iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH
IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 14 **Issue:** III **Month of publication:** March 2026

DOI: https://doi.org/10.22214/ijraset.2026.78730

Transformer Less Grid Feeding Current Source Inverter for Solar Photovoltaic System

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Abstract:** With increasing amounts of solar power being attached to the electrical grid, there has been a rush in developing improved, smaller power electronics capable of dealing with the task effectively. In the traditional grid-tied solar systems, individuals typically add large line-frequency transformers to maintain the electrical isolation of the PV panels. This arrangement is safe, but with disadvantages, including additional loss of energy, reduction of size and weight, and increased costs of construction and equipment. That is why the idea to design and simulate a transformer less grid-feeding current source inverter (CSI) in the specific case of solar PV systems has become quite popular. The aim is to make a smooth changeover between the solar panels and the utility grid and maintain good power quality and low harmonics. An Incremental Conductance MPPT algorithm is used to extract as much power as possible out of the PV array under varying conditions (such as sunlight variations). This algorithm is used with a DC-DC boost converter that varies the operating point of the PV, and injects the appropriate current into the inverter stage to maintain the current sent to the grid clean, and follow the reference (that is, under different conditions, etc.). Two methods are compared to control the current injected into the grid: A simple proportional-integral (PI) controller as the reference point. An Artificial Neural Network (ANN)-based smart controller as the control attempting to handle the nonlinear behaviour and adapt to new conditions and respond more quickly and correctly to new conditions and situations. The results of the simulations indicate that the ANN controller could provide much better results: reduced harmonic distortion of the grid current in comparison with the traditional PI approach; moreover, the solution remains easily within the IEEE harmonic limits and provides a more efficient, smaller scale solution to current solar PV grid integration.

I. INTRODUCTION

The growing worldwide energy demands as well as the environmental issues that have been brought about by the use of fossil fuels in energy production has increased the pace at which renewable energy technologies are being developed. Solar photovoltaic (PV) systems have become very popular among other renewable sources that are available today. This is principally because they are designed as modules, they are easy to install and the cost of installing them has been going down over the years. The advantage of grid-connected PV systems is it is particularly useful since the power created by the solar panels can directly be sent into the power grid without the use of large energy storage systems. Nonetheless, the effective implementation of solar PV systems into the power grid relies heavily on effective power electronic converters. These converters have the role of converting the direct current (DC) generated by the PV panels into alternating current (AC) which is of grid standards. The performance of these converters is important in deciding the effectiveness of the system, power quality, and reliability in the operation. This has made researchers pay much attention to the design of sophisticated inverter topology and the development of an excellent control strategy to improve the performance of grid-connected PV systems.

Conventional grid-connected photovoltaic (PV) systems often use line frequency transformers to provide electrical isolation between the PV array and the utility grid. These transformers help achieve galvanic isolation and minimize leakage current issues. However, they also introduce certain disadvantages, such as additional power losses and a significant increase in the overall size and weight of the system. For residential or small-scale solar installations, these factors can negatively affect the overall efficiency and economic feasibility of the system. To address these limitations, researchers have increasingly focused on transformer-less inverter designs in recent years. By removing the transformer, the system can achieve higher efficiency, lower cost, and a more compact structure. Nevertheless, the absence of galvanic isolation creates new technical challenges. In particular, issues such as leakage current and harmonic distortion become more critical. For this reason, careful design of both the inverter topology and its control strategy is essential to ensure safe, efficient, and reliable operation of transformer-less grid-connected PV systems.

Major concerns in grid connected PV systems is power quality degradation caused by harmonics generated by power electronic converters. Excessive harmonic distortion in grid current can lead to overheating of equipment, malfunction of sensitive loads, and violation of grid regulations. International standards such as IEEE-519 specify strict limits on total harmonic distortion (THD) to ensure reliable grid operation.

“Conventional control techniques such as proportional integral (PI) and proportional-resonant (PR) controllers are widely used for inverter control”. However, their performance degrades under non-linear conditions, parameter variations, and dynamic changes in irradiance. These limitations motivate the use of intelligent control strategies capable of adaptive and nonlinear control.

ANNs are computational models inspired by the human brain’s learning and decision-making capability. ANNs possess strong nonlinear mapping, adaptability, and “self-learning features, making them highly suitable for controlling complex power electronic systems. In this work, an ANN based controller is implemented for the grid-feeding current control of a transformer-less CSI”. The ANN controller adjusts control parameters based on system operating conditions, resulting in: ● Reduced grid current THD ● Faster transient response ● Improved robustness against parameter uncertainties ● Better performance under varying irradiance and grid disturbances The intelligent control approach enhances overall system performance beyond what is achievable with traditional controllers.

II. ARCHITECTURES AND CONTROL FUNDAMENTALS

The rising need to produce sustainable electricity has spurred a strong research base that dwells on the smooth incorporation of the renewable energy technologies into the modern power grids. Photovoltaic (PV) systems have become one of the most commonly used renewable sources with their environmental suitability and the constant reduction of the cost of manufacturing of PV modules. Solar energy is free and non-polluting and this energy can produce electrical power without releasing harmful gases. As a result, photovoltaic installations, especially grid-connected ones, are becoming popular in residential, commercial, and industrial environments. This is despite the high benefits that accrue to PV technology, and even after all the benefits, the achievement of effective power conversion and accurate control of the generated energy is a daunting task. A photovoltaic array is intrinsically a direct current (DC) source, but traditional utility grids use alternating current (AC) power. Thus, well planned power electronic conversion steps are necessary to convert the DC output of the PV array to AC power that can be connected to the grid. The effectiveness of these conversion steps determines the overall system performance, quality of power, and its ability to operate efficiently. In the last twenty years, there has been considerable research activity in an attempt to improve the performance of grid-connected PV systems by creating advanced inverter design and improved control strategies. Several works have focused on enhancing system efficiency, stability and power quality through converter topology optimization and intelligent control methods. The chapter provides an excellent overview of notable works involving research efforts in the area of photovoltaic power conversion, maximum power point tracking (MPPT) methods, type of inverter, and modern control software used to operate grid-integrated PV systems. This review aims at outlining the constraints of current solutions and justifying the novel transformer-less CSI using ANN based control algorithm.

A. *Transformer Based versus Transformer less Inverters*

“Traditional grid connected pv systems commonly employ transformers to provide electrical isolation between the PV array and the utility grid. The transformer ensures safety by preventing direct electrical contact between the PV system and the grid. However, the presence of transformer” introduces additional losses, increases system size, and raises installation cost. In recent years, transformer-less inverter configurations have gained attention as an alternative solution. By removing the transformer, these inverter systems can achieve higher efficiency and reduced weight. Transformer-less designs also reduce material requirements and improve power density. Although transformer-less inverters provide several advantages, they also introduce challenges related to leakage current and electromagnetic interference. Proper control techniques and circuit design are required to minimize these issues while maintaining system efficiency. Researchers have proposed various transformer-less inverter topologies to address these challenges. Some designs focus on reducing common-mode voltage variations, while others aim to improve harmonic performance. These developments have contributed to the growing adoption of transformer-less PV inverter systems in modern renewable energy installations.

