Implementation of an Optimized PI Controller for Design and Performance Analysis of an On-Grid Solar System for a Residential House

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Abstract--- This paper details the installation of a home-oriented on-grid solar system with an improved Proportional-Integral (PI) controller. The suggested setup connects a PV array to the grid, which guarantees stable operation regardless of load or solar irradiation, and efficient power transmission. When compared to traditional PI controllers, the improved version has better voltage regulation, faster dynamic response, and fewer steady-state faults. Power quality evaluation, grid voltage stability, and Total Harmonic Distortion (THD) are all part of the performance study. The simulation results show that the system's overall efficiency, transient responsiveness, and harmonics are all significantly improved. Power is reliably and continuously supplied by the solar PV system thanks to the improved controller's ability to synchronize with the grid. In order to make home on-grid solar systems more resilient and adjustable to actual operating circumstances, this study demonstrates how beneficial sophisticated control tactics are in improving their performance. Sustainable urban power solutions may be achieved with the help of the results, which optimize the integration of renewable energy sources.

Keywords: On-grid Solar system, PV, Optimized PI controller.

I. INTRODUCTION

Solar power has become a major player in the world of energy as people look for greener and more sustainable options. Because of their efficiency, ease of use, and role in lowering emissions of greenhouse gases, on-grid solar systems have become more popular among the many solar power configurations available [1]. These systems are changing the game when it comes to using solar energy to power houses, companies, and even neighborhoods. The goal of an on-grid solar system is to use photovoltaic (PV) solar panels to produce energy, which can then be fed into the existing electrical grid. An on-grid solar system is one that is bidirectionally connected to the main utility grid, as opposed to an off-grid system, which functions autonomously and uses batteries to store excess energy [2]. Because of this special feature, we may export excess energy to the grid and use grid electricity to satisfy demand when solar production is low. Solar panels, inverters, and a grid-tie connection are the main elements of a solar system that is connected to the grid [3]. Solar panels, which are usually placed on roofs or other open spaces that receive a lot of sunshine, use photovoltaic cells to transform the energy from sunlight into DC power [4]. After the panels produce DC power, it is sent to an inverter. An essential part of the system, the inverter transforms the direct current (DC) power generated by the solar panels into the more common alternating current (AC) power that houses and businesses rely on. To make sure it works with the current electrical system, the inverter synchronizes the AC power it produces with the utility grid's frequency and voltage [5] – [8]. There have been a lot of technical studies done on on-grid solar systems, looking at things like PV panel efficiency, inverter performance, and system component balancing. To improve energy output, researchers have looked into techniques to optimize the positioning, tilt angles, and tracking systems of solar panels. Furthermore, research has assessed how weather, shading, and system age affect the efficiency of on-grid solar power systems over time. If we want to know how to make on-grid solar systems more efficient and reliable, we need to look at these technical assessments. Prospective users must carefully evaluate the on-grid solar systems' financial viability [9] – [13]. For different system sizes and locations, researchers have examined the payback times and return on investment (ROI) using cost-benefit studies. There have been studies looking at the possible savings from net metering rules, tax credits, and government incentives, all of which might affect how financially appealing on-grid solar systems are. The environmental effect and life cycle assessment (LCA) of traditional fossil fuel power generation vs that of on-grid solar systems has been the subject of several comparisons. These studies show that if solar power is widely used, we can significantly reduce our emissions of greenhouse gases. In order to provide a whole picture of solar's effect on the environment, researchers have looked into the production process, recycling methods, and disposal of used panels. When it comes to determining the spread and expansion of on-grid solar power, policy frameworks are king. Subsidies, feed-in tariffs, net metering rules, renewable portfolio requirements, and other policy tools have all been studied for their potential to encourage solar investment [14] – [18]. To better understand how to encourage the deployment of solar energy, it is helpful to compare the policies of various nations. Getting people on board and involved is crucial for on-grid solar system integration to be a success. Research has looked at how people generally feel about solar power, what stops them from using it, and how to get the community involved in solar projects. In order to encourage favorable views towards on-grid solar systems, developers and legislators must have a firm grasp of social dynamics. There are still certain technological and regulatory hurdles to overcome before on-grid solar systems can fully realize their potential [19]. Voltage control, grid infrastructure upgrades, grid stability, and intermittent renewable energy integration are all topics that have been studied. Research has also looked at the technical and legal challenges that solar owners have, including regulations on net metering and interconnection standards [20]. There is an increasing amount of information available in the literature on on-grid solar systems that covers the technical, economic, environmental, and policy elements of solar energy integration. Policymakers, researchers, and stakeholders can use the study's findings to advocate for on-grid solar systems and their widespread adoption for a more sustainable energy future. The studies shed light on the pros, cons, and opportunities of these systems. When installed on a home's roof, photovoltaic (PV) panels can produce enough energy to cover the household's electrical needs during the day and trade surplus electricity for reduced use at night. The home is permanently hardwired into the electricity grid, so it can easily tap into it in the event that its electrical needs exceed what the solar system can provide. Solar photovoltaic (PV) systems may still power some household circuits for a few hours or even days if they include a battery backup or UPS capability, which is useful in the event of a utility outage.

