Integration of UPFC in Solar PV Systems for Enhanced Green Energy Transmission

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Abstract. The recent world is being focused on deriving methods for using renewable energy-based systems to meet the energy demands. There are various research areas to be focused upon for making the output from these energy systems more reliable and efficient. The focus of this paper is on examining on such key component, a Unified power flow Controller (UPFC) into solar Photovoltaic (PV) structures to enhance green energy transmission and efficiency. The UPFC structure has the benefits combining the STATCOM and SSSC, which is found to be vital in regulating the active and reactive power flows within the network, ensuring stability amidst system fluctuations. The software MATLAB/SIMULINK is being used for making a 400.0-kW PV-UPFC farm, the study explores the effect of UPFC on enhancing power quality and stability, addressing real-world challenges like harmonics and voltage fluctuations like sags/swells. The work also delves into novel control strategies, consisting of using Proportional-integral (PI) controllers and advanced optimization techniques, to manage the power flow effectively. It can be concluded that the research highlights the UPFC's capability in mitigating issues inherent in integrating solar energy into the grid, inclusive of voltage rise, reverse power flow, and system instability, by means of showcasing more desirable system voltage profiles and decreased energy oscillations in the designed system.

Keyword-: Green energy, transmission, UPFC, PI-controller, power quality.

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1 Introduction

The UPFC, which combines STATCOM and SSSC, regulates the network's active and reactive power fluxes to keep the target P and Q values despite system fluctuations by utilizing an automated power flow management mode. Researchers recognize that photovoltaic (PV) plays a major part in the unified power flow controller (UPFC), improving power quality and stability in real-world harmonics and frequency sag/swell scenarios. The MPPT method for enhancing stability has attracted attention recently in the field of PV integrating. Using a 400.0-kW PV-UPFC farm with 4 panels that have a peak power of 100.0-kW at 1k solar irradiation apiece, each with 64 parallel strings and five Solar-Power SPR/315E interfaces, the article simulates the EPS [1]. Technological developments drive boost the amount of electricity used, thus power engineers have to make sure there is always power. Solar photovoltaic, wind energy, and hydroelectricity are becoming more and more popular since conventional networks are unreliable. The work in [2] addresses problems such as load fluctuation, voltage increase, reverse power flow, and system instability in the integration of solar electricity with traditional networks. Novel FACTS-based UPFC increases system voltage profile by eliminating power oscillations at the utility network side and introducing AC bus power. Better system performance is demonstrated using Simulink in MATLAB simulation.

Electrical systems have to be dependable and of an excellent quality as power is essential for daily living. By preserving sinusoidal bus voltage, FACT devices can mitigate problems such as over voltage, voltage swell, and harmonic distortion, hence enhancing power quality. The study in [3] examines the effectiveness of a grid-connected hybrid solar photovoltaic power system with UPFC, enhancing power quality and model output with the use of MATLAB/SIMULINK. With a focus on their flexibility, high speed, and capacity to link many sources at a single power line junction, this investigation investigates the application of FACTS devices to enhance the quality of power in a hybrid energy system's integrations with PV, wind, and battery systems. The study in [4] examines the potential of unified power flow control (UPFC), a promising device in hybrid-grid linked systems, by controlling both the actual and reactive power flow as well as the voltage amplitude at the same time. A novel control method for managing power flow in grid-connected hybrid renewable energy systems, such sun-wind, integrates ordinary artificial neural networks (RNN) with binary gray wolf optimization (bGWO) is proposed in [5]. By way of estimating the excellent alerts for manage, this approach creates a dataset comprising signals to manipulate for shunted and series converters. The control approach recommended on this study reduces loss of power even as controlling voltage variant. It is contrasted with current methods such as grey wolf optimization, optimization of particle swarms, and a fuzzy logic controller. The hybrid approach has demonstrated its edge in problem solution by maximizing both gain settings and elapsed time.