B. *Intelligent Control Using Artificial Neural Networks*

Control strategies play a critical role in determining the performance of power electronic converters. Conventional control approaches, such as PI controllers, have been widely used because of their simplicity and ease of implementation. However, these controllers may experience performance degradation when system parameters vary or when nonlinear disturbances occur.

To overcome these limitations, researchers have investigated intelligent control methods such as ANN, fuzzy logic controllers, and adaptive control techniques. Artificial Neural Networks are particularly attractive because they are capable of learning nonlinear relationships between system variables. ANN controllers can be trained using system data to predict appropriate control actions for different operating conditions. Once trained, the ANN can respond to system variations more effectively than traditional fixed-gain controllers. This capability makes ANN-based control suitable for applications where operating conditions change frequently, such as solar PV systems affected by irradiance fluctuations. Recent research has shown that ANN controllers can improve inverter current regulation and reduce harmonic distortion in grid-connected renewable energy systems.

C. Research Gap and Novelty

From the reviewed literature, it is evident that transformer-less grid-connected PV systems offer superior efficiency and compactness but face challenges related to harmonics and control complexity. While CSIs provide inherent advantages for grid-feeding applications, their potential has not been fully explored in combination with intelligent control techniques. Most existing studies focus on VSI-based transformer-less systems with conventional controllers. Limited research addresses the integration of ANN based intelligent control with transformer-less current source inverters for solar PV applications, particularly with a focus on THD reduction and IEEE-519 compliance. This research aims to bridge this gap by developing an ANN-controlled transformer less grid feeding CSI for solar PV systems and evaluating its performance through detailed MATLAB/Simulink simulations.

III. SYSTEM OVERVIEW AND DESIGN

The overall performance of a grid connected pv system depends largely on the design of its power conversion stages and the effectiveness of the control strategy used to regulate power flow. In transformer-less solar PV systems, careful attention must be given to the configuration of the converter stages, since the absence of galvanic isolation requires proper current control and harmonic management. The proposed system focuses on delivering solar power from a photovoltaic array to the utility grid using a transformer-less current source inverter (CSI). The configuration combines a photovoltaic generation unit, a DC–DC boost converter with MPPT capability, and a current source inverter that injects controlled current into the grid. This chapter describes the configuration and operating principles of the proposed system. The individual subsystems are explained in detail so that the interaction between the PV source, power converters, and control system can be clearly understood before moving to the design and simulation stages.

A. System Configuration

The entire photovoltaic power conversion system consists of a number of working stages that work together to convert the solar radiation into useable electrical power that is consumed by the electrical grid. The key elements of the suggested system include a photovoltaic array, a DC-DC boost converter, a DC link current source stage, a current source inverter, as well as the grid interface filter. The photovoltaic array transforms solar energy into a DC electric energy. The DC–DC converter is used to adjust the operating point of the PV array since the output properties of the PV array change with the environmental conditions. The system manages to keep the PV modules near to their maximum power point by adjusting the duty cycle of the boost converter. The controlled DC power is then applied to the current source inverter. With this arrangement the DC-link inductor is very large and keeps the current at the inverter input nearly constant. This current is changed by the inverter switches to an alternating waveform in line with the grid voltage. The resulting AC current is taken via a filter and is injected into the grid. The general system design allows the movement of power in the PV system to the grid in an efficient way without compromising the quality of power and stability in the system.

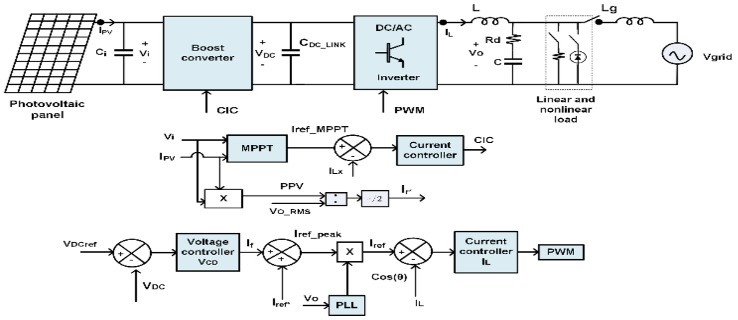


Figure 3.1: Overall block diagram of transformer-less grid-feeding CSI based solar PV system

B. Solar Photovoltaic Array

Photovoltaic (PV) array is the main source of energy in the system in question. Solar cells produce power through the photovoltaic effect where photo-neutrons of the incoming sunlight excite electrons in semiconducting material and in the process trigger an electrical current. Individual solar cells though only provide a relatively small voltage, typically less than one volt; therefore, very high numbers of cells are strung in series and parallel configurations to create PV modules and arrays, which are capable of providing the power levels required. The electrical properties of a PV module are non-linear in nature and depend on the solar irradiance, as well as the cell temperature. The model of current voltage characteristic of a PV cell is traditionally the single diode model, which includes a current source, or photocurrent, a diode that describes the pn junction characteristics, and resistive components that give internal losses. The nonlinear characteristics of PV modules make it necessary to employ a control technique that ensures the system operates at the maximum power point under varying environmental conditions. This requirement leads to the use of MPPT methods”.

C. DC–DC Converter and MPPT Stage

“Since the electrical output of a pv system varies with changes in irradiance and temperature, the operating point of the PV array must be continuously adjusted to extract the maximum possible power. MPPT techniques are used to achieve this objective. Among the various MPPT algorithms available, the Incremental Conductance method is widely recognized for its accuracy and reliability under dynamic conditions. The principle of this method is based on the observation that the slope of the power-voltage curve becomes zero at the MPP. By measuring incremental changes in voltage and current, the controller determines whether the operating point lies to the left or right of the maximum power point. Based on this information, the duty cycle of the DC–DC converter is adjusted to move the operating point toward the optimal region. The Incremental Conductance algorithm provides improved tracking performance compared to simpler techniques such as Perturb and Observe, particularly when solar irradiance changes rapidly. The DC–DC booster converter is used to regulate the voltage level of the PV array and to facilitate the MPPT operation. In addition to adjusting the PV operating point, the boost converter increases the output voltage so that it is suitable for the inverter stage. The boost converter operates in two switching states. During the ON state of the switching device, energy is stored in the inductor. When the switch turns OFF, the stored energy is transferred to the output through the diode, thereby increasing the output voltage.

By controlling the duty cycle using the MPPT algorithm, the boost converter ensures that the pv array operates at the optimal voltage corresponding to the MPP”.

D. DC-Link Current Source Stage

“In the proposed configuration, the inverter operates as a CSI rather than a VSI. To achieve this behavior, a large inductor is placed in the DC link between the boost converter and the inverter stage. The DC-link inductor plays an important role in maintaining a nearly constant current at the inverter input. This constant current characteristic allows the inverter to regulate the grid current more effectively. The inductor also acts as an energy storage element that smooths current fluctuations and reduces ripple caused by switching operations. Proper sizing of the DC-link inductor is essential to ensure stable inverter operation and minimize harmonic distortion”. Proper sizing of the DC-link inductor is critical. An insufficient inductance value can lead to excessive current ripple and instability, while an excessively large inductance increases system size and losses. In this work, the inductor value is selected based on allowable ripple current, switching frequency, and system power rating.

