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Evaluation of Grid-Connected Solar PV Systems: Design and Operational Analysis

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Abstract

Maximizing the power output of the solar PV system under changing environmental circumstances, such as partial shadowing, temperature fluctuations, and other variations, is the main goal of improving the tracking efficiency and resilience of the MPPT process. One of the most important ways to improve the efficiency of solar PV systems is to use the maximum power point tracking (MPPT) approach. This technique continually monitors the solar panels and pulls out the most power they can provide. In order to do this, the thesis begins by outlining the basics of photovoltaic (PV) systems, maximum power point tracking (MPPT) methods, and PSO algorithms. It takes a look at the problems with classic MPPT algorithms like Incremental Conductance (IncCond) and Perturb and Observe (P&O) and finds ways to fix them. This study's results improve the efficiency and dependability of solar PV systems, which helps to optimize renewable energy systems. We urge more research and experimental validations to evaluate the suggested controller in real-world settings and make it easier to integrate it into commercial PV systems. Through simulation tests conducted using MATLAB/Simulink, the suggested improved PSO controller is put into action and assessed.

Keywords- Grid-connected solar PV system,Performance analysis,Photovoltaic modules, Energy efficiency, Levelized cost of electricity

1. Introduction

Renewable energy sources, such as solar, wind, hydro, and biomass, offer a viable solution to address the environmental and economic challenges posed by fossil fuels. Among these, solar energy is particularly promising due to its vast availability and potential to meet a significant portion of global energy demand. The sun delivers approximately 173,000 terawatts of energy to Earth every hour—more than enough to satisfy the world's annual energy needs multiple times over [1].

Solar photovoltaic (PV) systems, which convert sunlight directly into electricity, have emerged as one of the most scalable and adaptable renewable energy technologies[2]. The deployment of solar PV systems has been accelerated by declining technology costs, improved efficiency, and supportive policy frameworks. Over the past decade, the cost of solar PV modules has decreased by more than 80%, making solar energy competitive with, or even cheaper than, conventional fossil fuel-based electricity in many regions [3].

In addition to cost reductions, governments worldwide have implemented various incentives to encourage solar PV adoption, including feed-in tariffs (FiTs), tax credits, and net metering schemes. These incentives have facilitated the rapid growth of solar PV installations in both developed and developing countries, contributing to a global renewable energy capacity exceeding 1,000 gigawatts (GW) as of 2023 [4].

Grid-connected solar PV systems represent a critical component of the renewable energy transition. Unlike stand-alone systems, which operate independently and often require energy storage solutions, grid-connected systems are integrated into the electrical grid, allowing for the direct transfer of electricity between the PV system and the grid. This integration offers several advantages:[5].

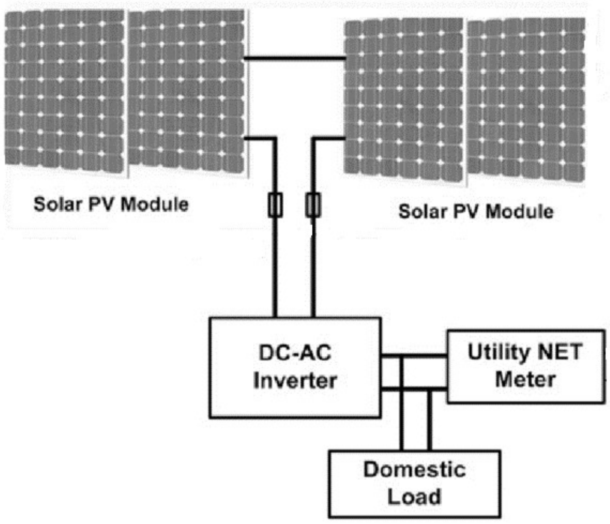

Figure-1: Grid Connected PV System

Despite these advantages, integrating solar PV systems into the grid presents challenges. The intermittent and variable nature of solar energy—caused by factors such as weather conditions and time of day—can lead to fluctuations in power output, affecting grid stability and reliability. Addressing these challenges requires advanced power management solutions, including smart inverters, energy storage systems, and grid-responsive technologies [6].

2. Literature Review

The load impedance is often matched to the output impedance of the solar array using a DC-DC power electronic converter [7]. This causes the solar array to produce its maximum power under specific weather conditions. A battery may be charged using the electricity from the solar array, or it can be converted into AC power for either single phase operation or grid connection [8]. This chapter provides a high-level summary of the processes required in developing a PV system performance model. In addition, the article provides an overview of DERs and the requirements for their interconnection with the distribution system. As an example of DER, this research primarily examines PV technology integration. Furthermore, this chapter provides an overview of the distribution network operating consequences, both local and system-wide, of integrating PV-DG. The standards and regulations for DG interconnection are covered in the latter section of this chapter.Utilities require PV power plants to run constantly at full efficiency to keep the grid reliable [9]. Distribution network architects expect PV systems to achieve their optimum output under ideal environmental circumstances, excluding the impacts of age and unpredictability in power production induced by climatic factors like sun irradiation and temperature [10]. The PV power output model has many applications in grid integration studies, including the ones listed below and :Blaabjerg et al. (2006), This paper provides a detailed overview of control and synchronization techniques for distributed power generation systems, emphasizing their critical role in ensuring stable operation. It highlights advances in voltage and frequency control for grid-connected PV systems. However, it notes the high cost and complexity of implementing these systems in diverse grid environments. [11] Esram and Chapman (2007), The authors compare various MPPT techniques, offering insights into their effectiveness under different environmental conditions. They highlight the potential of perturb and observe (P&O) and incremental conductance methods. However, limitations include slower response to rapidly changing irradiation levels. [12] Mekhilef et al. (2011), This review explores multi-level inverter topologies for grid-connected PV systems, emphasizing their ability to enhance energy efficiency and reduce harmonic distortion. The study identifies high initial costs and complex control mechanisms as significant challenges. Lund and Mathiesen (2009), The paper examines the integration of PV systems into 100% renewable energy systems, using Denmark as a case study. It demonstrates the technical feasibility of such systems but notes the need for significant policy support and technological advancements. [13]