Ever since the 1980s, power companies and utility have been deeply concerned about the quality of electricity. Power quality is impacted by variables like sag, expand, or factor change, especially in RES-based systems that are connected to the grid. To handle the fluctuation in harmonic in connected to the grid structures, this research suggests a Unified Power Flow Controller (UPFC). The study in [6] compares the efficacy of UPFC with traditional voltage-source-converter in wind and PV grid-connected systems, guaranteeing future harmonic reduction. In order to solve the issue of grid-connected inverters' performance, the study develops a Unified Power Flow Controller (UPFC) featuring VSG abilities. This controller can adjust for fluctuations in voltage at shared coupling sites and offer a steady voltage reference for distant RE systems. In [7], a comprehensive controlled strategy and small-signal analysis are developed for UPFC-VSG. It is then compared with STATCOM and validated using a 100-MVA RE system simulation. Using thyristorcontrolled devices, the Flexible AC Transmission System (FACTS) optimizes current power networks by managing voltage variations, transient stability, and reactive or active electrical flow during periods of peak electricity demand. The Unified Power Flow Controller (UPFC), a power electronic device that regulates power flow through shunt and series converters, is introduced in [8]. It enhances variations in voltage and stability during transients while facilitating the incorporation of energy from renewable sources into the smart energy system. In transmission networks, erratic and inconsistent renewable energy sources affect system performance. Reduced power loss, lower voltage variation, and increased branch loadability are all achievable with unified electrical flow controllers (UPFCs). Under common situations, loss of power, penalty expenses, investment, and operating expenses are minimized through the use of stochastic programming. The suggested model in [9] presents a linearization strategy and approximation method, develops the issue as a mixed-integer nonlinear programming issue, and uses a Benders decomposition-based solution technique to solve it. Case studies provide efficacy and efficiency as examples.

With an emphasis on managing renewable energy resources and battery energy storage systems for flexibility AC power flow regulation in moderate-voltage systems, this study extends the idea of variable AC transmission networks (FACTS) for electrical distribution systems. In order to provide advantages like congestion relief, sag reduction, power flow reverse reduction, deferral of updates, Volt/VAr support, peak shaving, and a controllable storage bus, the proposed flexible electricity travel management system (FACPFCS) optimizes the use of renewable energies and BESSs in the current distribution grid [10]. The efficacy of the technology in managing power flows inside distribution lines has been confirmed by simulation experiments. In order to provide a more compact, lightweight, and cheap option, [11] explores a modified topology of unified energy flow regulators (UPFCs) for medium voltage distribution systems. Single-phase back-to-back series and shunt voltage source converters make up the modified UPFC. By processing a portion of the power transfer through the converter, the improved UPFC, which was created in MATLAB Simulink, was found to separately regulate both reactive and active power in a distribution feeder, indicating its potential in distribution lines that have low X/R ratios. The study conducted in [12] looks at the feasibility and efficacy of using more controllers in a unified energy flow controller (UPFC) to dampen oscillations with low frequencies in an inadequately coupled system. The work in [13] investigates the application of dynamic time-domain simulation and eigen analysis methods to power oscillations damper devices in a wind farm combined energy system in order to reduce oscillations. Based on dynamic time-domain simulation findings and eigenvalue evaluation, simulations conducted on two power systems show that the UPFC with the intended PODC successfully suppresses oscillation across a range of disturbance situations. Because of its real-time operations, the reorganization of the power sector in the twenty-first century requires rigorous examination. Under realistic security limitations, a self-adaptive differentially evolutionary (SADE) algorithm that takes converter, transmission, and linking transformers loss into account is offered for optimizing and controlling the flow of electricity utilizing the Universal Powers Flow Control (UPFC). According to [14], utilizing UPFC improves power flow and lowers line losses, with the Security Constraint SADE algorithm demonstrating the highest performance. A mathematical representation for cost functions is developed and used to comply with IEEE standards and ill-conditioned test systems. For both practical and financial reasons, power systems are linked to create intricate networks. Delays in information transmission have an impact on system performance, which impacts damping controllers. Wide area gauging system' remote signals are used as modulation inputs by flexible alternate current transmission system (FACTS) devices to enhance dynamic stability. The study in [15-18] finds that, even in the presence of information transmission delays, supplemental controller design combining PSAT simulations and programming in MATLAB can efficiently dampen frequencies and load angle shifts in multi-zone power networks [19].