II. METHODOLOGY

A on grid solar system of 795 kW consisting of 349 kW solar PV, 1 kW wind turbine, Converter of 278 kW and 360 Ah Battery Bank with 155,520 kW grid connection.

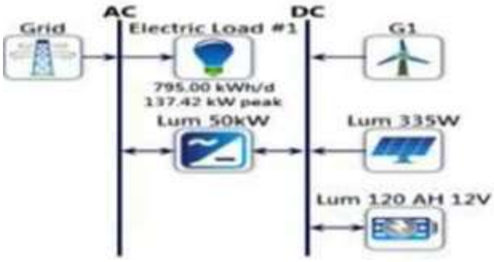


Fig: Block Diagram

PV details & specifications

Here in Table-I, the costing parameters according to specifications have been discussed of photovoltaic.

Description	Specifications
Size (kW)	0.335
Capital Cost (Rs.)	10,385
Replacement (Rs.)	8,308
O & M (Rs.)	519.25
Life Time (Yrs.)	25
Derating Factor	0.8
Temp. Coefficient of Power (%/°C)	0.41
Efficiency at standard test condition (%)	15
Ground reflectance (%)	20

Table 1: Costing details for PV

Solar Resources

Months	Clearness Index	Daily Radiation kWh/m^2/d
January	0.650	4.177
February	0.647	4.929
March	0.631	5.750
April	0.620	6.437
May	0.616	6.834
June	0.610	6.902
July	0.510	5.680
August	0.512	5.395
September	0.622	5.870
October	0.673	5.352
November	0.666	4.423
December	0.644	3.897
Average (kWh/m^2/d)		5.47

Table 2: Base line data solar resources

Storage details

Manufacturer	Luminous
Nominal capacity (Ah)	120AH
Nominal voltage (V)	12
Round trip efficiency (%)	80
Minimum state of charge (%)	40
Float life (Years)	10
Max. charge rate (A/Ah)	1
Max. charge current (A)	21
Lifetime throughput (kWh)	392

Table 3: General specification of battery

Description	Specifications
Rating (Ah)	120 AH
Capital Cost (Rs.)	12,695
Replacement (Rs.)	10,156
O & M (Rs.)	126.95
Life Time (Years)	5
Nominal capacity (kWh)	1.42
Lifetime throughput (kWh)	392

Table 4: Costing parameters of battery

Description	Specifications
Size (kW)	50
Capital Cost (Rs.)	Rs.318,024.00
Replacement (Rs.)	Rs.286,221.60
O & M (Rs.)	Rs.500.00
Life Time (Years)	20
Efficiency (%)	90

An on-grid converter, also known as a grid-tie inverter or grid- connected inverter, is a critical component of an on-grid solar system. Its primary function is to convert the direct current (DC) electricity generated by the solar panels into alternating current (AC) electricity, which is compatible with the electrical grid. The AC electricity produced by the on-grid converter can then be used to power electrical appliances within the premises, or it can be fed back into the grid.

Key features and details of on-grid converters include:

1. **Conversion Efficiency:** On-grid converters are designed to maximize the efficiency of the DC to AC conversion process. High conversion efficiency ensures that a large proportion of the solar energy harvested from the panels is effectively used or exported to the grid.

2. **Maximum Power Point Tracking (MPPT):** Many on-grid converters incorporate MPPT technology. MPPT allows the inverter to dynamically adjust its operating parameters to ensure it operates at the maximum power point of the solar panel array. This optimization results in improved energy production, especially under varying weather conditions and shading.

3. **Synchronization with Grid Frequency and Voltage:** On- grid converters must synchronize the AC output with the grid's frequency (typically 50 or 60 Hz) and voltage levels. This synchronization ensures that the electricity generated by the solar system is in-phase and compatible with the grid's electricity supply.

4. **Anti-Islanding Protection:** On-grid converters are equipped with anti-islanding protection mechanisms. Islanding refers to the scenario where a solar system continues to feed electricity into the grid during a grid outage, potentially posing a risk to utility workers attempting to restore power. The anti-islanding protection ensures that the solar system disconnects from the grid during a power outage, complying with safety standards.