E. Transformer-less Grid-Feeding CSI

“The CSI converts the regulated DC current into AC synchronized with the grid voltage. The inverter uses power semiconductor switches arranged in a bridge configuration to control the direction and magnitude of the output current. In CSI operation, the switching devices are controlled such that the current waveform follows a sinusoidal reference signal. The output current is injected into the grid in phase with the grid voltage to achieve unity power factor operation”. Compared with conventional voltage source inverters, CSI systems provide improved current control capability and enhanced protection against short circuit conditions. These characteristics make the CSI topology suitable for grid connected renewable energy applications.

F. Grid Interface and Filtering Stage

Power electronic converters generate high-frequency switching components that can introduce harmonics into the grid current. To ensure that the injected current meets power quality standards, a filter is used between the inverter and the grid. An LC filter is commonly employed to suppress switching harmonics and produce a smooth sinusoidal current waveform. The filter parameters are selected so that the cutoff frequency lies between the grid fundamental frequency and the inverter switching frequency. Proper design of the filter improves the quality of grid current and ensures compliance with harmonic standards of IEEE-519.

G. Control Strategy Overview

The control system coordinates the operation of the different subsystems in the photovoltaic power conversion system. Two main control functions are implemented: MPPT for the PV array and current control for the grid connected inverter. The MPPT controller processes measurements of PV voltage and current and adjusts duty cycle of the boost converte. Meanwhile, the inverter control system regulates the grid current so that it follows a sinusoidal reference synchronized with the grid voltage. To evaluate system performance, two control strategies are considered in this work. The first approach employs a conventional PI controller for current regulation. The second approach introduces an Artificial Neural Network based controller designed to improve dynamic response and harmonic performance. The effectiveness of these control strategies is analyzed through detailed simulations described in the subsequent chapters.

H. List of Components

Sl. No	Components	Specification
1	Solar PV Array	As per datasheet
2	DC–DC Boost Converter	High-frequency
3	MPPT Controller	Incremental Conductance
4	DC-Link Inductor	Designed value
5	Current Source Inverter	Transformer-less
6	Power Switches	IGBT / MOSFET
7	Grid Filter	LC / LCL
8	Controller	ANN-based
9	Simulation Tool	MATLAB/Simulink

I. System Design and Modeling

The architecture of a grid-connected PV power conversion system requires careful coordination between the power source, the power electronic converters, and the control architecture. All of the stages are to be designed in a manner that optimizes the delivered solar energy to the electrical grid without altering the stable operation and power quality as well. The photovoltaic array, boost converter, DC-link current-source stage, and current-source inverter work together in the system in question to control power movement. The rational arrangement of every element makes the PV subsystem to capture as much energy as possible, maintain linear current curves, and deliver high-quality AC current to the grid. This chapter outlines the design process that has been followed in the major elements of the proposed transformer-less, grid-connected CSI system. It also gives an in-depth discussion of the modelling of the photovoltaic source, boost converter design, DC-link inductor sizing, inverter operation, and the implementation of the control strategies.

The complete control process follows: 1. PV measurement 2. MPPT computation 3. DC-link current regulation 4. Grid current reference generation 5. ANN-based control 6. Inverter switching

J. Proposed System

This paper outlines the design of a transformer-less current source inverter (CSI) which is intended to convert electrical energy collected by a solar photovoltaic source into utility-scale power. Its structure synergistically incorporates photovoltaic power production, maximum-power-point control (MPPT), DC-DC converting, and advanced inverter functioning. Its main goal is to utilize as much solar irradiance available as possible and maintain acceptable power quality as well as maintain a stable connection with the grid. The system consists of a photovoltaic array, a boost converter stage, which implements the MPPT algorithm, a DC-link inductor which forms the current source stage and a CSI, which injects a controlled current into the grid.

The smart control strategy that is based on an artificial neural network (ANN) is integrated to optimize the existing regulation to reduce harmonic distortion. The overall picture of the suggested system can be developed as a result of the systematic analysis of the energy flow between the photovoltaic source and the grid as well as the related control signals regulating the process of power conversion.

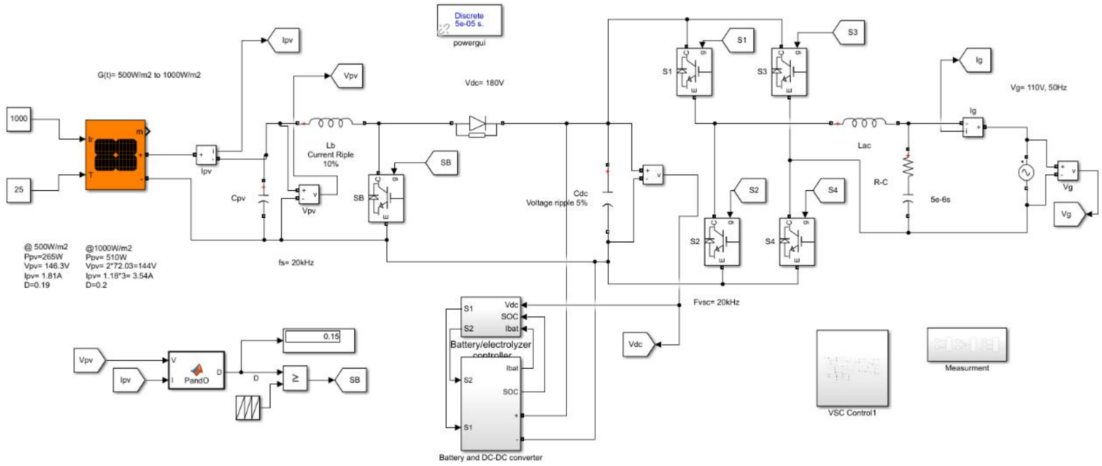


Figure 3.2: Overall MATLAB/Simulink model of the proposed system

1) Energy Flow and Signal Flow in the System: The operation of proposed system can be better understood by distinguishing between energy flow and control signal flow. The energy flow represents the path through which electrical power moves from the PV array to grid, while the signal flow represents the control signals used to regulate the conversion process. Energy generated by the photovoltaic array first enters the boost converter stage, where it is regulated and conditioned. From the boost converter output, the energy passes through the DC-link inductor and then into the CSI. The inverter converts the DC to AC current and transfers it to the grid through the output filter Simultaneously, various electrical parameters such as PV voltage, current, grid voltage, currents are measured by sensors within the system. These measurements are used by the MPPT controller and the inverter control system to determine the appropriate switching signals required for efficient operation. Thus, the power conversion process is continuously regulated through a combination of energy transfer and feedback control signals.
2) Operation of Solar PV Array under Dynamic Conditions: "The pv array operates under environmental conditions that vary continuously during the day. Changes in solar irradiance and temperature directly affect the electrical output of the PV modules". As irradiance increases, the generated current increases, while temperature variations mainly influence the output voltage.