2 Methodology

Transformers and conversion devices connect the substantial solar power based grid in Fig. 1. The UPFC, a power factor correction equipment, is integrated into the grid to enhance the temporary voltage profile of the expansive solar-power network [20]. This integrated strategy is usually recommended to similarly refine numerous key metrics, together with voltage THD, current THD, and dynamic power output [21].

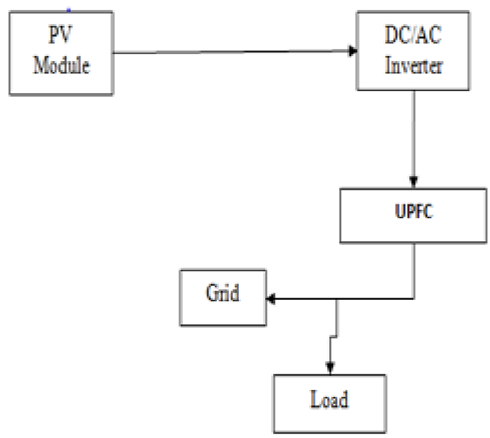

Fig. 1: Topology of Hybrid energy system

The UPFC is a complicated system consisting of Gate-Turn-Off-based voltage supply converters—a shunt and a series converter—arranged together by a common DC hyperlink [22]. The series converter's number one characteristic is to create an AC voltage of controllable importance and phase angle, Vc, and to inject this in series with the power line on the essential frequency [23-26]. This permits for the alternate of real and reactive power on the AC terminals via the series converters. The numerous equations pertinent to this function within a 14-bus system have been explored as properly. The shunt converter's role is to manipulate the DC voltage across the capacitor by way of supplying the suitable amount of actual power at the DC terminals [27]. It additionally adjusts the voltage at the shunt connection factor via modulating reactive power—both producing or absorbing it. Independently of the DC link, both converters have the capability to either generate or absorb energy [28]. The UPFC can enforce reactive power reimbursement, series compensation, and segment transferring by means of superimposing the voltage Vc, with the right value and section, onto the terminal voltage Vu, thereby fulfilling multiple operational objectives. Within the power system, synchronous machinery is incorporated through a transmission line [29]. The UPFC incorporated to a bus in proximity to the machine, and its configuration is depicted in Fig. 2 as a really perfect transformer's version. There is additionally an energy distribution version that includes the UPFC. For an entire information and management of the system dynamics, it's critical to derive the dynamical rotor equations and its variables, contemplating the dimensions, to create a simplified block diagram mentioned in Fig. 3 [30].

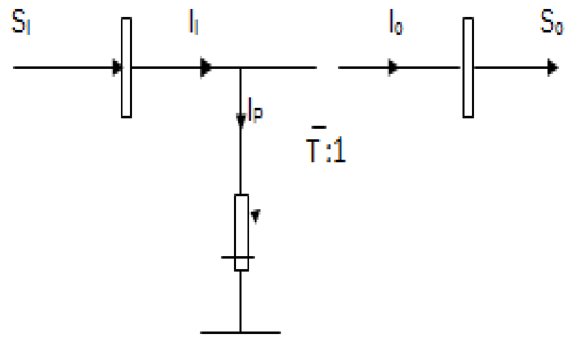

Fig. 2: Ideal transformer model of UPFC

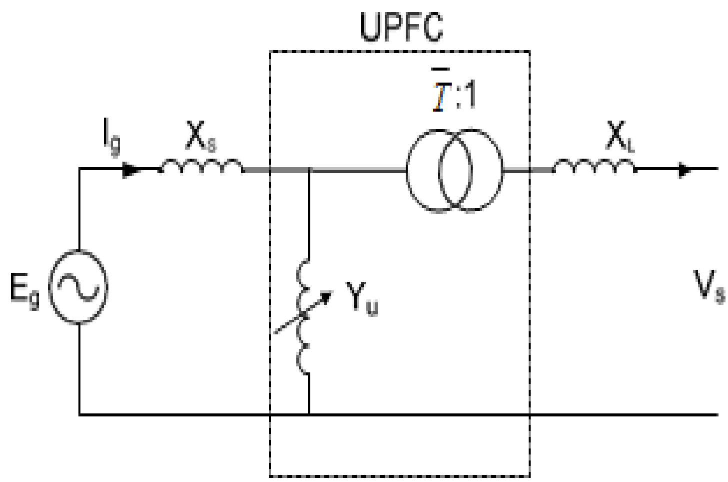

Fig. 3: Power system model including UPFC.

