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Evolutionary Controller Directed Modular Converter Modelling for Per Phase Power Distribution in a Solar System

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Abstract: *Renewable energy has been a longstanding source of power for humanity, evolving from ancient hydro, wind, solar, and biofuel sources to the energy demands of the 18th-century Industrial Revolution. However, the detrimental environmental effects of fossil fuel combustion, such as carbon dioxide emissions and global warming, have prompted a reevaluation of energy generation strategies. This research paper explores the critical aspects of renewable energy, power quality, and solar energy, with a particular focus on distributed generation and solar photovoltaic systems. Using MATLAB/SIMULINK, the study models and simulates a solar PV system, optimizing its output, stability, and efficiency for grid integration. The paper evaluates the performance of the system under varying irradiation and load conditions and proposes control strategies to enhance its operation.*

Keywords: *Renewable energy, solar energy, power quality, distributed generation, solar photovoltaic system, MATLAB/SIMULINK, grid integration, maximum power point tracking (MPPT), microgrids.*

I. INTRODUCTION

Renewable energy has been harnessed by humanity for countless centuries. In ancient times, solar, wind, hydro, as well as biofuel energy constituted the sole available sources of power. The 18th-century Industrial Revolution ushered in a new epoch of energy production and consumption methodologies, propelling civilization's progress and advancement. However, the past few decades have revealed significant detrimental environmental effects. The combustion of fossil fuels—coal, oil, and gas—has released carbon dioxide, causing global warming and elevating environmental pollution levels. Recognizing these grave concerns, numerous governments have sought to reevaluate energy generation and consumption strategies to minimize emission-related pollution, curb global warming, and mitigate nuclear accident risks [1]. Maximum Power Point Tracking (MPPT)

In the age of smart technology, microprocessor-controlled devices, as well as digital, electronic, and nonlinear eqsuipment, have become prevalent across various industrial sectors. These devices are highly sensitive and prone to disruptions in their electrical supply, leading to operational challenges. Furthermore, the proliferation of various power sources has contributed to a decline in power quality (PQ). Inadequate power quality can give rise to issues such as data errors, automatic resets, memory loss, UPS alarms, equipment malfunctions, software corruption, circuit board failures, power supply disturbances, and elevated temperatures in electrical distribution systems. Given these realities, the significance of power quality continues to escalate. Voltage-related problems are also of paramount importance, particularly concerning sensitive nonlinear loads and end-users [2].

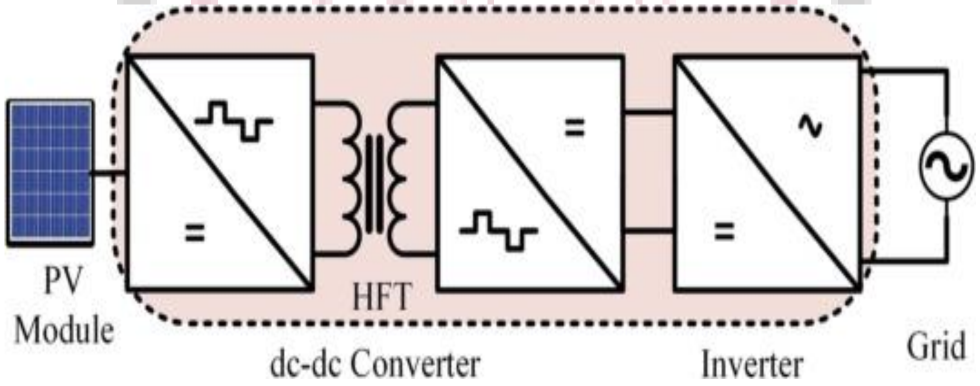

Figure 1. PV system with a high-frequency transformer and inverter [3].

A. Inverter-based Microgrid

Microgrids (MGs) represent one of the most promising avenues toward ensuring sustainable power supply and facilitating rural electrification, particularly in cases where extensive investment in main grid expansion might not be economically justified. Within MGs, the equitable sharing of distributed loads assumes a pivotal role in upholding a harmonious equilibrium between power generation and consumption. An MG founded on inverter technology comprises an assemblage of micro-sources, distribution lines, and loads that interconnect with the main grid through static switches. These inverter models encompass a range of variable frequencis and voltage amplitudes.

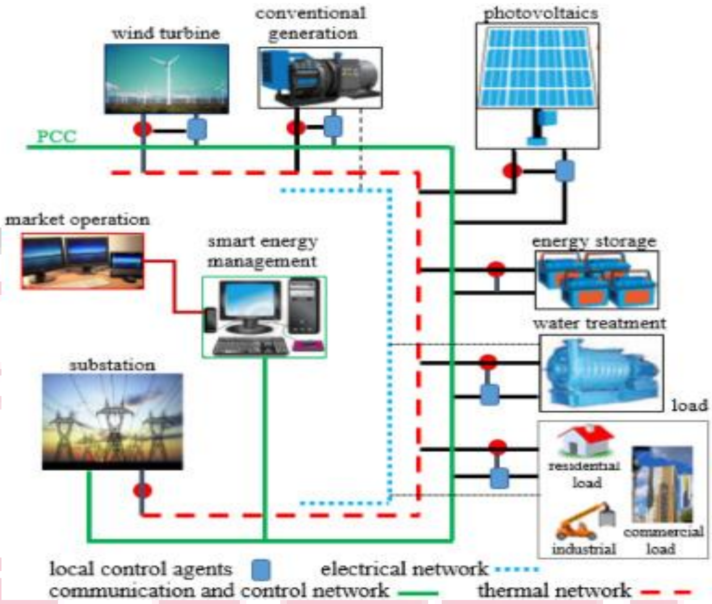

Figure 2. Typical scheme of an inverter-based MG [4]

Microgrids (MGs), predominantly reliant on inverter technology, are progressively assuming greater significance due to their capacity to adeptly integrate diverse Distributed Generators (DGs) while upholding superior power quality. Numerous investigations have been conducted on inverter-based MGs, encompassing a spectrum of topics.

B. Potential and Advantages of Solar Energy

Solar heating, solar thermal energy, photovoltaics, molten salt power plants, solar architecture, as well as synthetic photosynthesis are just a few instances of the many constantly developing technologies used to capture solar energy, which includes the radiant light and heat emitted by the Sun. In terms of techniques for capturing, disseminating, and converting solar radiation into usable power, passive solar and active solar energy methods can be broadly categorized as vital renewable energy sources. The use of concentrated solar power, photovoltaic systems, and solar water heating are active solar methods for capturing solar energy. The sun-facing orientation of buildings, the use of materials with advantageous thermal mass or light-dispersing qualities, and the development of naturally ventilated spaces are all examples of passive solar strategies.

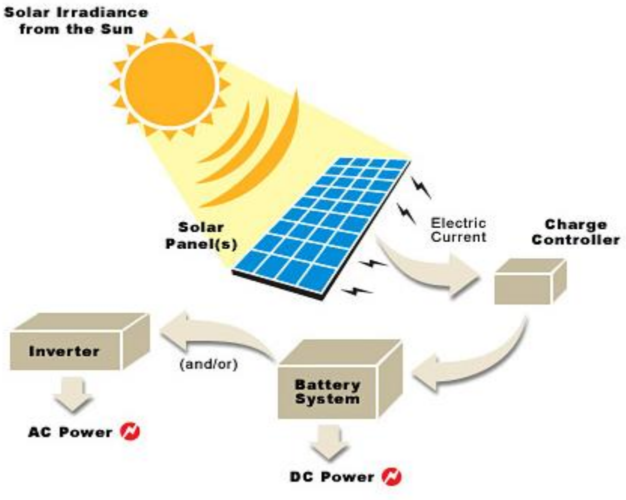

Figure 3. Solar Energy

Because of the vast amount of solar energy accessible, it is a very tempting source of electricity. In its 2000 World Energy Assessment, the United Nations Development Programme determined that the annual potential of solar energy ranged from 1,575 to 49,837 exajoules (EJ).

C. Role of Distributed Generation in Energy Transition

Given their ability to be closer to end-use loads and connected to lower voltage distribution networks, distributed generating technologies are an important component of the energy transition. Distributed generators complement huge central power plants as an electricity source, enabling for new uses and contributing to an expanding community of users who also produce electricity. Surprisingly, before huge centralised power systems were introduced, distributed generation technologies met the majority of the world's electrical needs in the late 1800s and early 1900s. Distributed generation contributed for 10% of power capacity additions in the 1950s, largely as a backup supply or in transportation, while it accounted for 36% of power capacity additions in 2010.

II. LITERATURE REVIEW

Bhupender Sharma et al., (s2019) [5] A grid-connected hybrid wind-solar energy conversion system (HWSECS) is discussed in this article, with an emphasis on power quality and an enhanced cascaded H-Bridge multilevel inverter (CHBMLI). With the help of specialized DC/DC converters equipped with maximum power point tracking (MPPT) systems, the HWSECS integrates solar and wind energy conversion systems. Each of these systems are connected to a separate dc-link within the CHBMLI. While the CHB topology, when employed as a PWM rectifier, addresses capacitor imbalances among dc-links supplying distinct dc loads, challenges arise during regenerative operation as uneven power flows into individual cells. The proposed HWSECS system faces similar voltage imbalances, as two separate sources (WECS and SECS) are introduced across isolated dc-links. The author's approach seeks to leverage topology advantages while simultaneously tackling operational and control issues. The system and control scheme are designed to maximize power extraction from renewable energy sources (RES) and facilitate grid injection, alongside other benefits. Simulation studies were conducted using MATLAB/Simulink, with experimental validation performed on a dSPACE-1104 prototype. Additionally, the paper presents a mathematical model of the CHB-MLI based HWSECS for analysis.