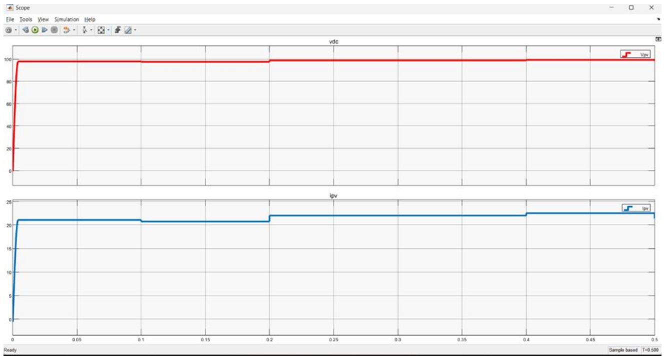


Fig 3.3: PV voltage and current waveforms

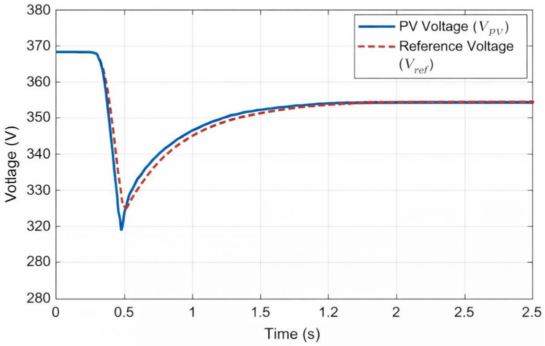


Fig3.4: MPPT tracking response showing PV voltage and reference

Such variations make the operating point of the photovoltaic array to move around nonlinear current voltage characteristics of the photovoltaic array. Deviations of the array with respect to its maximum power point (MPP) leave some of the incident solar irradiance unutilized. The voltage and current of the PV array is always checked in the proposed system to determine the current operating status. The controller then utilizes these observations to make sure the array is kept within its optimum operating point, thus to maximize the amount of power acquired by the solar panels.

3) Maximum Power Extraction Using Incremental Conductance MPPT: The achievement of efficient energy harvesting of photovoltaic systems is attained by applying the Incremental Conductance (IC) technique of the Maximum Power Point Tracking (MPPT). The IC algorithm finds the maximum power point (MPP) by comparing the incremental conductance of the PV array to the current conductance. The slope of the power voltage characteristic of the MPP goes to zero. The derivation of current with respect to voltage can be continuously assessed and therefore the controller can establish whether the operating point is above or below the MPP. The controller adjusts the duty cycle of the boost converter when the operating point is below the MPP; the controller reduces the duty cycle when the operating point is beyond the maximum power region. In this cyclic process, the MPPT controller is able to control the converter to operate until the PV array is working at its best power output.

4) Working of DC–DC Boost Converter Stage: “The boost converter acts as an intermediate power conditioning stage between PV array and the inverter. Its main function is to regulate the PV operating point and increase the voltage level obtained from the PV modules. The converter operates through a switching process that alternates between energy storage and energy transfer. When switch is ON, energy stores in the inductor. When the switch is off, stored energy will be released through the diode and transferred to the output. By controlling the duty ratio of the switching signal, the boost converter maintains the desired voltage level and supports the MPPT algorithm in extracting maximum power from the PV array”.

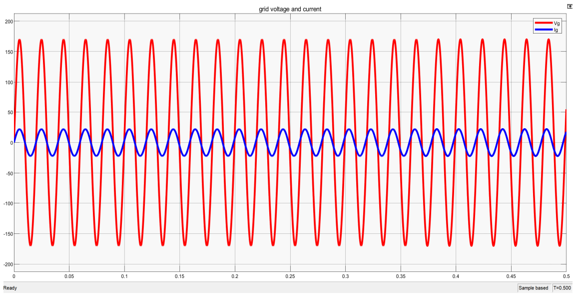


Figure 3.5: Boost converter voltage and current waveforms

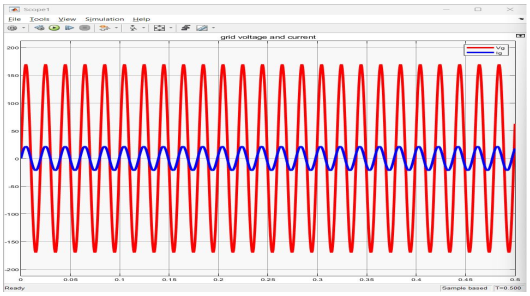


Figure3.6: Grid voltage and inverter current waveforms

5) DC-Link Current Source Operation and Significance: A distinctive feature of proposed system is use of a DC-link inductor to create a current source behavior at the inverter input. This inductor maintains a nearly constant current despite fluctuations in input voltage or load conditions. The presence of the DC-link inductor provides several advantages. It reduces current ripple, stabilizes the inverter operation, and improves the overall performance of the current control system. Additionally, it helps protect the inverter switches from sudden current spikes that may occur during switching operations. Because of these advantages, the DC-link inductor plays significant role in ensuring reliable operation of the current source inverter.

6) Operation of Transformer-less CSI: The transformer less CSI converts the DC current provided by the DC-link stage into AC synchronized with the grid. The inverter uses semiconductor switches arranged in a bridge configuration to control the direction and magnitude of the current flow. The switching sequence of inverter is controlled such that the output current follows a sinusoidal reference waveform. Because the inverter directly controls the current injected into grid, it becomes easier to regulate power delivery. The absence of a transformer reduces system size, cost, and power losses. However, careful control is required to ensure safe operation and acceptable power quality.

7) Grid Synchronization and Current Injection Mechanism: “For proper grid interaction, the inverter output current must be synchronized with the grid voltage. Synchronization ensures that the generated power is transferred efficiently and prevents instability in the power system. In the proposed system, the grid voltage signal is used as a reference to generate the current command for the inverter. The control system ensures that the injected current remains in phase with the grid voltage, thereby achieving unity power factor operation. The LC filter connected between the inverter and the grid suppresses switching harmonics and produces a smooth current waveform suitable for grid injection”.

8) ANN-Based Intelligent Control in the Proposed System: To enhance system performance, an ANN based controller is implemented in current control loop. The ANN is designed to learn the nonlinear relationship between the system inputs and the required control action.The neural network receives signals related to current error and system conditions and generates appropriate control outputs for the inverter switches. Through training, the ANN develops the ability to respond effectively to dynamic system variations. Compared with conventional PI controllers, ANN-based control can provide improved current regulation and reduced harmonic distortion, particularly when system parameters change or external disturbances occur.

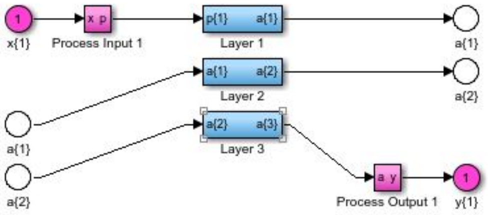


Figure 3.7: ANN controller block diagram

9) Switching Pulse Generation and Control Execution: The switching pulses required for inverter operation are generated using the control signals obtained from the PI or ANN controller. These pulses determine the switching pattern of the inverter devices. The pulse generation circuit ensures that the inverter switches operate at the required frequency and duty ratio. By adjusting the switching pattern according to the controller output, the system regulates the magnitude and shape of the grid current. The accurate generation of switching pulses is essential for maintaining proper inverter operation and minimizing harmonic distortion.