3 Result and Discussion

In an era of dwindling power reserves, leveraging renewable energy turns into vital for maintaining future power demands. The employment of solar and wind power stands as the foremost opportunity to the consumption of exhaustible sources, with the introduced benefit of being a clean and pollutants-free energy source [31-34]. Our observations are actually channelled in the direction of advancing the abilities on this area. This study leverages MATLAB/SIMULINK as analytical equipment to examine a solar-based power device. The system is engineered to synchronize with the power grid to improve efficiency. Distortion levels for both current and voltage have been measured, except for the system's initial transient segment. This phase delves into solar/wind power systems incorporated with a UPFC, which employs PI-controlled electronic converters. in the solar PV system, the solar array receives temperatures and irradiance as input indicators. The system's DC output voltage is then transformed into AC by means of an inverter [35]. The solar-based panel is modeled the usage of PV arrays comprising 10 cells in step with series and 40 parallel branches, collectively delivering the device's DC output. The configuration is installation to

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deal with variable lighting conditions of one thousand lux and a temperature gradient of 25°C. This DC output is ultimately routed to the inverter for AC conversion. The resulting DC output waveform is illustrated inside the diagram provided [36-39].

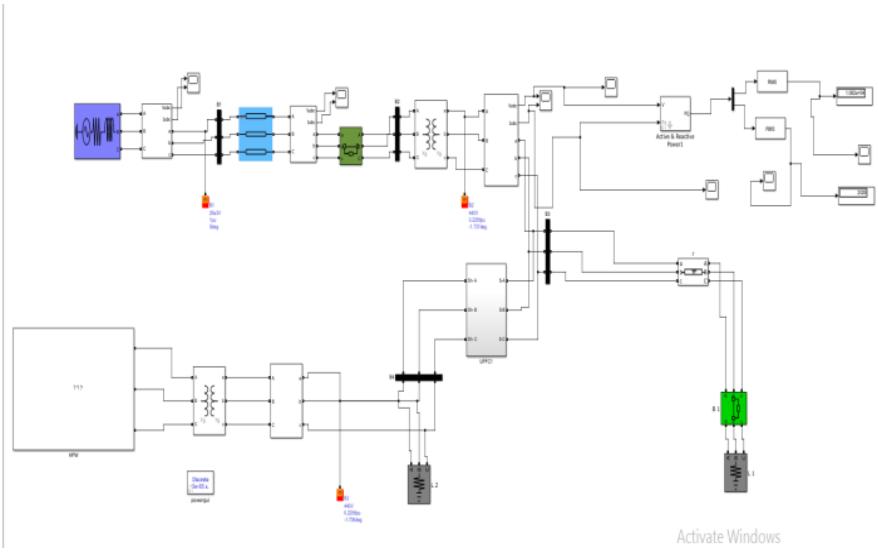

Fig. 4: GCPV integrated with UPFC in Simulink

According to Fig. 4, Grid-connected Photovoltaic (GCPV) system incorporated with a Unified power flow Controller (UPFC) in Simulink is a simulation version that investigates the interaction of solar energy generation with advanced power flow control. This proposed setup allows the analysis of performance provided by GCPV system that can be optimized for stability of grid and its efficiency, using UPFC's functionality for controlling voltage, phase, and impedance in real-time applications. The values obtained are shown in Table 1.