3. THEORITICAL MODELS OF SOLAR ARRAY

A direct association between radiation and temperature is shown by such a current. As the two dimensions are increased, the power supplied in Eq. (1) increases, and the I-V bending is the P-V. The result of including two dimensions is this sections respectively. Both the radiation level and the cell's temperature have an impact on this. For optimal module operation, there is a maximum power point (Maximum power point) for each bend [14].

In order to determine the MPP, one must use Eq. (3) in conjunction with the condition Eq. (3.4). Another important element of this bend is the open circuit voltage (Voc), which is also known as the short out current (Isc). The maximum voltage at zero current (not loaded) on the board is represented by the open circuit voltage, while the maximum mobile current on the module is represented by the short current.

$$P = V\left[n_{PP}\left\{I_{PV} - I_D\left(e^{q(V/nss+npp/AK\;)}(V/n_{ss} + R_S I/n_{PP})\right)/R_P\right\}\right] \quad 1$$

$$P = VI \quad 2$$

$$P = V\left[n_{pp}\left[I_{PV} - I_0\left[e^{q(V/nss+npp/AKT)} - 1\right] - (V/n_{ss} + R_S I/n_{PP})/R_P\right]\right] \quad 3$$

$$dp/dv = 0 \quad 4$$

$$I_{o,n} = \frac{I_{SC,n}}{exp\left(\frac{V_{OC,n}}{aV_{t,n}}\right) - 1} \quad 5$$

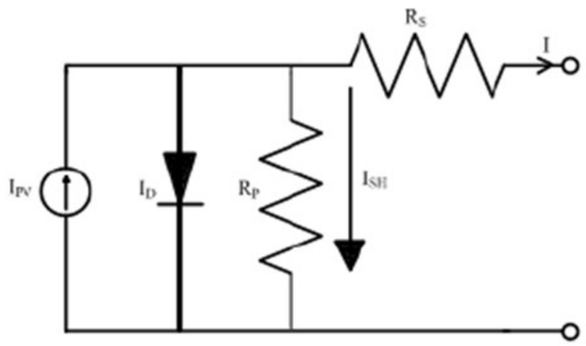

Figure-2 PV module Equivalent PV circuit

4. Simulation Results and Discussion

A grid-connected solar PV system harnesses the sun's power to generate clean electricity for your home. Sunlight hits solar panels which convert it to DC electricity. An inverter then transforms it into AC electricity for your appliances. Excess power flows back to the grid, potentially earning you credits, while the grid acts as a backup during low sun hours. While there's an upfront cost and sun dependency, these systems can significantly reduce electricity bills and promote environmental sustainability with government incentives making them a more attractive option.