10) MATLAB/Simulink Implementation of Proposed System: The proposed system is simulated with MATLAB/Simulink. Each component of the system, which includes the pv array, boost converter, DC-link inductor, inverter, and control system, is implemented using appropriate simulation blocks. The modular structure of the simulation model allows individual subsystems to be analyzed independently while still representing the complete system behavior. The simulation environment also enables the evaluation of different control strategies and operating conditions. Through simulation studies, the performance of proposed system is examined in terms of current waveform quality, power transfer efficiency, and harmonic distortion. The results obtained from these simulations are discussed in the subsequent chapters.

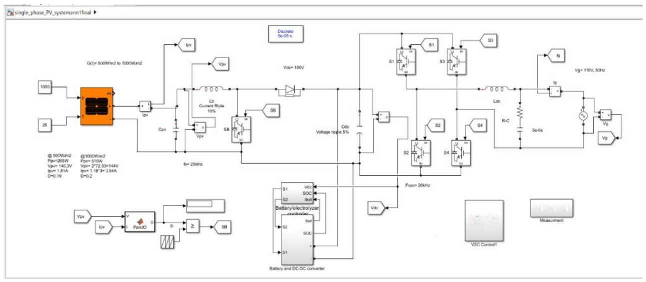


Figure 3.8: Simulink model for ANN system

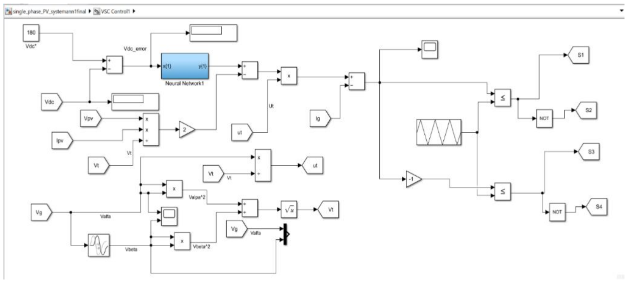


Figure 3.9: Simulink model for ANN controller

IV. SIMULATION RESULTS AND DISCUSSION

Once the mathematical model is developed and the proposed system is loaded into MATLAB/ Simulink, simulation studies are done to test the performance of the proposed transformer less current source inverter-based photovoltaic system. These simulations have the aim of questioning the system in terms of its ability to effectively extract power off the solar PV source and supply it to the grid without compromising on the quality of power. To study the dynamic behaviour and harmonic performance of the proposed system, the system is put to test under various operating conditions. This work considers two methods of control: the first one uses a traditional PI controller to control the inverter current, and the second one uses ANN-based controller, which is aimed at improving the response of the system and minimizing harmonic distortion. The simulations made are examined in terms of waveform quality, harmonic distortion and stability of the system. The PI-based and ANN-based control strategies are also compared thus demonstrating the merits of intelligent based control methods in a grid-connected photovoltaic system.

A. *Simulation Scenario and Test Conditions*

“The entire photovoltaic power conversion system is modeled and simulated using MATLAB/Simulink. The Simscape Electrical toolbox provides the necessary blocks for implementing power electronic converters, renewable energy sources, and control systems. The simulation model includes the pv array, the DC–DC boost converter with MPPT control, the DC-link inductor forming the current source stage, the current source inverter, and the grid interface filter. Sensors are used throughout the model to measure important electrical quantities such as PV voltage, PV current, grid voltage, and grid current”.

The grid is modeled as a sinusoidal voltage source operating at a frequency of 50Hz with a nominal voltage of 230V. The inverter switching frequency and filter parameters are selected based on design calculations described in the previous chapter. The same system parameters are used for both control strategies to have fair comparison over the PI controller and the ANN-based controller. By keeping the operating conditions identical, the influence of the control algorithm on system performance can be clearly observed.

B. Performance of the Baseline PI/PIR Controller

"In the first set of simulations, the inverter current control loop is regulated using conventional PI controller. The PI controller finds the error between the reference current and the measured grid current and generates the appropriate switching signals for the inverter. Under steady operating conditions, the PI controller is able to regulate the grid current and maintain synchronization with the grid voltage. The injected current waveform follows the reference signal and the system operates with acceptable stability. However, when the system is subjected to dynamic changes such as variations in solar irradiance, the PI controller exhibits certain limitations. Because the controller parameters remain fixed, its ability to adapt to rapidly changing system conditions is restricted. As a result, small deviations in the current waveform and increased harmonic content may be observed during transient conditions". The simulation results obtained with the PI controller provide a useful baseline for comparing the performance of the ANN-based control strategy.

1) Grid Voltage and Current Waveforms (PI Control): Under nominal operating conditions, the PI controller maintains sinusoidal grid current aligned with grid voltage. However, small distortions and ripple are observed due to the limited adaptability of the PI controller.

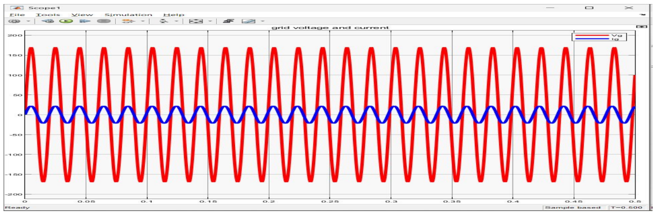
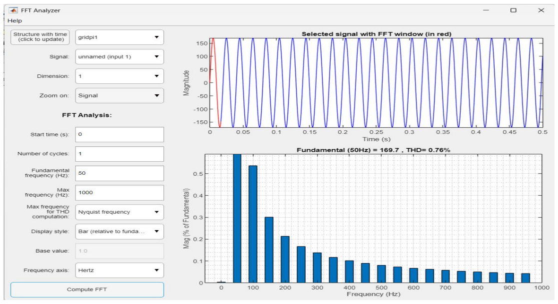


Figure 4.1: Grid voltage and current waveforms with PI control (Case 1)

2) Harmonic Analysis with PI Controller FFT analysis is performed on the grid voltage and current to evaluate harmonic content.