N. Tak et al., (2022) [6] This article offers a creative approach to problems with grid-connected solar photovoltaic (PV) system design, concentrating on power conditioning units in particular. These difficulties cover a range of issues, including reliability, efficiency, and implementation costs as well as power quality. The suggested method introduces a distinct high-resolution multilevel inverter topology with a double-level-doubling network that is based on a single dc source. This topology is made to handle the practical limitations that are frequently present in applications using central inverters. A two-stage, high-resolution, multilevel inverter configuration is the key component of the suggested solution. It not only doubles inverter utilization but also significantly boosts overall efficiency. The system's ability to handle reactive power and block faults is also showcased. Extensive simulations using MATLAB/Simulink were conducted, and laboratory prototype experiments corroborate the effectiveness of the presented concepts.

B. Pakkiraiah et al., (2016) [7] In the present era, addressing the rising energy demands while combating global warming has led to the adoption of renewable energy-based systems. Among various renewable sources, solar energy stands out as a primary alternative. However, solar panel systems currently convert only around 30–40% of solar irradiation into electrical energy, lagging behind other sources. Extensive research has been dedicated to enhancing the performance of photovoltaic (PV) systems and tackling associated challenges. This paper aims to explore diverse PV panel systems, algorithms for maximum power point tracking control, utilization of power electronic converters with control strategies, deployment of controllers, harmonic content reduction filters, and the integration of battery systems into PV setups. The paper also addresses present and future issues in advancing PV system performance. An appended list of 185 research publications offers further reference in this field.

Kumar. J, C.R et al., (2020) [8] The primary aim behind the integration of renewable energy sources in India is to foster economic growth, enhance energy security, ensure energy access, and alleviate the effects of climate change. Achieving sustainable development hinges on utilizing sustainable energy sources and guaranteeing affordable, reliable, modern energy for the populace. India has established itself as a key player in the global renewable energy market, benefiting from strong government support and a favorable business climate. To attract foreign investment and speed up the nation's progress in the renewable energy sector, the government has put policies, initiatives, and a welcoming environment in place. The growth of this sector is anticipated to generate a significant number of domestic job opportunities in the coming years. This article aims to highlight India's outstanding accomplishments, future potential, anticipated improvements in electricity generation, as well as the difficulties, investment opportunities, and job prospects brought on by the country's expansion of renewable energy. The review includes an analysis of the challenges faced by the renewable sector, with the findings offering insightful information for policy-makers, project developers, investors, stakeholders, industries, research organizations, and the scientific communities.

D. Remoaldo et al., 2021 [9] This study compares the performance of two maximum power point tracking (MPPT) strategies used on a photovoltaic (PV) system made up of five solar panels connected in series. Both the conventional Perturb and Observe (P&O) algorithm and a fuzzy logic controller (FLC) integrated into a boost converter are used in this study**.** The primary objective is to assess whether an artificial intelligence (AI)-based MPPT approach offers improved efficiency, stability, and adaptability compared to the conventional method, particularly under varying environmental conditions such as solar irradiation and temperature. The investigation also aims to evaluate how well these methods work in steady-state conditions. The recently proposed Fuzzy Logic Controller (FLC), which has a rule base made up of 25 rules, surpassed the conventional Perturb and Observe (P&O) controller in terms of performance. It demonstrated an adaptive step size that allowed for quick adaptation to shifting environmental conditions. In steady-state conditions, the FLC efficiently located the Maximum Power Point (MPP) with increased speed and less oscillations. As a result, energy production was increased while losses were reduced under both steady-state and dynamic conditions. The research employed MATLAB (Version 2018)/Simulink for conducting simulations.

M. Kaliamoorthy et al., (2014) [10] This study introduces a novel single-phase grid-connected cascaded multilevel inverter for PV -based power systems. It employs an Evolutionary Programming (EP) based MPPT algorithm for optimal power tracking. The inverter design maximizes voltage levels with fewer switches, reducing gate driving circuits, size, and power consumption. The technique employs mixed modulation, resulting in reduced output waveform THD. The paper details circuit layout, theoretical operations, and MATLAB/SIMULINK simulations. The EP-based MPPT ensures efficient power extraction from PV arrays.

III. OBJECTIVES

This study aims to achieve the following objectives:

- A solar photovoltaic system's output capacity can be increased using MATLAB/SIMULINK before it is connected to the grid.
- Investigate how variable radiation and temperature affect individual solar modules and overall power output, striving for optimal extraction under changing inputs.
- Improve solar system stability and dynamic power output through an AI-optimized controller for the DC to AC inverter.
- Enhance system efficiency and reliability by integrating with the grid using a transformer at specified voltage and frequency, evaluating performance across various loads.

IV. METHODOLOGY

The model was constructed within the MATLAB/SIMULINK environment, utilizing a matrix/matrix language enriched with control flow instructions, input/output handling, functions, object-oriented programming capabilities, as well as data structures. The primary attributes of this environment encompass:

- A high-level language tailored for scientific and technical computing.
- A user-friendly desktop setting for iterative problem exploration, design, and resolution.
- Graphing tools for data visualization, including customization options.
- Application capabilities for tasks such as data classification, signal analysis, and control optimization.
- Complementary toolboxes catering to diverse scientific and technical needs.
- Tools for creating personalized user interfaces and applications.
- Distribution options, allowing the sharing of MATLAB programs without cost.

In practice, the power generated by a single module frequently is insufficient for commercial usage, necessitating the connection of modules to create arrays capable of meeting the load demands. The manner in which the cells are organized inside a module is mirrored by this array connection process. Additionally, modules can be connected in parallel to increase current or in series to increase voltage.

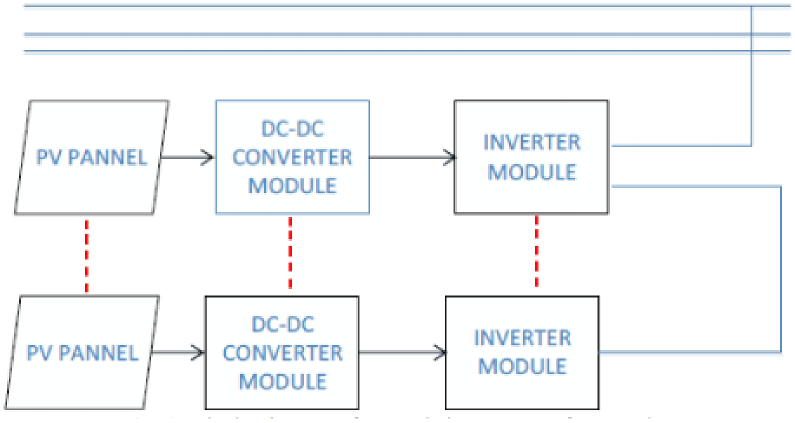

Figure 4. Proposed Modular Control Scheme for Phase-Inverter Modeling

A. PV Module modeling

In the context of the double exponential model, which applies to monocrystalline PV cells, an optimal solar cell has been represented by a parallel combination of a current source and a diode. The PV cell's output current relies on the photon current, influenced by the load current and solar insolation during its operation. PV cells possess a singular operating point at which the voltage (V) and current (I) of the cell combine for achieving optimal power output. These specific values correspond to a distinct resistance, equivalent to the ratio of V to I.

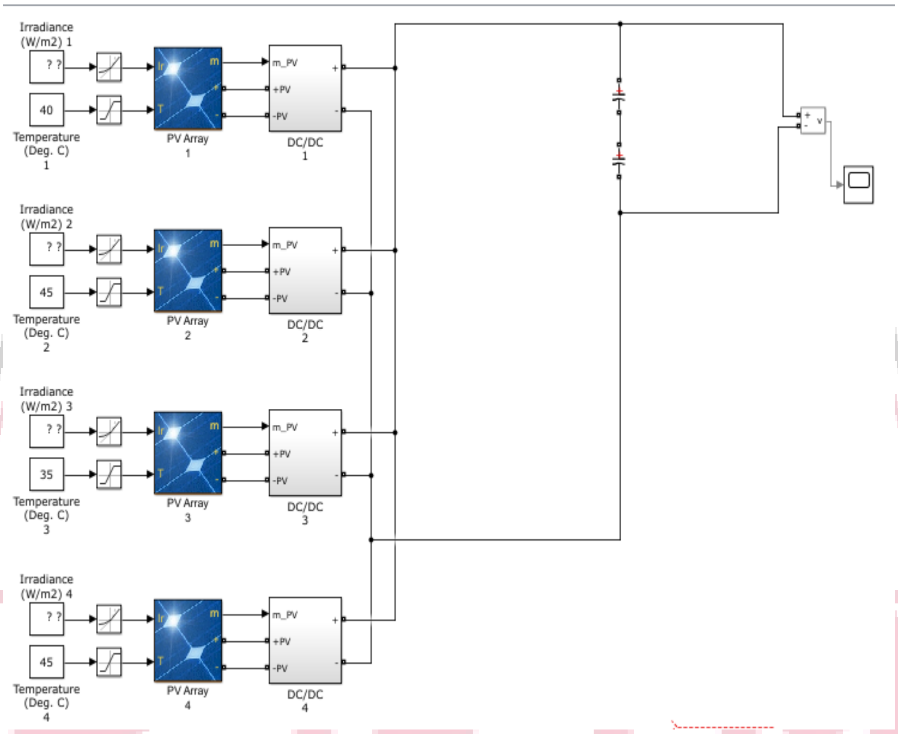

Figure 5. Simulated Solar System

Table 1: Characteristics of Solar PV System Module

S. No.	**System Parameters**	**Values**
1	Maximum power point voltage	52.7V
2	Maximum PV power	314.0 W
3	Maximum power point current	5.66A
4	Short-circuit current	6.11A
5	Open circuit voltage	65.6V
6	Nominal utility frequency	50 Hz
7	DC-bus capacitor	100 µF
8	modules in series	5
9	modules in parallel	64