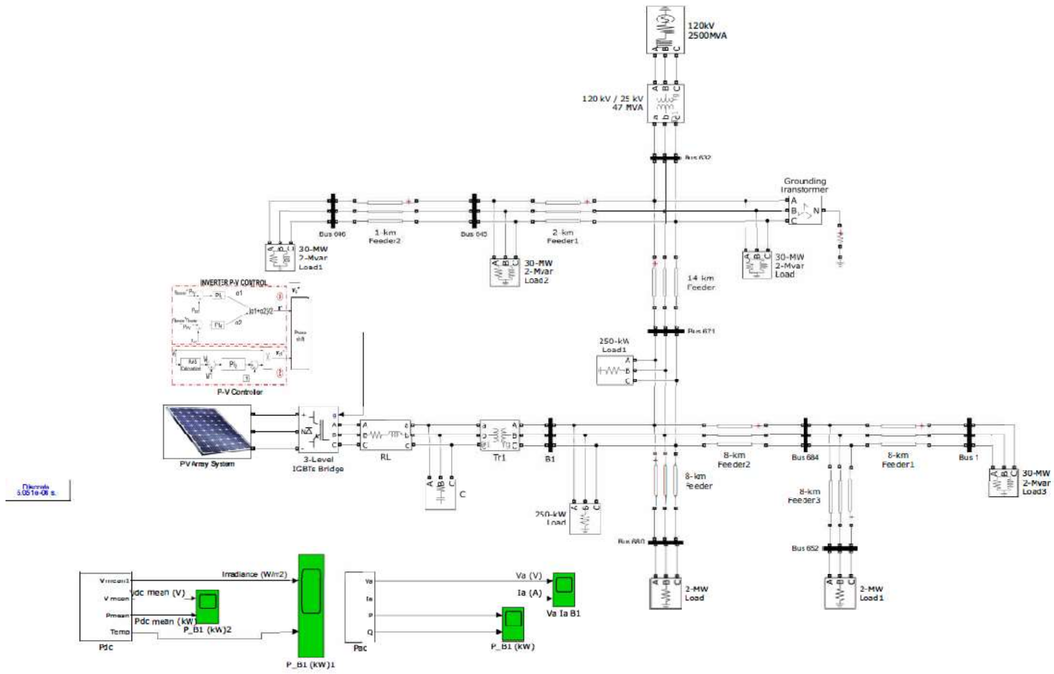

Figure3 Grid connected PV System

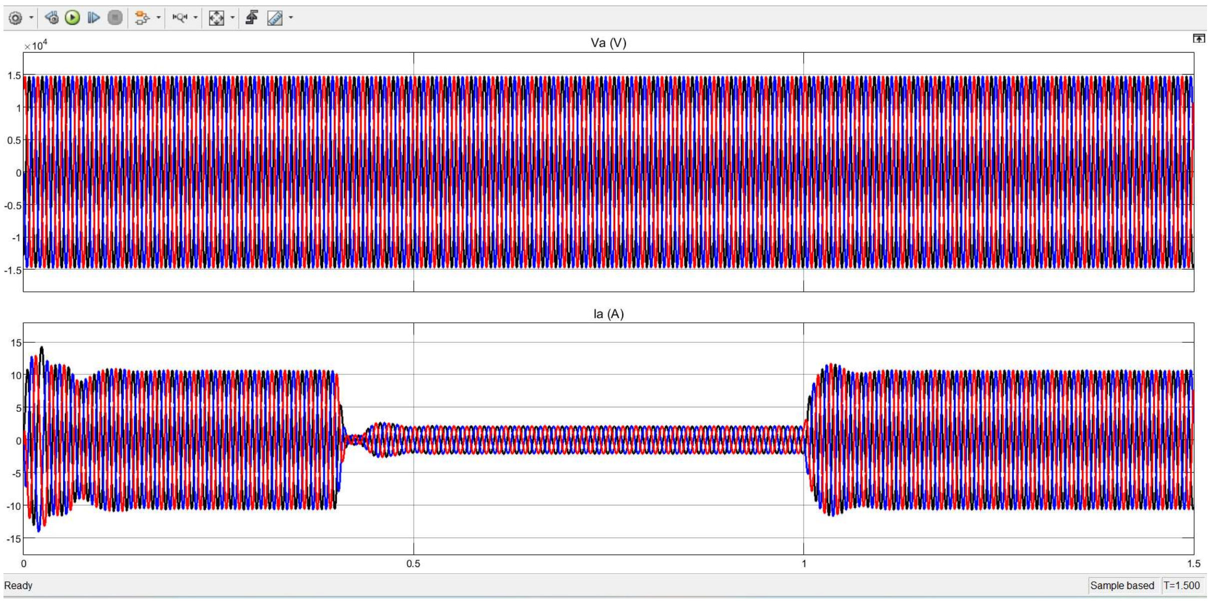

Figure4 AC Voltage and AC Current at PV Pannel

The PV system (A) performance was investigated under changing solar radiation, as shown in Figure 4. During the period of the simulation, the system surface temperature is presumed to be

45^o C. Figure 5.6 presents the variation in solar radiation; it shows the changes in irradiation during the t=0.4 and t=1. Figure 5.8 depicts the active power injected from the PV system into the grid. The power varies with solar radiation, and the reactive power is zero at the unity power factor. The three-phase current and voltage injected is shown in Figure 4. It was observed that as a function of the injected power, the inverter controller regulates the current amplitude. Consequently, the grid voltage is in phase with the injected current owing to the unity power factor. The duty cycle keeps the output voltage proportional to the set reference voltage. Once the peak power is detected, the MPPT algorithm utilizes a variable duty cycle to reduce the oscillations in injecting power.

5. Conclusion

The analysis of grid-connected solar photovoltaic (PV) systems integrated with the IEEE 13 bus system underscores the transformative potential of solar energy in modern power systems. Through meticulous investigation and simulation, several key insights have emerged, shedding light on the technical, economic, and environmental implications of solar PV integration at the distribution level.

First and foremost, the performance analysis of grid-connected solar PV systems within the IEEE 13 bus system has revealed promising results regarding their ability to augment local electricity generation, reduce grid reliance, and contribute to renewable energy targets. By harnessing solar radiation and converting it into clean electricity, these systems have demonstrated their capacity to alleviate grid congestion, enhance voltage stability, and mitigate line losses, thereby bolstering the overall resilience and reliability of the distribution network.

Moreover, the declining costs of solar technology, coupled with advancements in financing models and regulatory frameworks, have rendered solar PV an increasingly attractive option for decentralized electricity generation and distributed energy resource management.

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