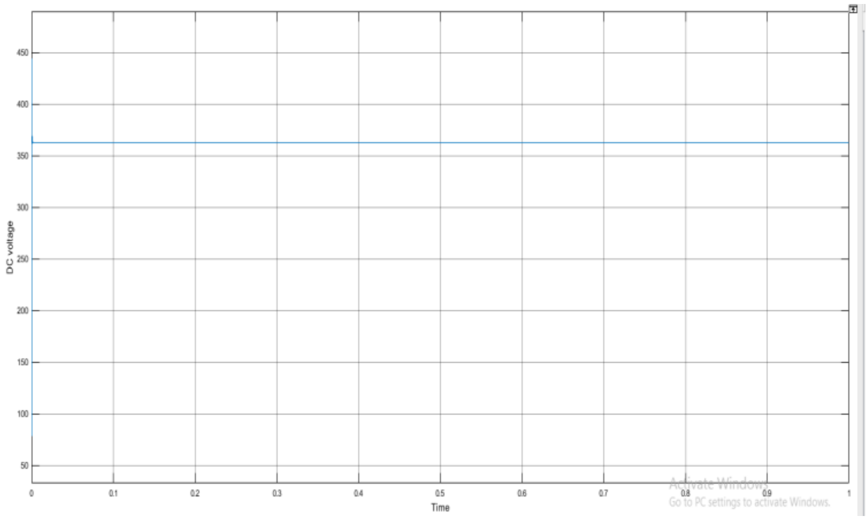

Fig. 5: DC output voltage from the GCPV

The DC output voltage obtained from a GCPV device as shown in Fig. 5, refers to the electric voltage that is generated by means of the solar panels prior to the condition when it is converted into alternating current (AC) for grid compatibility. This direct current (DC) is typically passed through an inverter to appropriately match with the voltage and frequency requirements of the power grid.

4 Grid connected PV system with UPFC having PI controller

The system in this modeling scenario is made to mimic how solar radiation is converted into electrical power through the use of a photovoltaic array, and the output is controlled by a UPFC that is controlled by a PI-based controller. This setup ensures the transformed power is efficaciously synchronized with the power grid. Furthermore, the model examines essential waveforms, such as voltage, current, power factor, and the distribution of real and reactive energy, to evaluate the system's overall performance and its effect on grid stability and power performance.

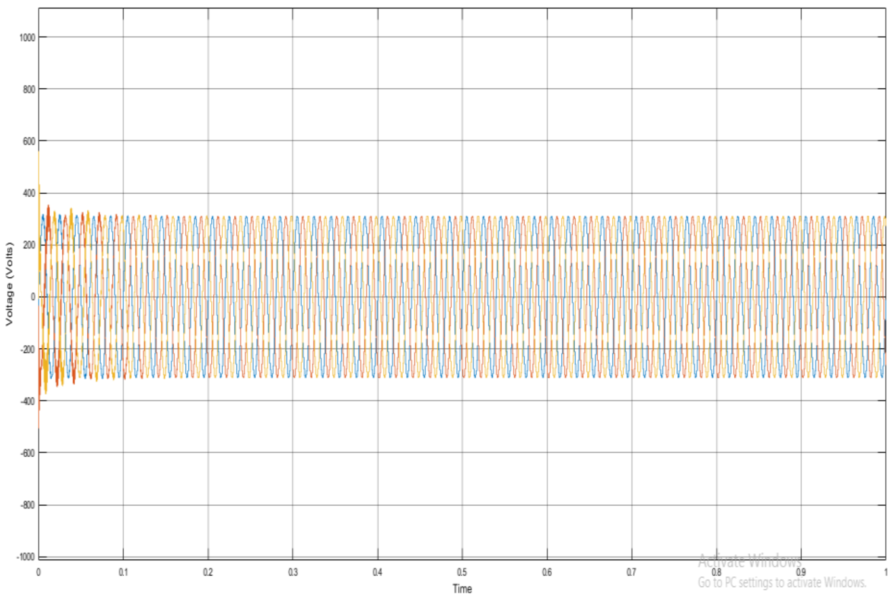

Fig. 6: Voltage within transmission line in the GCPV-UPFC having PI controller

In a GCPV-UPFC system with a PI controller, the voltage in the transmission line (as depicted in Fig. 6) is actively regulated to maintain stability and enhance power quality. The UPFC, managed by using the PI controller, adjusts the voltage significance and phase angle at the transmission line. This guarantees that the voltage stays inside favored levels, compensates for fluctuations, and facilitates to balance the load, thereby enhancing the general performance of electricity transmission from the GCPV-system