5. **Communication and Monitoring:** Advanced on-grid converters come with communication interfaces that enable remote monitoring and management. These interfaces allow users or system operators to monitor the performance of the solar system, track energy production, and troubleshoot potential issues.

6. **Grid Support and Compliance:** On-grid converters may be designed to comply with specific grid regulations and requirements, such as voltage and frequency ride-through capabilities. Some countries have specific grid codes that inverters must meet to ensure grid stability and safety.

7. **Power Limitation and Reactive Power Control:** In some regions, grid operators impose power limitation requirements on solar systems to maintain grid stability. On-grid converters can implement power curtailment when necessary to adhere to such regulations. Additionally, some on-grid inverters can provide reactive power control to support grid voltage regulation.

8. **Cooling and Heat Dissipation:** On-grid converters generate heat during operation, and efficient cooling mechanisms are essential to maintain optimal performance and prolong the inverter's lifespan.

It is crucial to select an on-grid converter that matches the specifications and requirements of the solar panel array and the specific grid connection. Consulting with a qualified solar installer or electrician is recommended to ensure the proper selection and installation of the on-grid converter in the solar system.

Case 1: Solar PV-Wind-Battery-Grid Connected System

This system integrates multiple renewable sources—Solar PV, Wind energy, and a battery backup—connected to the grid. The Optimized PI Controller effectively balances power injection from different sources while regulating Solar PV, Wind, Grid, and Load parameters. The improved controller achieves better synchronization between sources, ensuring optimal power flow. The Battery's SOC and charging dynamics are efficiently managed to store excess energy and release it as needed. The THD analysis reveals improved power quality, demonstrating the controller's ability to mitigate harmonics. This system enhances grid reliability by reducing dependency on a single power source.

Case 2: Solar PV-Wind-Battery-Grid Connected System for varying loads

This case examines the system's adaptability under varying load conditions. With Solar PV, Wind, and Battery connected to the grid, the Optimized PI Controller regulates power delivery dynamically based on load variations. The results highlight better load voltage and current stability, with efficient power sharing between different energy sources. The battery's charge-discharge cycles are optimized, ensuring sustained power supply without excessive strain. Compared to a standard PI controller, the optimized version reduces transient fluctuations, enhances voltage regulation, and significantly lowers THD in Grid Voltage and Current. The system exhibits improved efficiency in handling real-time load variations.

III. RESULTS

Case 1: Solar PV-Wind-Battery-Grid Connected System

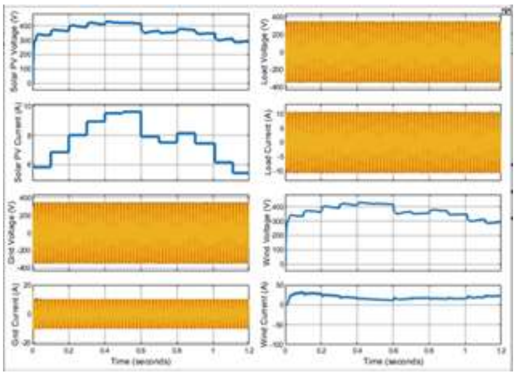


Fig: Solar PV Voltage, Solar PV Current, Grid Voltage, Grid Current, Load Voltage, Load Current, Wind Voltage, Wind Current