- Case 1: Voltage THD = 0.76%, Current THD = 1.52%


Structure with time (click to update): gridpi1
Signal: unnamed (input 1)
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Zoom on: Signal
FFT Analysis:
Start time (s): 0
Number of cycles: 1
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max frequency for THD computation: Nyquist frequency
Display style: Bar (relative to funda...
Base value: 1.0
Frequency axis: Hertz

Figure 4.2: FFT spectrum of grid voltage with PI control

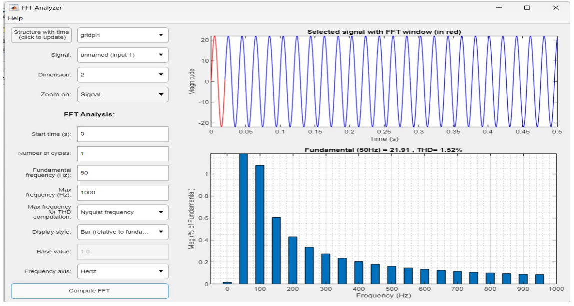

Structure with time (click to update): gridpi1
Signal: unnamed (input 1)
Dimension: 2
Zoom on: Signal
FFT Analysis:
Start time (s): 0
Number of cycles: 1
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max frequency for THD computation: Nyquist frequency
Display style: Bar (relative to funda...
Base value: 1.0
Frequency axis: Hertz

Figure 4.3: FFT spectrum of grid current with PI control

- Case 2: Voltage THD = 1.59%, Current THD = 2.47%

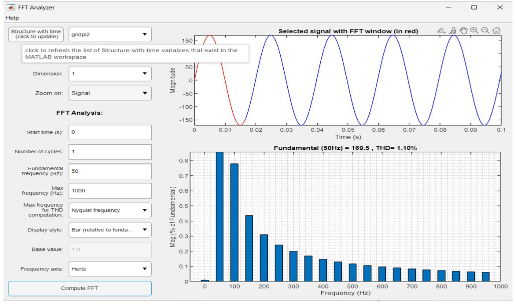
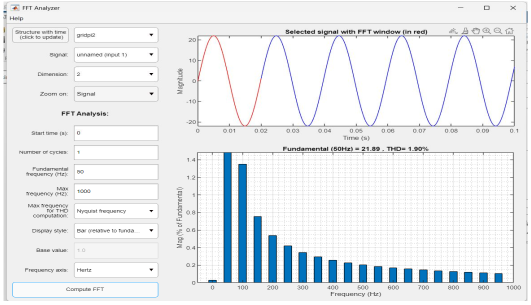

Structure with time (click to update): gridpi2
click to refresh the list of Structure-with-time variables that exist in the MATLAB workspace
Dimension: 1
Zoom on: Signal
FFT Analysis:
Start time (s): 0
Number of cycles: 1
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max frequency for THD computation: Nyquist frequency
Display style: Bar (relative to funda...
Base value: 1.0
Frequency axis: Hertz

Figure 4.2: FFT spectrum of grid voltage with PI control


Structure with time (click to update): gridpi2
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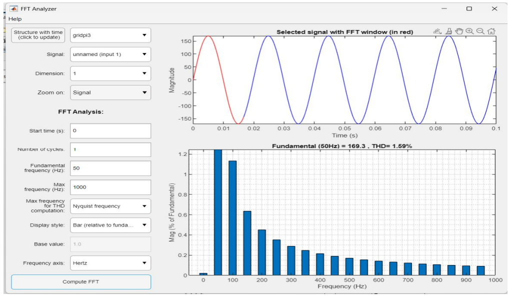
FFT Analysis:
Start time (s): 0
Number of cycles: 1
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max frequency for THD computation: Nyquist frequency
Display style: Bar (relative to funda...
Base value: 1.0
Frequency axis: Hertz

Figure 4.3: FFT spectrum of grid current with PI control

- Case 3: Voltage THD = 1.10%, Current THD = 1.90%


Structure with time (click to update): gridpi3
Signal: unnamed (input 1)
Dimension: 1
Zoom on: Signal
FFT Analysis:
Start time (s): 0
Number of cycles: 1
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max frequency for THD computation: Nyquist frequency
Display style: Bar (relative to funda...
Base value: 1.0
Frequency axis: Hertz

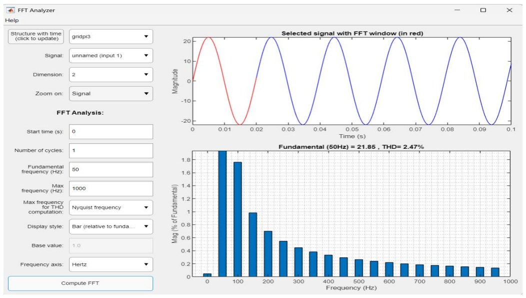

Structure with time (click to update): gridpi3
Signal: unnamed (input 1)
Dimension: 2
Zoom on: Signal
FFT Analysis:
Start time (s): 0
Number of cycles: 1
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max frequency for THD computation: Nyquist frequency
Display style: Bar (relative to funda...
Base value: 1.0
Frequency axis: Hertz

Figure 4.2: FFT spectrum of grid voltage with PI control

Figure 4.3: FFT spectrum of grid current with PI control

Although the PI-controlled system satisfies IEEE-519 harmonic limits, a noticeable increase in current THD is observed under dynamic conditions, indicating reduced robustness.

C. *Performance with ANN-Based Intelligent Controller*

In the second group of simulation experiments, an artificial neural network (ANN)-based control architecture takes the place of the proportional-integral (PI) controller. The ANN-based controller is designed to provide the nonlinear relationship between system inputs and the necessary control signals to the inverter regulation. During operation, the neural network receives information related to the current error and system state. Based on the trained network parameters, it produces control signals that determine the switching pattern of the inverter. Simulation results show that the ANN controller responds more effectively to dynamic operating conditions. When irradiance variations occur, the ANN controller adjusts the inverter operation quickly and maintains a smoother current waveform. The improved adaptability of the neural network allows the system to maintain better current regulation compared with the conventional PI controller. Another noticeable improvement observed in the ANN-based system is the reduction in harmonic distortion of the grid current. Because the controller can respond more precisely to system variations, the output current waveform becomes closer to a pure sinusoidal signal.

1) Grid Voltage and Current Waveforms (ANN Control) With ANN control, the grid current waveform exhibits smoother sinusoidal behavior and improved alignment with grid voltage. Reduced ripple and faster transient response are observed compared to PI control.

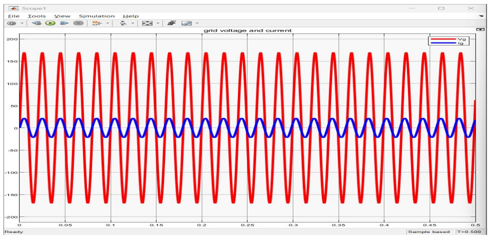
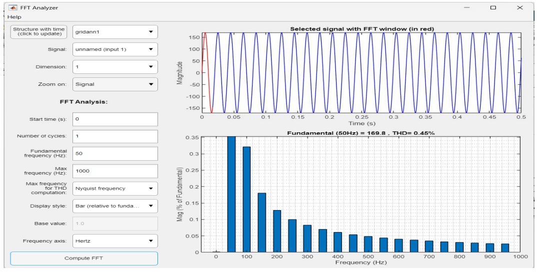


Figure 4.4: Grid voltage and current waveforms with ANN control (Case 1)

2) Harmonic Analysis with ANN Controller FFT analysis of grid voltage and current demonstrates significant harmonic reduction with ANN control.