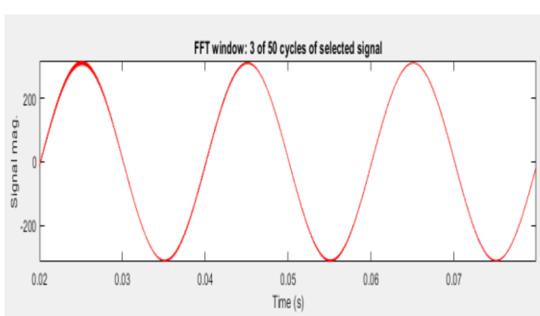

Fig. 7: FFT assessment of Voltage within transmission line GCPV-UPFC system

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The FFT evaluation in Fig. 7 allows for the decomposition of the voltage waveform into its constituent frequencies, revealing the harmonic content and other distortions present. This evaluation is crucial for comprehending the quality of the voltage in the transmission line, identifying the impact of the GCPV-UPFC system at the power grid, and making sure the voltage stays inside proper limits for grid stability and efficiency.

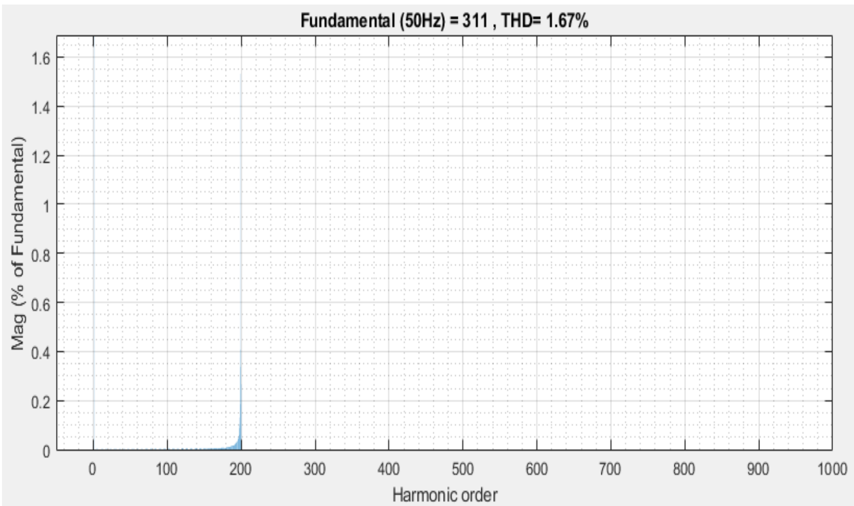

Fig. 8: THD% of Voltage within transmission line GCPV-UPFC system

According to Fig. 8, THD% quantifies the distortion of the voltage waveform as compared to its ideal sinusoidal form, in the prior stage because of the presence of harmonics generated by power electronic devices like inverters inside the GCPV system and the operations of the UPFC. The THD% is calculated as the ratio of the sum of the powers of all harmonic voltage components to the power of the essential frequency aspect, expressed as a percentage.