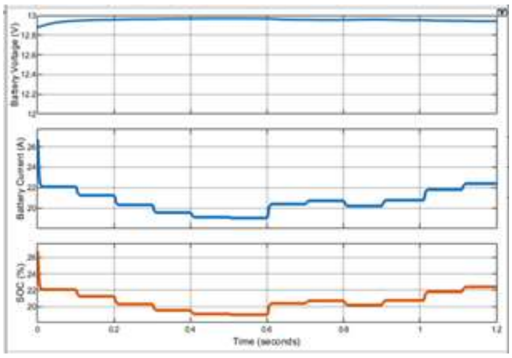


Fig: Battery Voltage, Battery Current and State of Charge

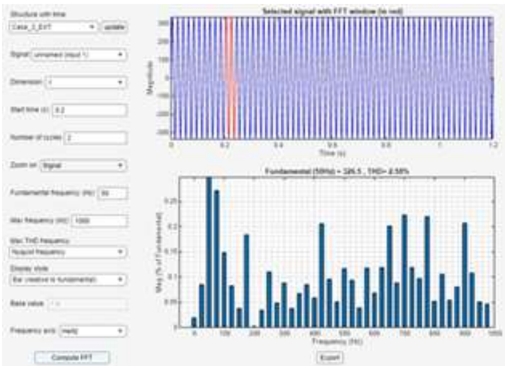


Fig: THD of Grid Voltage

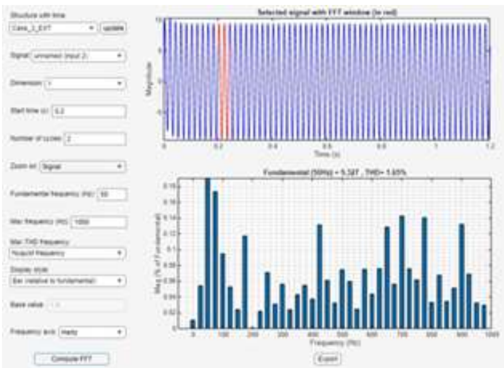


Fig: THD of Grid Current

Case 2: Solar PV-Wind-Battery-Grid Connected System for varying loads

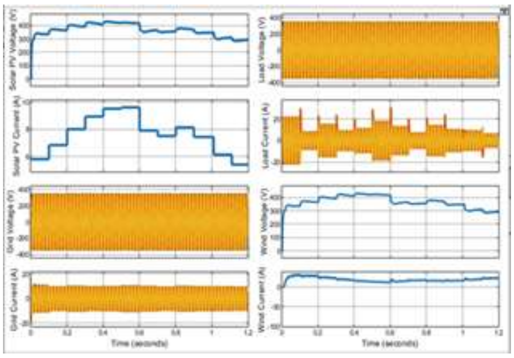
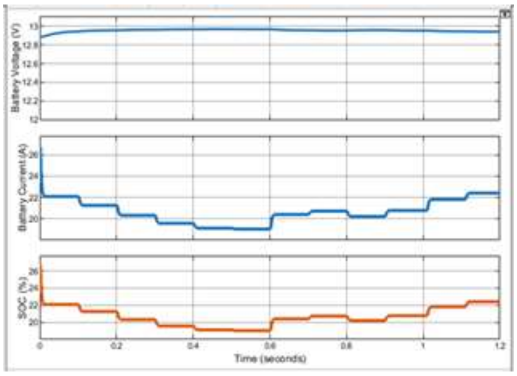


Fig: Solar PV Voltage, Solar PV Current, Grid Voltage, Grid Current, Load Voltage, Load Current, Wind Voltage, Wind Current



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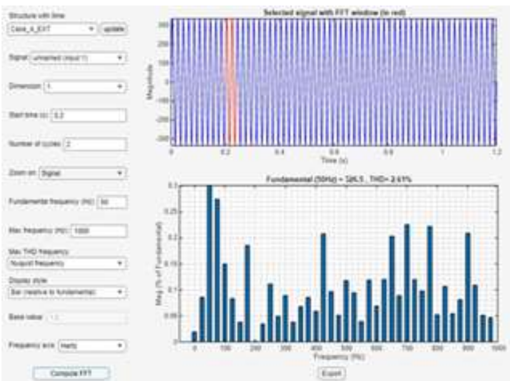

Fig: THD of Grid Voltage

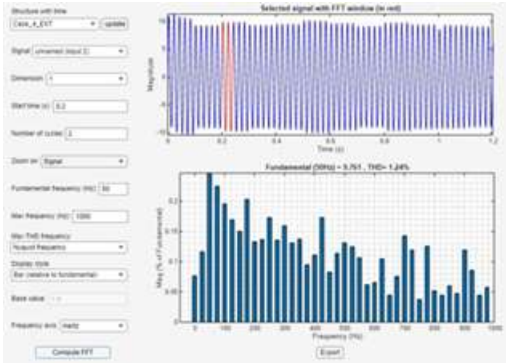

Fig: THD of Grid Current

IV. CONCLUSION

This study demonstrates the effectiveness of implementing an optimized PI controller in an on-grid solar system for residential applications. Compared to the conventional PI controller, the optimized version significantly improves active and reactive power regulation, voltage stability, and dynamic response. The simulation results confirm that the optimized controller effectively reduces Total Harmonic Distortion (THD), ensuring better power quality and seamless grid integration. By enhancing system stability and minimizing steady-state errors, the proposed control strategy ensures efficient power transfer under varying solar irradiance and load conditions. Furthermore, the optimized PI controller enables better synchronization between the solar PV system and the grid, making the system more reliable and resilient. The findings highlight the importance of advanced control techniques in improving the performance of renewable energy systems. This work contributes to the development of efficient and stable solar grid systems, promoting sustainable energy solutions for residential applications while addressing the challenges of conventional PI-based control strategies.

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