A cell's series resistance (Rs) and a parallel configuration made up of the cell photocurrent (Iph), shunt resistance (Rsh), and exponential diode (D), are both present in an electrical circuit. Ipv and Vpv stand for the current and voltage of the cell, respectively. This relationship may be described as follows:

$$I_{pv} = I_{ph} - I_s\left(e^{q(V_{pv}+I_{pv}*R_s)/nKT} - 1\right) - (V_{pv} + I_{pv} * R_s)/R_{sh} \tag{1}$$

Where:

I_{ph}- Current generated by solar radiation

I_S - Saturation current of the diode

q - Charge of an electron (1.6e^{-19}C)

K - Boltzmann constant (1.38e^{-23}J/K)

n - Ideality factor (1~2)

T - Temperature in Kelvin (^{0}K)"

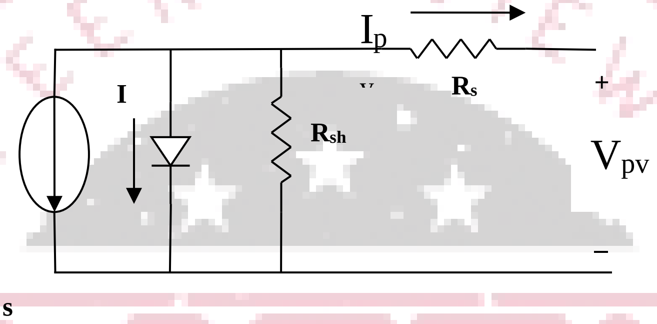

Figure 6. Solar PV Cell's Equivalent Circuit

It is possible to express the solar induced current of the solar PV cell, that depends on the solar irradiation level and working temperature, as follows: (2)

$$I_{ph} = I_{sc} - k_i(T_c - T_r) * \frac{I_r}{1000}$$

Where:

I_{SC}- Short-circuit current of the cell at Standard Test Conditions (STC)

k_i - Temperature coefficient for cell short-circuit current (A/K)

I_r - Irradiance in w/m

T_C - Cell working temperature at STC

T_r - Reference temperature at STC

The maximum power point (MPP) of a PV cell is located at the knee of the curve, as illustrated in Figure 7. PV cells exhibit an exponential relationship between current and voltage."

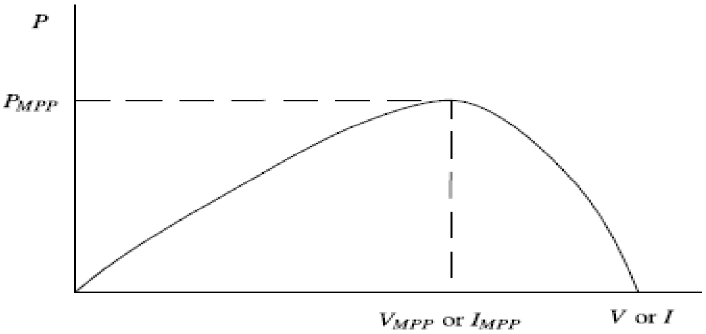

Figure 7. PV Array Power Curve Characteristic

The Perturb and Observe (P&O) algorithm will monitor and optimize power delivery to the Distributed Control Management Systems (DCMGs). The model assumptions consider the PV's behavior as an ideal current source. Furthermore, it is assumed that all power converters function in the continuous conduction mode (CCM) along with the influence of harmonics is disregarded.

B. Control of Multi-Modular Cell Modeling

The modeling process takes into consideration the fluctuating irradiation and temperature conditions encountered by the four PV arrays that collectively make up the distributed generation system based on PV farms. Numerous elements, including module materials, construction, mounting arrangements, incident irradiance (which can be affected by shading and soiling), wind speed at the array level, ambient temperature, and others, have an impact on the temperature of PV cells. For various modules, the temperature can range from 35 to 45 degrees Celsius. Additionally, during the 1-second simulation period, there is a brief 0.5-second reductions in irradiation. The system prototype is designed to cater to distributed generation at multiple nearby locations. Its outputs are aggregated and incorporated with the grid, consequently alleviating equipment requirements. One PV array block contains 64 parallel strings, each string made up of five SunPower SPR-315E modules wired in series. Each PV array is connected to an averaging DC/DC converter, which gives the inverter a unified DC input voltage. To maximize power generation, each boost converter is regulated through a separate Maximum Power Point Tracker (MPPT) that uses the "Perturb and Observe" technique. Each string's total DC output voltages are used as the inverter's input voltage. A buck-boost converter controlled inverter is produced for each phase at the end of the process, allowing for later integration with the grid system.

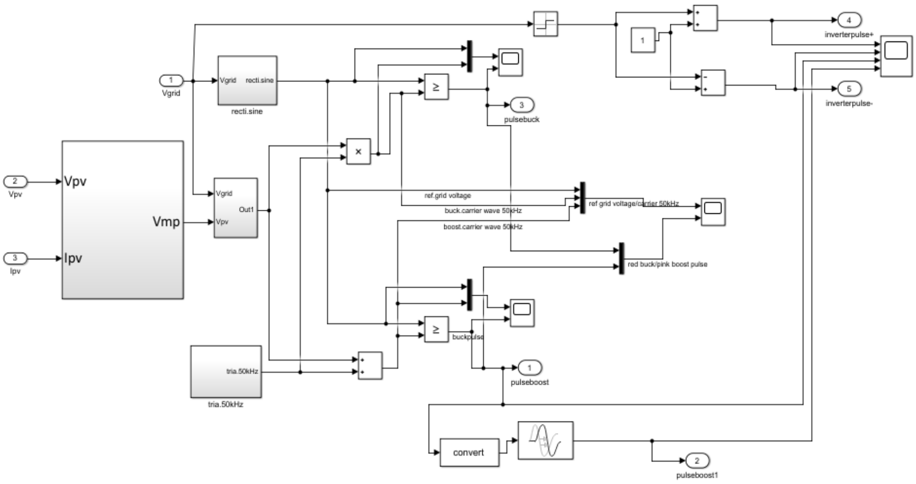

Figure 8. Combine pulse generation for per phase inverter with buck boost control in MATLAB/SIMULINK

The optimization of this control is achieved through the application of the differential evolutionary technique. This approach makes utilization of load line power as the optimization criterion to achieve efficient load balancing and adaptability to load changes. The optimization algorithm was implemented in MATLAB and can be seen in the flowchart below, which also includes pertinent equations and code for generating boost pulses and per-phase converter pulses.

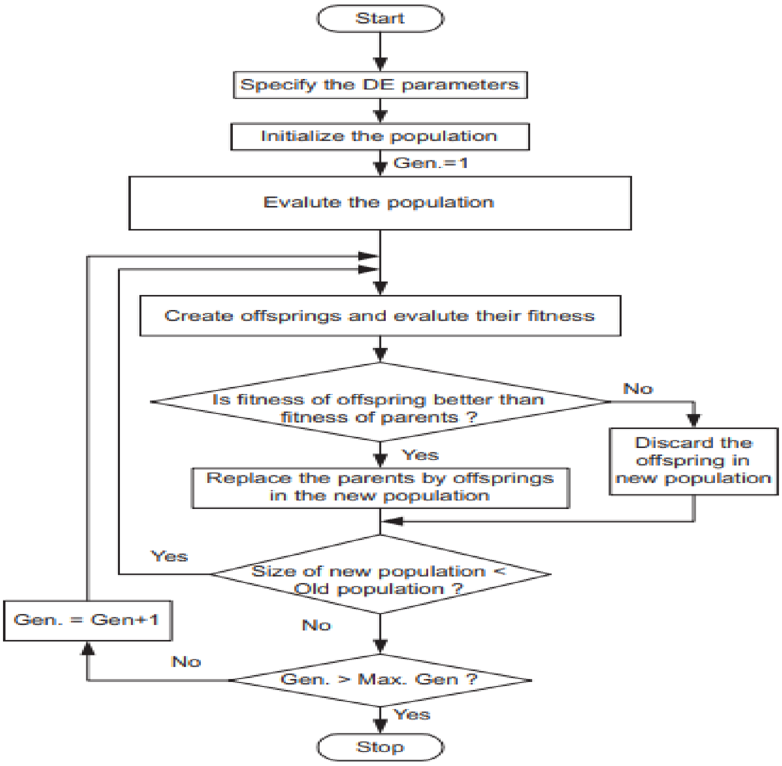

Figure 9. Flowchart Demonstrating the Proposed Differential Evolutionary Algorithm for Converters

Differential Evolution (DE) is a population-based heuristic algorithm produced to address global optimization issues in various continuous spaces. Despite being simple, DE has demonstrated exceptional performance when it comes to solving optimization problems involving non-differentiable, non-continuous, and multi-modal scenarios. An initial population of NP individuals, denoted as where $\overrightarrow{X_j}$, j=1, 2,.., NP, is randomly generated following a uniform distribution within predefined lower and upper boundaries (x_j^L , x_j^U), according to the fundamental DE approach, known as DE/rand/1/bin. "These enes undergo evolutionary processes involving crossover and mutation, leading to the formation of a trial vector. This trial vector subsequently competes with its parent to identify the most fit individual for propagation into the next generation. The DE procedure follows these steps:

C. LOAD Analysis

To assess stability, an analysis of the system's stability is conducted, encompassing a power converter and constant power loads. The analysis of power converters is used as the main tool for determining the stability of a networked AC and DC distribution system.