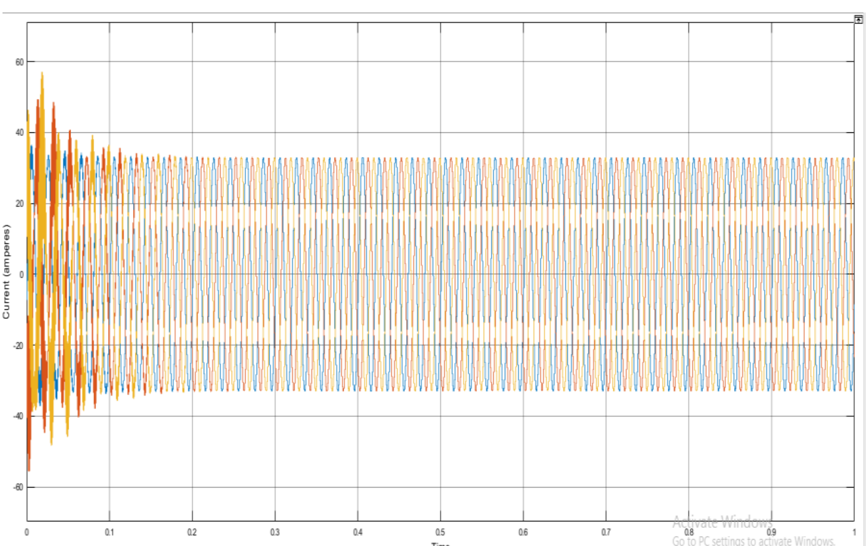

Fig. 9: Current within transmission line GCPV-UPFC system

According to Fig. 9, The current conducted in this type of system can vary significantly because of the intermittent nature of solar energy, the dynamic loads at the grid, and the operational strategies of the UPFC. by way of using a combination of collection and shunt converters, the UPFC can inject or soak up reactive energy and also can regulate the phase perspective, thereby at once influencing the magnitude and direction of the current in the transmission line.

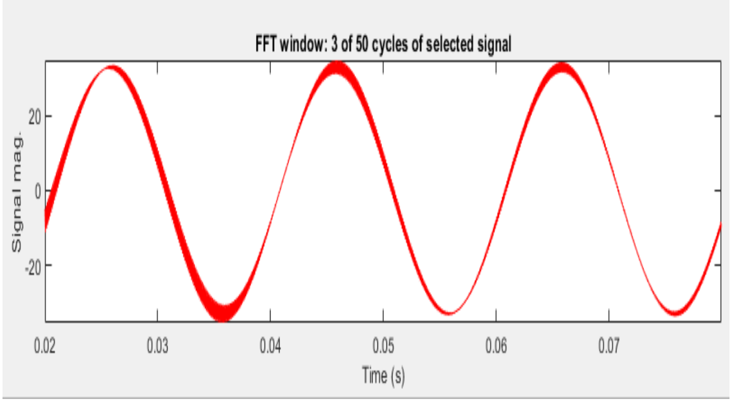

Fig. 10: FFT Analysis of Current within transmission line GCPV-UPFC system

The assessment shown in Fig. 10, decomposes the time-domain signal of the current into its constituent frequencies, providing perception into the harmonic content and other frequency-related traits of the electrical current because it flows from the solar PV array by the grid. An FFT evaluation reveals not just the fundamental frequency issue (generally 50 or 60 Hz, relying on the region) however also higher-order harmonics that may be present because of the nonlinear traits of power electronic devices like inverters within the GCPV system and the switching operations in the UPFC.

Table 1: Evaluation of a GCPV System Enhanced with UPFC and PI Controller:

Factors	**Evaluations**	**Green energy system incorporated with UPFC and PI controller**
Power output	Active (W)	9785
	Reactive (VAR)	2383
Total Harmonic Distortion (%)	Voltage	1.68
	Current	6.75
Output Voltage	(V)	311

Table 1 evaluates a green energy system enhanced with a Unified power flow Controller (UPFC) and a Proportional-integral (PI) controller, focusing on power output, overall harmonic distortion (THD), and output voltage. It exhibits an energetic strength output of 9785 Watts (W) and a reactive power output of 2383 Volt-Amps Reactive (VAR), showcasing the device's efficient power era capabilities. The THD values indicate a high quality voltage waveform at 1.68% and a reasonably optimum values at 6.75%, suggesting minimum distortion and indicating the effectiveness of the UPFC and PI controller in preserving electricity exceptional. moreover, an output voltage of 311 Volts (V) demonstrates the machine's potential to maintain a stable voltage level, essential for the seamless integration of the generated inexperienced power into the grid.

5 Conclusion

The study underscores the substantial role of UPFC in optimizing the integration of solar PV systems into the electricity grid, ensuring enhanced green energy transmission. Through special simulation analyses, it's been confirmed that UPFC, complemented by PI controllers and progressive control techniques, can efficaciously manage the demanding situations of renewable energy integration. This includes enhancing the energy quality, stabilizing the grid against fluctuations, and facilitating green power transmission. The findings suggest for the broader adoption of UPFC in renewable power structures, emphasizing its efficacy in enhancing the stability, excellent, and reliability of green energy provided to the grid. the integration of UPFC emerges as a promising option to leverage renewable power resources fully, paving the way for a greater sustainable and resilient power infrastructure.

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