- Case 1: Voltage THD = 0.45%,Current THD = 1.17%


Structure with time (click to update): gridann1
Signal: unnamed (input 1)
Dimension: 1
Zoom on: Signal
FFT Analysis:
Start time (s): 0
Number of cycles: 1
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max frequency for THD computation: Nyquist frequency
Display style: Bar (relative to funda...
Base value: 1.0
Frequency axis: Hertz

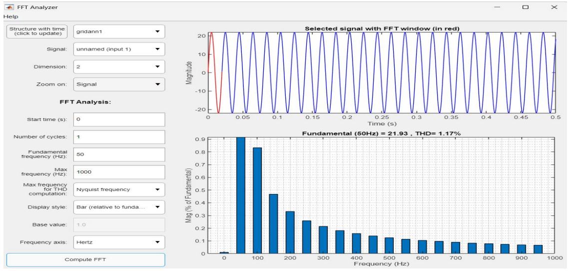
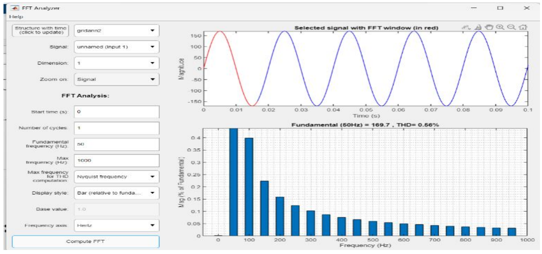

Structure with time (click to update): gridann1
Signal: unnamed (input 1)
Dimension: 2
Zoom on: Signal
FFT Analysis:
Start time (s): 0
Number of cycles: 1
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max frequency for THD computation: Nyquist frequency
Display style: Bar (relative to funda...
Base value: 1.0
Frequency axis: Hertz

Figure 4.5: FFT spectrum of grid voltage with ANN control

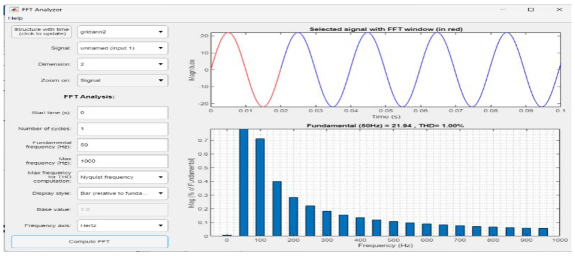
Figure 4.6: FFT spectrum of grid current with ANN control

- Case 2: Voltage THD = 0.81% Current THD = 1.19%



Structure with time (click to update): gridann2
Signal: unnamed (input 1)
Dimension: 1
Zoom on: Signal
FFT Analysis:
Start time (s): 0
Number of cycles: 1
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max frequency for THD computation: Nyquist frequency
Display style: Bar (relative to funda...
Base value: 1.0
Frequency axis: Hertz

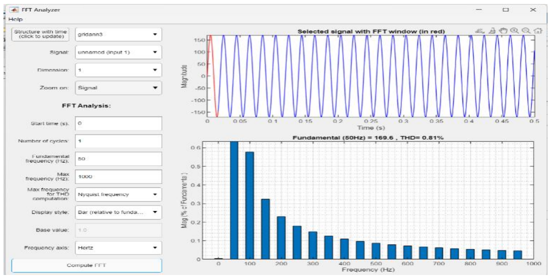
Figure 4.7: FFT spectrum of grid voltage with ANN control



Structure with time (click to update): gridann2
Signal: unnamed (input 1)
Dimension: 2
Zoom on: Signal
FFT Analysis:
Start time (s): 0
Number of cycles: 1
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max frequency for THD computation: Nyquist frequency
Display style: Bar (relative to funda...
Base value: 1.0
Frequency axis: Hertz

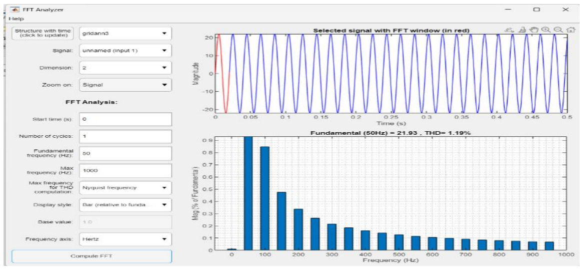
Figure 4.8: FFT spectrum of grid current with ANN control

- Case 3: Voltage THD = 0.56%, Current THD = 1.00%



Structure with time (click to update): gridann3
Signal: unnamed (input 1)
Dimension: 1
Zoom on: Signal
FFT Analysis:
Start time (s): 0
Number of cycles: 1
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max frequency for THD computation: Nyquist frequency
Display style: Bar (relative to funda...
Base value: 1.0
Frequency axis: Hertz

Figure 4.9: FFT spectrum of grid voltage with ANN control



Structure with time (click to update): gridann3
Signal: unnamed (input 1)
Dimension: 2
Zoom on: Signal
FFT Analysis:
Start time (s): 0
Number of cycles: 1
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max frequency for THD computation: Nyquist frequency
Display style: Bar (relative to funda...
Base value: 1.0
Frequency axis: Hertz

Figure 4.10: FFT spectrum of grid current with ANN control

D. Validation of Simulation Results with Literature

The simulation results presented in this work — specifically the THD performance and dynamic behaviour of the transformer-less CSI under PI and ANN control — have been checked against published findings from the literature to demonstrate consistency with established research.

1) MPPT behaviour (Incremental Conductance). The Incremental Conductance (IC) MPPT implemented here shows fast tracking and reduced oscillation around the MPP under step irradiance changes. This behaviour aligns with comparative MPPT studies that identify IC as having superior tracking accuracy and better dynamic performance than simple P&O, especially under rapidly changing irradiance. The observed tracking speed and small steady-state oscillation are consistent with established results.
2) ANN-based control and harmonic reduction. The ANN-based current controller developed in this work produced consistent reductions in current THD (observed 1.00–1.19% for ANN vs. 1.52–2.47% for PI across test cases). Similar reductions in harmonic content and improved transient response using ANN or ANN-hybrid controllers are reported in recent studies of grid connected PV inverters, which show that intelligent controllers can reduce THD and improve robustness under dynamic conditions. These prior investigations support the conclusion that ANN control provides meaningful harmonic improvement over fixed-gain PI controllers.
3) Suitability of CSI. The choice of a CSI for a grid-feeding, transformer-less configuration is supported by review and application literature that highlight CSI advantages such as inherent current regulation, lower common-mode EMI, and improved fault tolerance — all of which help explain the better current waveform quality observed in simulation. Reported CSI studies also discuss the importance of proper DC-link inductor sizing and suitable switching strategies to achieve low THD. Transformer-less operation and leakage/THD trade-offs. Transformer-less PV systems usually reduce weight, cost and losses but introduce common-mode and leakage current concerns. A number of transformer-less topology reviews and measurement studies indicate that THD and leakage current are topology dependent and can be kept within acceptable limits by careful topology and filter design. The low THD levels obtained in the present simulations are therefore consistent with transformer-less topologies that have been optimized for harmonic performance.
4) Comparison with domain-specific studies. For context, prior conference work on solar-EV systems (Premchand & Gudey, IEEE SCES 2020) provides system-level architecture and control rationale for PV-to-grid and V2G systems; although that study addresses EV charging control and bidirectional operation rather than CSI-specific THD metrics, it corroborates the practical system choices (MPPT + two-stage conversion + grid synchronization) used in this thesis.

