340. doi:10.1016/j.egyr.2024.09.029.

[22] Chellakhi, A., El Beid, S., Abouelmahjoub, Y., & Doubabi, H. (2024). An Enhanced Incremental Conductance MPPT Approach for PV Power Optimization: A Simulation and Experimental Study. Arabian Journal for Science and Engineering, 1–20. doi:10.1007/s13369-024-08804-1.

[23] Adouairi, M. said, Bossoufi, B., Motahhir, S., & Saady, I. (2023). Application of fuzzy sliding mode control on a single-stage grid-connected PV system based on the voltage-oriented control strategy. Results in Engineering, 17, 100822. doi:10.1016/j.rineng.2022.100822.

[24] Siwakoti, Y. P., & Blaabjerg, F. (2018). Common-ground-type transformerless inverters for single-phase solar photovoltaic systems. IEEE Transactions on Industrial Electronics, 65(3), 2100–2111. doi:10.1109/TIE.2017.2740821.

[25] Ibrahim, M. H., Ang, S. P., Dani, M. N., Rahman, M. I., Petra, R., & Sulthan, S. M. (2023). Optimizing Step-Size of Perturb & Observe and Incremental Conductance MPPT Techniques Using PSO for Grid-Tied PV System. IEEE Access, 11, 13079–13090. doi:10.1109/ACCESS.2023.3242979.

[26] Hata, N., Belhaouchet, N., & Sayah, S. (2023). Design and experimental validation of an efficient control based on variable step size P&O MPPT technique and predictive current controller for a single-phase grid-connected photovoltaic system. Electrical Engineering, 105(5), 2637–2652. doi:10.1007/s00202-023-01831-5.

[27] Lakshmi, M., & Hemamalini, S. (2019). Coordinated control of MPPT and voltage regulation using single-stage high gain DC–DC converter in a grid-connected PV system. Electric Power Systems Research, 169, 65–73. doi:10.1016/j.epsr.2018.12.011.

[28] Rahmani, B., Li, W., & Liu, G. (2015). An Advanced Universal Power Quality Conditioning System and MPPT method for grid integration of photovoltaic systems. International Journal of Electrical Power & Energy Systems, 69, 76–84. doi:10.1016/j.ijepes.2014.12.031.

[29] Bahri, H., & Harrag, A. (2021). Ingenious golden section search MPPT algorithm for PEM fuel cell power system. Neural Computing and Applications, 33(14), 8275–8298. doi:10.1007/s00521-020-05581-4.

[30] Yang, B., Yu, T., Shu, H., Zhu, D., An, N., Sang, Y., & Jiang, L. (2018). Perturbation observer based fractional-order sliding-mode controller for MPPT of grid-connected PV inverters: Design and real-time implementation. Control Engineering Practice, 79, 105–125. doi:10.1016/j.conengprac.2018.07.007.

[31] Almutairi, A., Abo-Khalil, A. G., Sayed, K., & Albagami, N. (2020). MPPT for a PV grid-connected system to improve efficiency under partial shading conditions. Sustainability (Switzerland), 12(24), 1–18. doi:10.3390/su122410310.

[32] Pilakkat, D., & Kanthalakshmi, S. (2020). Single phase PV system operating under Partially Shaded Conditions with ABC-PO as MPPT algorithm for grid connected applications. Energy Reports, 6, 1910–1921. doi:10.1016/j.egyr.2020.07.019.

[33] Ali, A. I. M., Mousa, H. H. H., Mohamed, H. R. A., Kamel, S., Hassan, A. S., Alaas, Z. M., Mohamed, E. E. M., & Abdallah, A. R. Y. (2023). An Enhanced P&O MPPT Algorithm with Concise Search Area for Grid-Tied PV Systems. IEEE Access, 11, 79408–79421. doi:10.1109/ACCESS.2023.3298106.

[34] Sunddararaj, S. P., Rangarajan, S. S., Subramaniam, U., Collins, E. R., & Senjyu, T. (2021). Performance of P/PI/PID Based controller in DC-DC Converter for PV applications and Smart Grid Technology. 2021 7th International Conference on Electrical Energy Systems (ICEES), 171–176. doi:10.1109/icees51510.2021.9383671.

[35] Jeremy, L. J., Ooi, C. A., & Teh, J. (2020). Non-isolated conventional DC-DC converter comparison for a photovoltaic system: A review. Journal of Renewable and Sustainable Energy, 12(1), 013502. doi:10.1063/1.5095811.

[36] Pardhi, P. K., & Sharma, S. K. (2021). High Gain Non-Isolated DC Converter Employed in Single-Phase Grid-Tied Solar Photovoltaic Supply System. IEEE Transactions on Industry Applications, 57(5), 5170–5182. doi:10.1109/TIA.2021.3095439.

[37] Varma, R. K., Siavashi, E., Mohan, S., & McMichael-Dennis, J. (2021). Grid Support Benefits of Solar PV Systems as STATCOM (PV-STATCOM) through Converter Control: Grid Integration Challenges of Solar PV Power Systems. IEEE Electrification Magazine, 9(2), 50–61. doi:10.1109/MELE.2021.3070937.

[38] Alali, M. A. E., Sabiri, Z., Shtessel, Y. B., & Barbot, J. P. (2021). Study of a common control strategy for grid-connected shunt active photovoltaic filter without DC/DC converter. Sustainable Energy Technologies and Assessments, 45, 101149. doi:10.1016/j.seta.2021.101149.