A wide range of loads, including everything from industrial machinery to home appliances, can be powered by power systems, which are designed to do so. These loads require a certain range of voltages, and in the case of AC devices, they also need a certain range of frequencies and phases. The study examines three distinct industrial loads, and the findings support the suggested methodology’s efficiency, which is a useful tool for designing and assessing power generation systems. To optimize the sizes and configurations of the system's components, MATLAB simulations are used.

Table 2 gives a summary of the factors considered for the balanced load scenario. When all three phases (lines) of a three-phase system carry the same amount of current while maintaining an evenly spaced phase difference, this is known as a balanced load. The power quality enhancement device can handle a 0.47 MW load for each phase of the line and was designed to manage a balanced load.

Table 2: Parameters for balanced load

Phase One Resistive Load (MW)	**Phase Two Resistive Load (MW)**	**Phase Three Resistive Load (MW)**
0.47	0.47	0.47

Table 3 gives a summary of the factors considered for the unbalanced load scenario. A non-zero total at the neutral point is caused by unbalanced loads, which result in different current magnitudes across lines or phases. The net unbalanced current in the neutral is caused by the fact that each phase has a unique current magnitude. A variety of resistive loads for each phase are included in our analysis.

Table 3: Parameters for unbalanced load

Phase One Resistive Load (MW)	Phase Two Resistive Load (MW)	Phase Three Resistive Load (MW)
0.1	0.2	0.3

The aforementioned figures give an illustration of the simulation's parameters and load types. The system's successful modeling under various loading conditions is confirmed by the mixed load analysis. Furthermore, it has been assessed how well the suggested controller manages these loads.

V. RESULT

MATLAB, derived from MATrix LABoratory, is a programming platform created to simplify logical computations and streamline input/output operations efficiently. It encompasses a wide array of built-in functions catering to diverse computations, along with numerous specialized toolboxes tailored for specific analytical disciplines, including statistics, optimization, and solving partial differential equations, among others.

In the scope of this research, the MATLAB platform has been utilized to demonstrate the implementation and simulation of the algorithm's performance.

Solar energy stands out as an abundant and environmentally friendly renewable energy source. Modern technology has enabled the harnessing of solar energy for various applications, such as electricity generation, illumination, and water heating for domestic, commercial, and industrial purposes. Photovoltaic (PV) systems have emerged as a prominent solar-based renewable energy solution, owing to their distinct benefits. Utilizing the benefits of distributed generation (DG) systems and renewable energy sources (RESs), this trend is particularly noticeable in grid-connected circumstances. The conversion of solar energy into electricity within these PV systems connected to the grid requires power converters. Large-scale solar photovoltaic (PV) systems are frequently incorporated into medium-voltage distribution grids.

The performance of the solar-based renewable energy system that is intended for grid integration is covered in detail in this chapter. During the initial power ramp-up phase, a comparative analysis has been performed taking into consideration the power output and its evaluation in terms of THD. The subsequent sections of this chapter explore the outcomes within the following three scenarios:

Scenario 1: Distributed Generation (DG) with Per-Phase Multilevel Converter under Changing Irradiation and Fundamental Regulatory PWM Control

Scenario 2: Enhanced DG System with Differential Evolutionary PI Pulse Regulation in Power Regulatory Per Phase Inverter

A. Outputs at various loading conditions

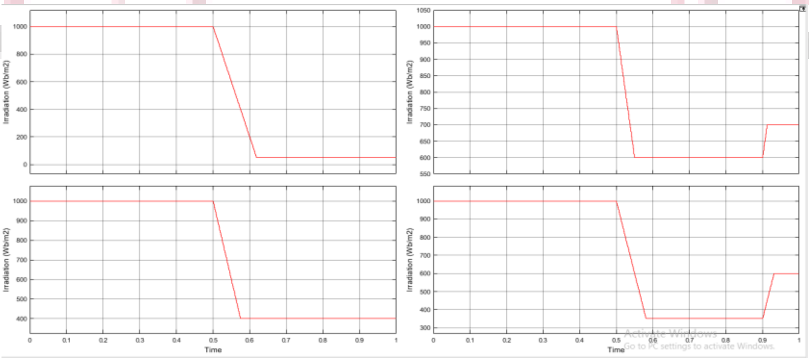

Figure 10. Fluctuating Irradiance Input to Solar Panels

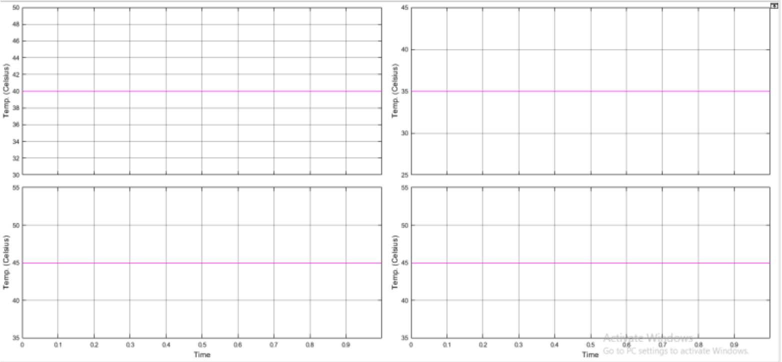

Figure 11. Changing Irradiance Input for Solar Panels

B. Scenario 1: Distributed Generation (DG) with Per-Phase Multilevel Converter under Changing Irradiation and Fundamental Regulatory PWM Control

Solar panels exposed to varying irradiation and temperature conditions are incorporated into a distributed generation system using MATLAB/SIMULINK. The resulting system output is scrutinized to comprehend its response to input variations. The DC output voltage is subsequently converted into AC using an inverter. This inverter is regulated through a basic pulse-width modulation (PWM) control technique, employing a PWM generator to generate regulating pulses. The AC output is then directed to a transformer before grid-integration. Loads are linked to the 10-kV high voltage line.

Graphical waveforms depicting active power, reactive power, and voltage, current are depicted in the following figures. Different loads are also applied to assess efficiency and reliability of the system.

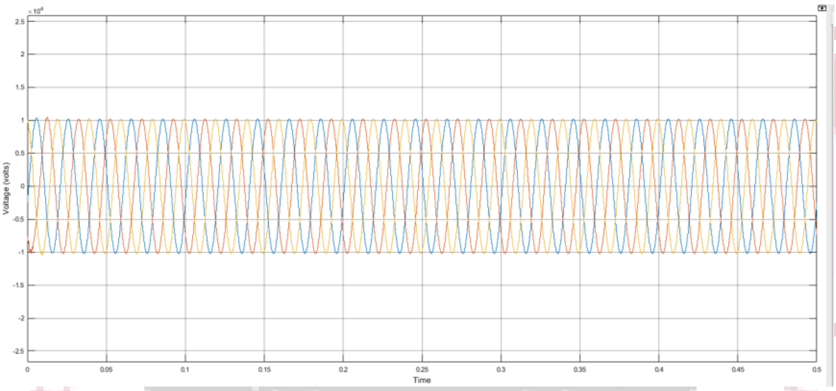

Figure 12. System Voltage with Basic Regulatory PWM Control Using Multilevel Converter per Phase

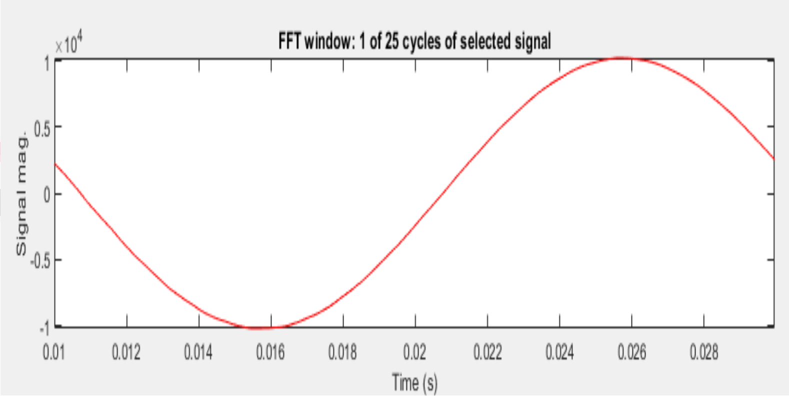

Figure 13. Frequency Domain Analysis of Voltage Output Using PWM-Controlled Per Phase Converter