5) Conclusion of validation. Taken together, the above comparisons demonstrate that (a) the MPPT dynamics, (b) the ANN-based reduction in THD, and (c) the CSI + transformer-less architecture behaviour observed in this work are consistent with published literature. Where numerical differences exist, they are typically attributable to differing system ratings, filter cut-off design, and training data / ANN architecture; these factors are discussed below and can be investigated further by hardware tests or parametric sensitivity runs. Below Table 6.3 compares the THD values obtained in this work with representative literature. The ANN results lie within or below the typical ranges reported for optimized transformer-less inverters and ANN-controlled systems, confirming the validity of our simulations.

E. Comparative THD Performance Analysis (PI vs ANN)

A direct comparison of PI - ANN controllers clearly demonstrates the superiority of the ANN-based approach.

Case	Controller Type	Voltage THD (%)	Current THD (%)
Case 1	PI Controller	0.76	1.52
	ANN Controller	0.45	1.17
Case 2	PI Controller	1.59	2.47
	ANN Controller	0.81	1.19
Case 3	PI Controller	1.10	1.90
	ANN Controller	0.56	1.00

Table 4.1: Comparative THD analysis for PI and ANN controllers

V. DISCUSSION OF RESULTS

Power quality is a critical component in grid-based renewable energy systems. Poor quality of waveforms may initiate augmented losses, create interference with auxiliary devices, and violate grid regulations. The analysis of the simulation data shows that the current injected into the grid by the proposed ANN-based control strategy improves the quality of the injected current. The resultant reduction of harmonic distortion produces a waveform that is virtually an ideal sinusoid with fidelity. In addition, high current quality increases grid connected system stability and reduces the tendency of power-quality concomitant issues (voltage distortion and electromagnetic interference).

“The IEEE-519 standard will specify acceptable limits for harmonic distortion in power systems. According to this standard, total harmonic distortion of current injected into grid must remain within specified limits to ensure safe and reliable operation of electrical networks. The simulation results obtained in this work indicate that the harmonic levels produced by the proposed system remain within permissible limits defined by IEEE-519 standard. The ANN-based control strategy further improves compliance by reducing harmonic distortion compared with conventional PI controller”. Therefore, the proposed transformer-less current source inverter with intelligent control can be considered suitable for grid connected photovoltaic applications where power quality and regulatory compliance are important requirements.

VI. CONCLUSION

This thesis is an in-depth design and simulation study of a transformerless grid connected, current-source inverter (CSI) adapted to be used in solar photovoltaic (PV) applications. The overall goal of the task was to design an effective system of power conversion that can achieve the maximum power output out of the PV array and provide the output power to the utility grid with an acceptable power quality. The proposed structure incorporates a PV array, a DC-DC boost converter with an Incremental Conductance based maximum power point tracking (MPPT) algorithm, a DC-link current source stage, and a CSI to enable an easy access to the grid. The boost converter controls the operating point of the PV array and puts the system under operating conditions that are within the vicinity of the maximum power point even with changing conditions in solar irradiance. DC-link inductor maintains a constant current source on the inverter input and in this way, simplifies the current regulation and makes the system very reliable. There were two different control strategies introduced to control the inverter output current. The first step involved the use of a traditional proportional integral (PI) controller with the aim of creating a reference performance benchmark. Although the PI controller managed to hold the basic current regulation in steady state conditions, its operation under dynamic variation in operating parameters was worse. In order to overcome these limitations, a controller using artificial neural network (ANN) was proposed. ANN controller was developed to adjust to the nonlinear nature of system hence enhancing grid current regulation. The findings of the simulation carried out with the help of the MATLAB/Simulink were that in the cases when the ANN-based control method was applied, the current waveforms were smoother and less harmonic distortion was present compared to the standard PI controller. These results further supported the fact that the proposed system is effective in injecting current into the grid and ensuring that it is synchronized with the grid voltage. Analysis of harmonic showed that grid-current distortion was within the acceptable maximums of the IEEE-519 standard. The overall results prove that the transformer-less CSI topology, in combination with smart control, is able to significantly enhance the output of PV systems connected to the grid. On the balance, the paper has testified to the feasibility of the suggested system as a trusted method of solar photovoltaic generation into the electric grid, and at the same time maintain quality power and optimal energy conversion.

The significant findings of this study can be formulated as follows:

1) Construction of a transformer-free grid-connected photovoltaic power conversion system based on a current-source inverter topology.
2) Application of the Incremental Conductance MPPT algorithm to ensure the extracting solar energy is efficient in different environmental conditions.
3) To ensure a constant current input to the inverter a DC-link current source stage was designed and simulated.
4) Implementation and evaluation of a conventional PI controller for inverter current regulation.
5) Development of an ANN-based intelligent controller to improve dynamic performance and reduce harmonic distortion.
6) Comparative analysis of PI and ANN control strategies based on simulation results and harmonic performance.
7) Verification that the proposed system satisfies IEEE-519 harmonic standards for grid-connected operation.

VII.FUTURE SCOPE

Although the proposed system demonstrates promising performance through simulation studies, several opportunities exist for further research and development.

One possible extension of this work is the implementation of proposed system in hardware. Experimental validation using a laboratory prototype would provide deeper insight into practical challenges such as switching losses, electromagnetic interference, and real-time controller performance.

Another area of future work involves extending the system to three-phase grid applications. Three-phase systems are widely used in commercial and industrial environments, and adapting the proposed control strategy to such systems could improve its practical applicability. Further research may also explore hybrid intelligent control techniques that combine neural networks with other advanced control strategies such as fuzzy logic or adaptive control. These methods could potentially enhance system stability and improve dynamic response under rapidly changing operating conditions.

1) Hardware Implementation The proposed transformer-less CSI with ANN control can be implemented using DSP or FPGA platforms to validate simulation results experimentally.
2) Three-Phase Grid Integration Extending the system to a three-phase grid-connected configuration would make it suitable for higher power and industrial applications.
3) Advanced Intelligent Control Techniques Hybrid control strategies combining ANN with fuzzy logic, adaptive control, or reinforcement learning can be explored for further performance improvement.
4) Online ANN Training Real-time adaptive ANN training can be implemented to enhance system response under rapidly changing grid and environmental conditions.
5) Leakage Current and EMI Analysis Detailed investigation of leakage current suppression and electromagnetic interference in transformer-less CSI systems can be carried out.
6) Integration with Energy Storage and EV Systems The proposal can be extended to include BES or EV charging systems with bidirectional power flow capability.

In addition, the integration of energy storage systems such as batteries or supercapacitors could be investigated to support grid stability and enable bidirectional power flow. Such an approach would allow the system to participate in advanced applications such as EV charging and smart grid energy management. Finally, future studies may consider advanced inverter topologies and improved filtering techniques to further reduce harmonic distortion and enhance overall system efficiency.

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