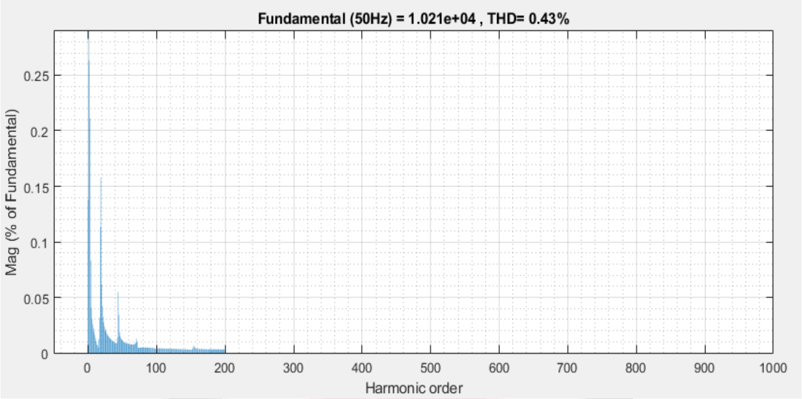

Figure 14. Voltage Output Total Harmonic Distortion (THD%) in PWM-Controlled Per Phase Converter

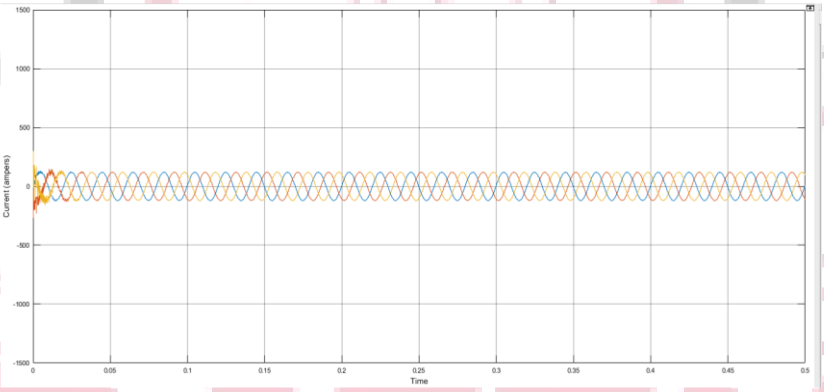

Figure 15. Current Output in Per Phase Multilevel Converter System with Basic PWM Control

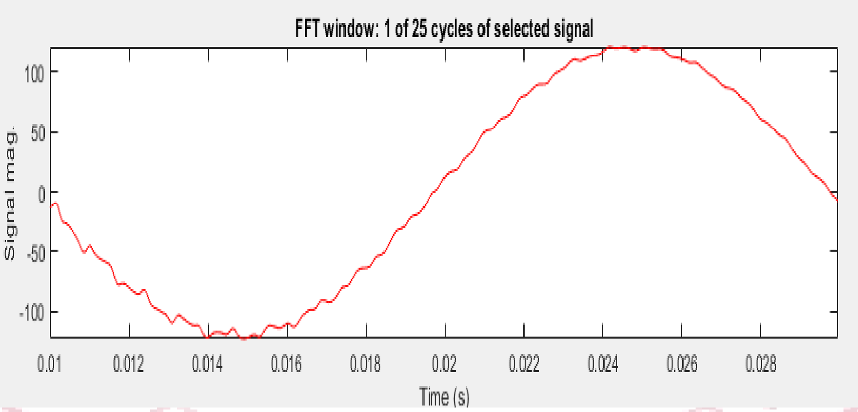

Figure 16. FFT Analysis of Current Output using PWM Control in Per Phase Converter

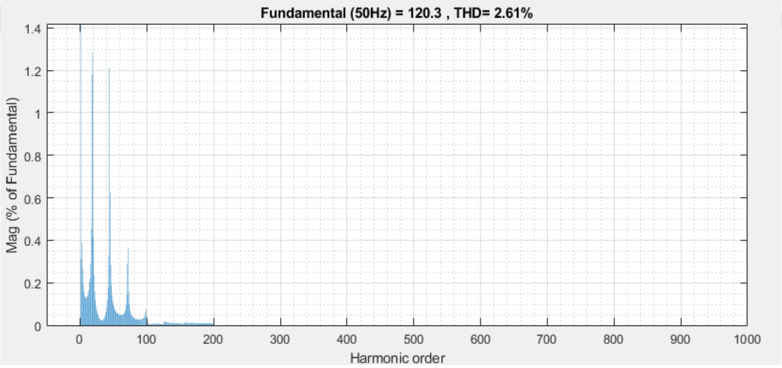

Figure 17. Current Output Total Harmonic Distortion with PWM Control in Per Phase Converter

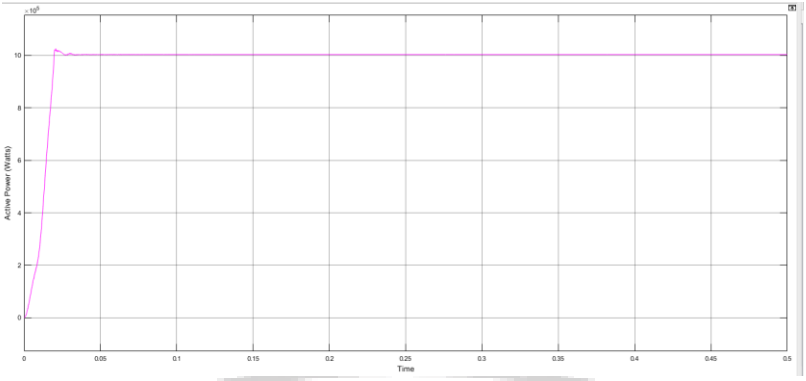

Figure 18. Active Power Analysis in System with Per Phase Multilevel Converter and Basic Regulatory PWM Control

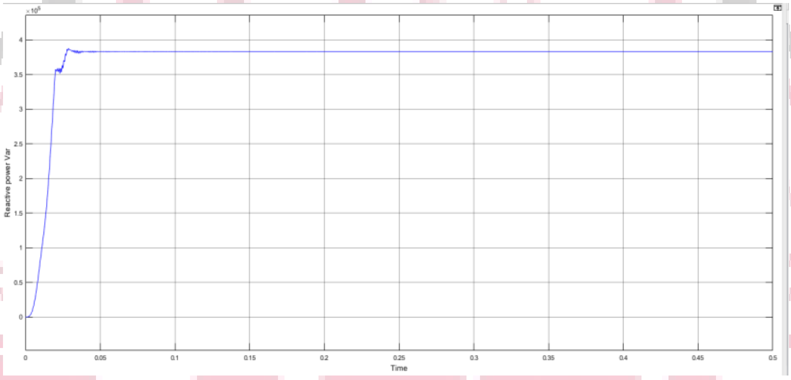

Figure 19. Reactive Power Analysis in PWM-Controlled Per Phase Multilevel Converter System

The waveforms presented above illustrate the voltage output, current output, active power output, and reactive power in the system employing a basic regulatory PWM control with a multilevel converter per phase. The analysis reveals that the voltage output stabilizes at around 10 kilovolts. Concurrently, the current output is observed to be approximately 120 amperes, resulting in an active power output of 1.003 megawatts and a reactive power output of 0.38 megavars.

C. Scenario 2: Enhanced DG System with Differential Evolutionary PI Pulse Regulation in Power Regulatory Per Phase Inverter

The converter was set up using an optimization algorithm, more specifically the differential evolutionary method. System performance was enhanced as a result of the production of optimized pulses that were customized to match both DC and AC voltage references. To seamlessly incorporate the solar system with the 3-phase AC system, the converter was meticulously designed. A per-phase inverter has been developed alongside its control mechanism, catering to diverse loads connected to the high voltage line of the DGs.

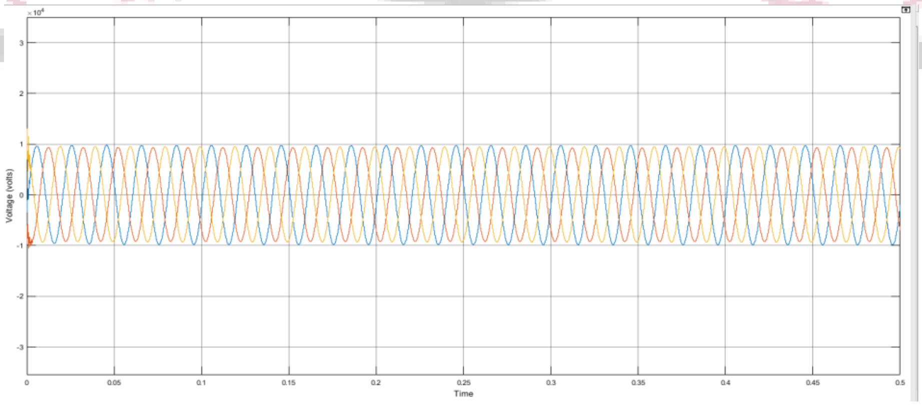

Figure 20. Voltage Analysis in DG System with Differential Evolutionary Control

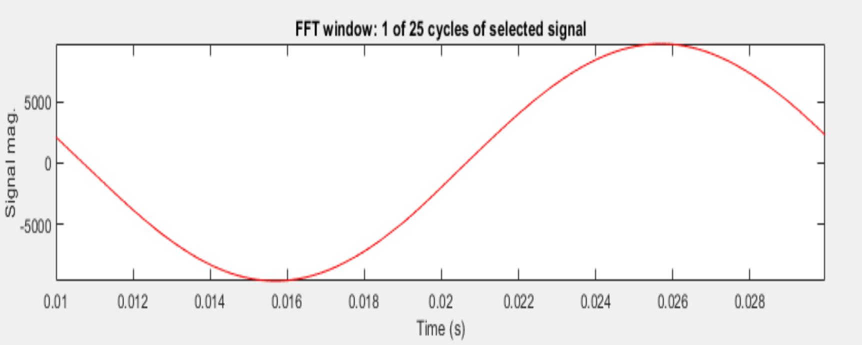

Figure 21. FFT Analysis of Voltage Output with Proposed Controller

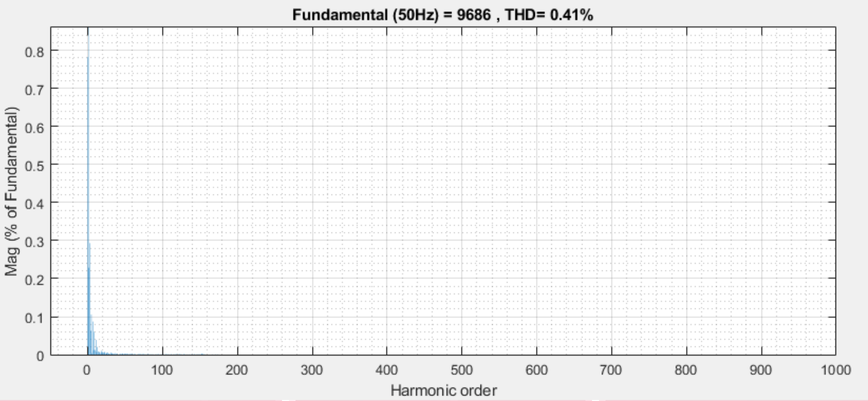

Figure 22. Voltage Output THD% with Proposed Controller

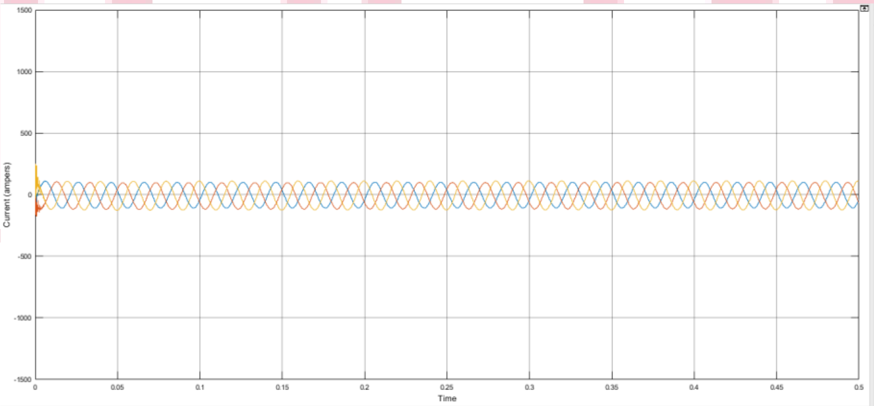

Figure 23. Current in Distributed Generation System Controlled by Proposed Differential Evolutionary Method

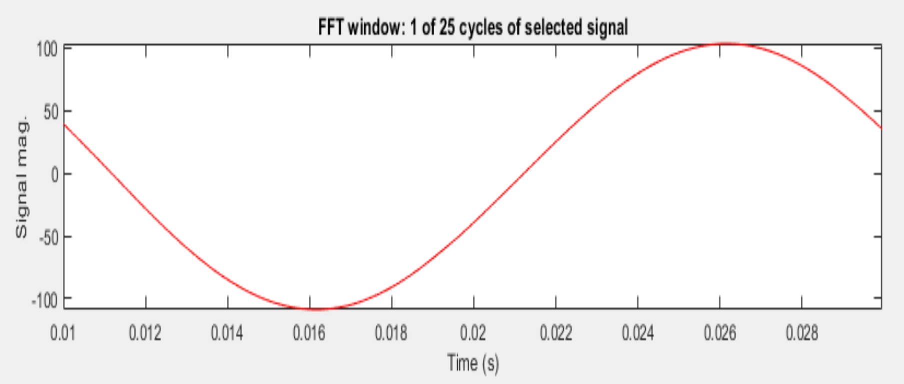

Figure 24. FFT Analysis of Current Output with Proposed Controller in the Frequency Domain

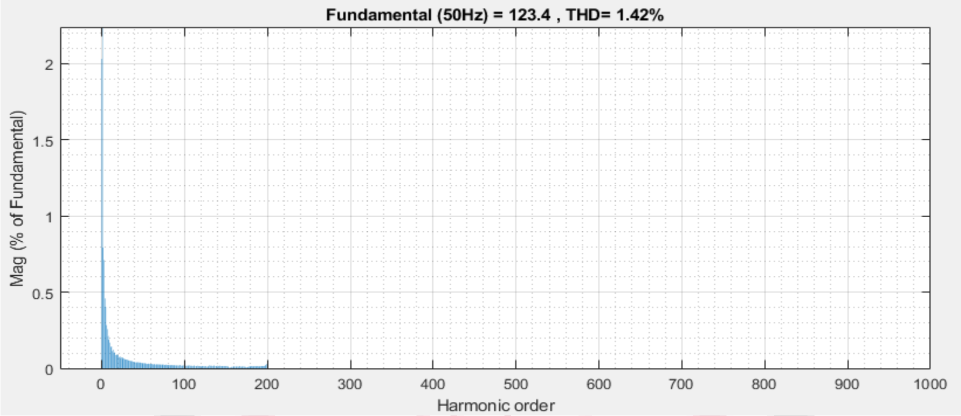

Figure 25. Total Harmonic Distortion Percentage in Current Output with Proposed Controller

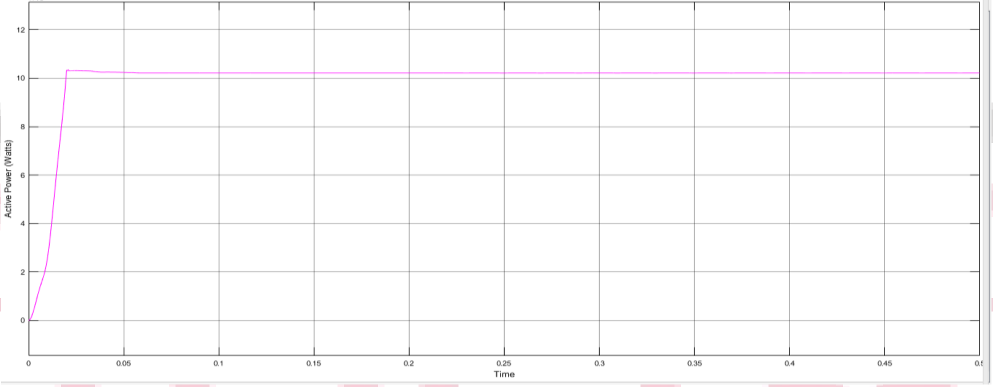

Figure 26. Active Power in DG System with Proposed Differential Evolutionary Control

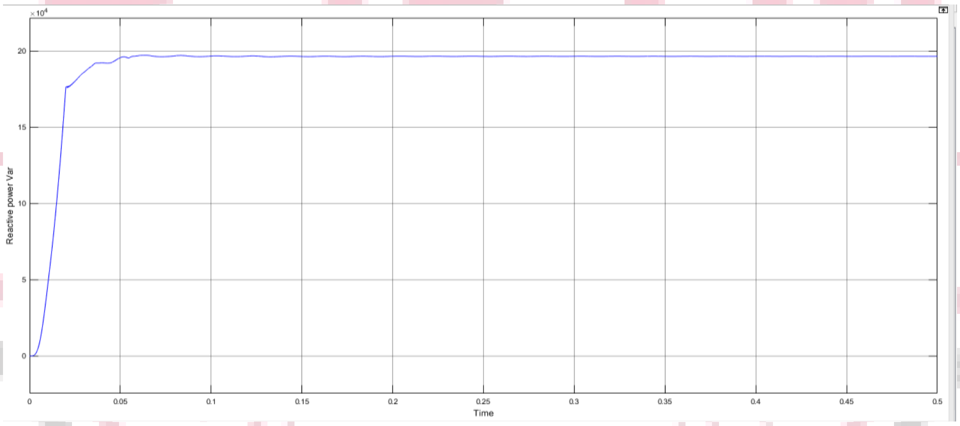

Figure 27. Reactive Power Analysis in Distributed Generation System with Proposed Differential Evolutionary Control

The measured voltage output in the DG system incorporating the recommended DG configuration, which includes per-phase inverters with power regulation controlled by the suggested differential evolutionary pulse regulation technique, reached approximately 10 kilovolts. Meanwhile, the current output was approximately 123 amperes, resulting in an active power output of around 1.022 megawatts and a reactive power output of approximately 0.196 megavars.

D. Validation

Table 5.1: Validation Comparison

Parameters	Voltage	Active Power	Reactive Power	Current	THD% in current	THD % in voltage

Solar Distributed Generation System Employing Proposed Differential Evolutionary Power Pulse Regulation Control	10KV	1.022 MW	0.196 Mvar	123	1.42%	0.41 %
Solar Distributed Generation System Utilizing Per-Phase Multilevel Converter and Basic Regulatory PWM Control	10KV	1.003 MW	0.38 MVar	120	2.61%	0.43%

The results revealed a noticeable enhancement in the active power output, increasing from approximately 1.003 MW to 1.022 MW, while maintaining a constant voltage of 10 kV. The main goal was to achieve consistent and balanced active power output, which was successfully attained by implementing the controller using an inverter equipped with differential evolutionary pulse regulation control for every phase of the system. Moreover, a reduction in reactive power was observed, indicating that the converter was designed with the capability to stabilize and compensate for reactive power, as facilitated by the designed controller.

E. Analysis of the System with Varied Loads

Three Phase Balanced Load:

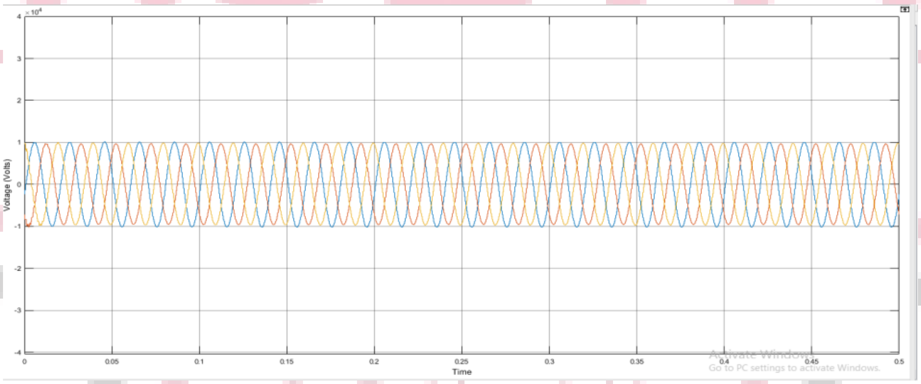

Figure 28 Voltage at Balanced Load Terminal

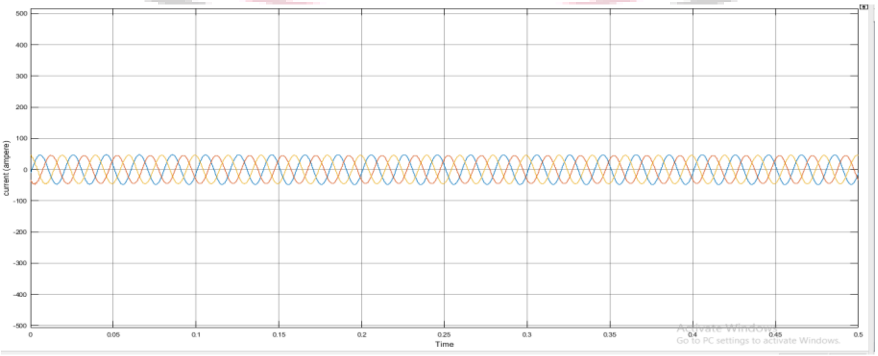

Figure 29. Current at Balanced Load

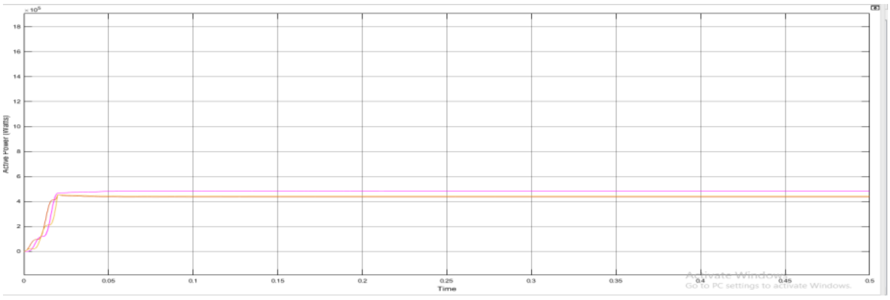

Figure 30. Active Power at Balanced Load Terminal

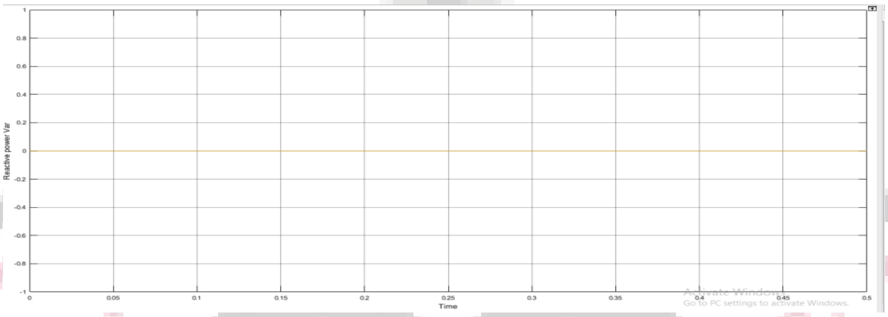

Figure 31. Reactive Power at Balanced Load Terminal

The introduced DG system, featuring the power regulatory per phase inverter with the proposed differential evolutionary pulse regulation control, successfully operated with a balanced load of around 0.5 MW. The load's power delivery exhibited stability, accompanied by a consistent terminal voltage of 10 kV.

Three Phase Unbalanced Load:

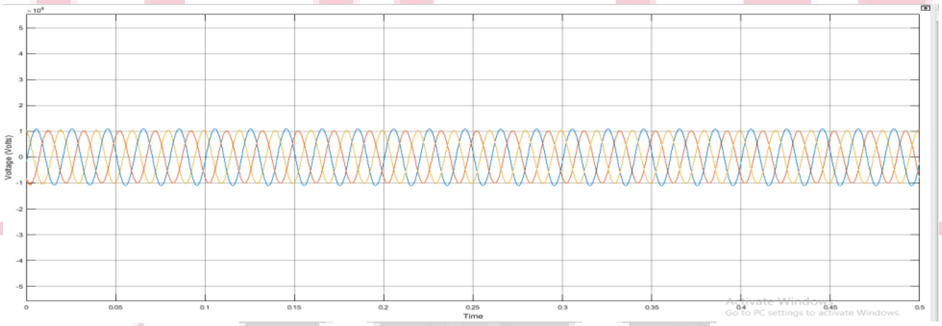

Figure 32. Voltage across the unbalanced load

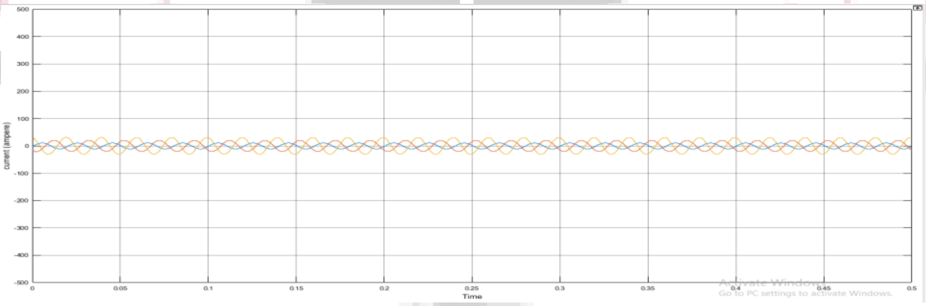

Figure 33. Current at the unbalanced load

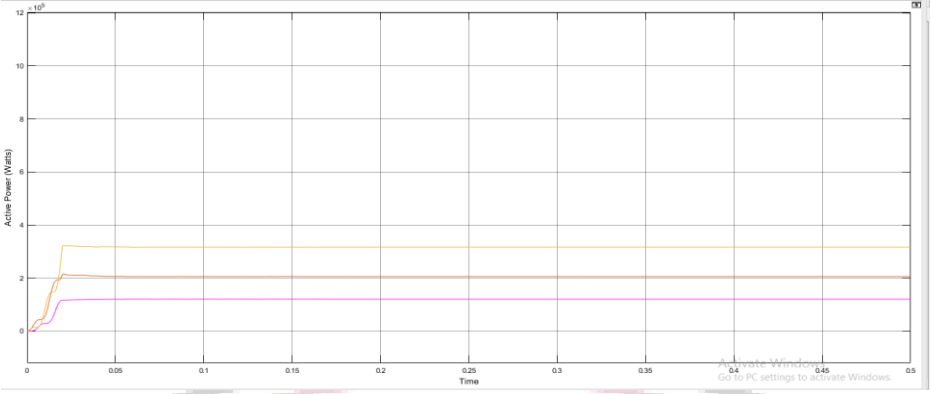

Figure 34. Active power at the terminal with unbalanced load

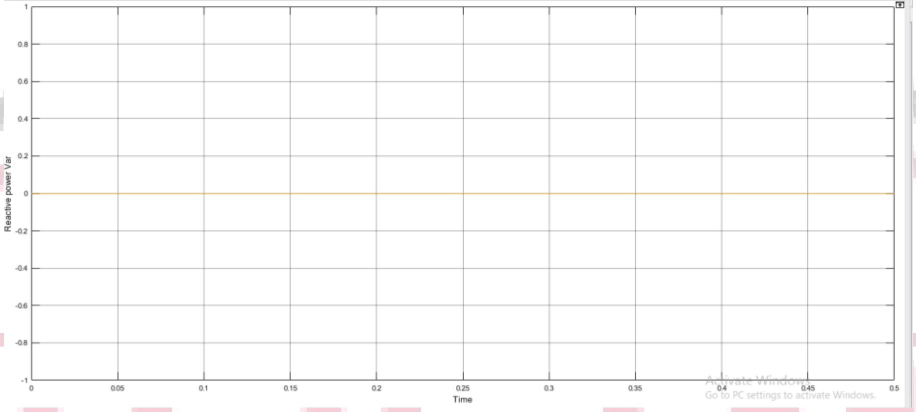

Figure 35. Reactive power at the terminal with unbalanced load

Under these circumstances, the loading for each phase is distinct. The examination showed that the voltage at the load point consistently stays at 10 kV and that the power is stable across each phase. It's important to note that the presence of various resistive loads causes the current for each phase to vary.

F. Transient Load Switching

Different loads in megawatts are sequentially introduced and removed at predetermined intervals to test the system's performance under various load conditions at the load point. As heavy loads are added to and removed from the load line, we can see how the system reacts to those changes. The suggested differential evolution strategy for power stabilization is implemented in the conduct of this assessment. The system's objective is to maintain a constant voltage level at its terminal without any voltage spikes, only adjusting the current values to accommodate changing load demands. An R load is used when the system is first operating. The RL load is introduced at 0.1 seconds and remains there for the next 0.3 seconds of the simulation. The RC load is added to the load line at 0.2 seconds and removed at 0.3 seconds later. The system returns to its regular operating state after 0.3 seconds.

The smooth changes in active power demonstrate how effectively the proposed DG system, which consists of power-regulating per-phase inverters and the proposed differential evolutionary pulse regulation control, adapts to load variations. A steady state is also reached by the reactive power within milliseconds of balancing it.

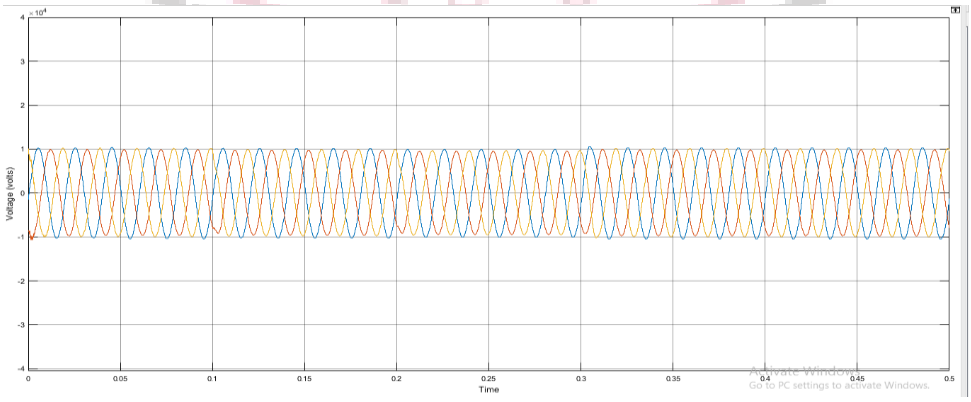

Figure 36. Voltage Variations in the Load Line Across the Entire Switching Durations

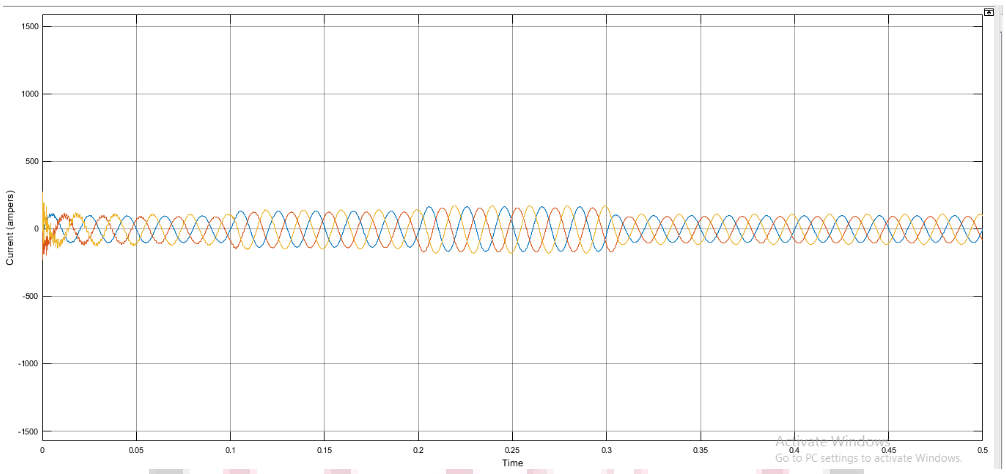

Figure 37. Current Fluctuations in the Load Line throughout the Entire Switching Cycles

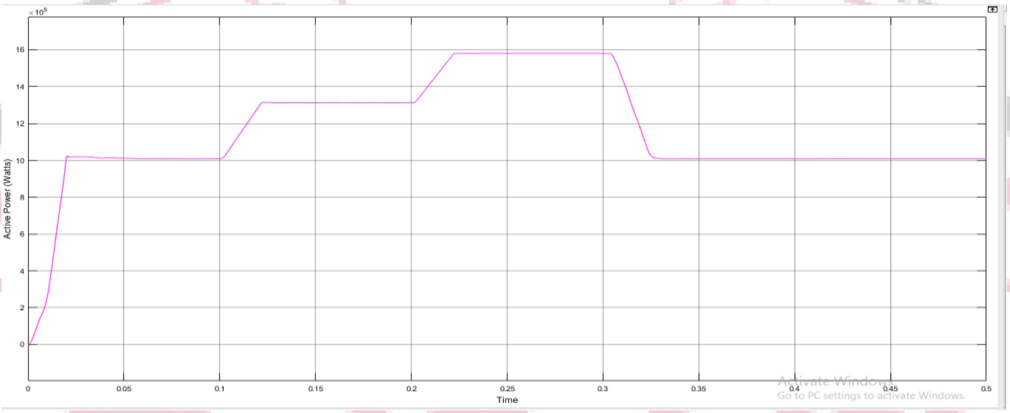

Figure 38. Variations in Active Power Along the Load Line Throughout Switching Cycles

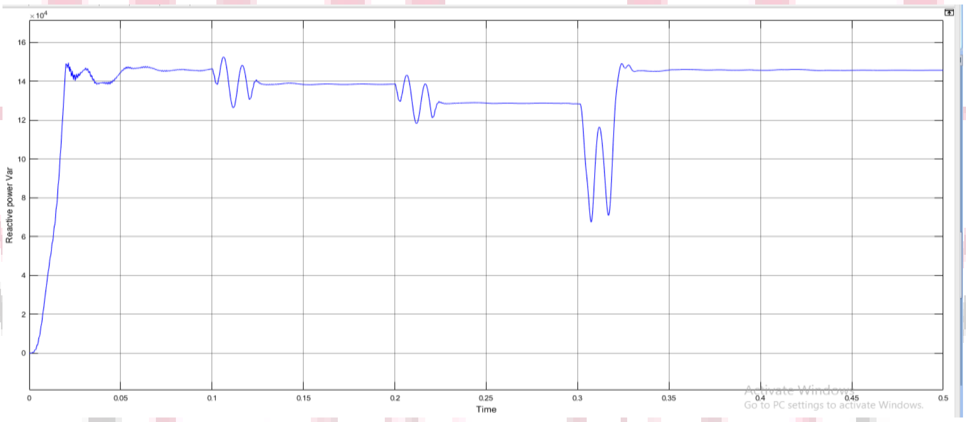

Figure 39. Fluctuations in Reactive Power Along the Load Line Throughout Switching Cycles

V. CONCLUSION

This research paper underscores the pivotal role of renewable energy, particularly solar photovoltaic systems, in addressing environmental concerns and transitioning towards sustainable energy sources. Through rigorous modeling and simulation in MATLAB/SIMULINK, the study has demonstrated the potential for optimizing solar PV systems for grid integration. The outcomes indicate that distributed solar power generation can be made significantly more effective, stable, and efficient by using cutting-edge control techniques like Maximum Power Point Tracking (MPPT) and differential evolutionary PI pulse regulation. Additionally, the research highlights the importance of addressing power quality issues, particularly in the context of sensitive nonlinear loads, to ensure reliable and high-quality electrical supply.

As governments and industries worldwide seek cleaner and more efficient energy solutions, the findings of this study contribute valuable insights into harnessing the vast potential of solar energy within distributed generation systems. The research serves as a foundation for further advancements in renewable energy technologies and emphasizes the importance of sustainable energy sources in mitigating environmental challenges and fostering a greener and more sustainable future.

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