

Modeling and Power Quality Enhancement of PV Interfaced with Power Grid System

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ABSTRACT

Recently, photovoltaic (PV) technology has significantly contributed to the utilization of renewable energy sources. It plays a crucial role in addressing the challenges posed by climate change, enhancing energy affordability, ensuring power supply stability, and facilitating energy accessibility. PV technology represents a significant opportunity for addressing the issue of energy access among distant areas that now lack reliable access to electricity. Using a traditional grid is limited due to cost and feasibility constraints. These difficulties are to be addressed in the appropriate timeframe to improve the dependability of the supply. The expansion of the grid into these regions diminishes the overall resilience of the grid system. This leads to a situation where PV systems are integrated into an AC grid with low power quality (PQ) or limited capacity. Nevertheless, the integration of solar power into an AC grid with low capacity. The presence of PQ problems imposes limitations on the levels of penetration. Other factors impose limitations and penetration levels encompass several factors such as non-linear loads, dynamic loads, fluctuating irradiations, and partial shade, among others. This article aims to address the PQ difficulties that arise from a weak electrical infrastructure. The purpose of this compilation is to provide engineers with a readily accessible resource, offering them a distinct advantage in their professional endeavors and scholars engaged in this field of investigation. In this context, the photovoltaic (PV) array is methodically organized into 86 parallel strings. The aforementioned strings are meticulously constructed, consisting of a sequence of seven SunPower SPR-415E solar modules that are intentionally interconnected.

INTRODUCTION

In the year 2022, solar photovoltaic (PV) generation experienced a significant surge, with a remarkable gain of 270 TWh, or a growth rate of 26%. This surge propelled the total solar PV generation to about 1,300 TWh (IEA, 2022). The economic appeal of PV technology is anticipated to experience sustained expansion, bolstered by significant advancements in the supply chain and augmented regulatory backing, particularly in China, the United States, the European Union, and India. Consequently, this is projected to expedite the rise of solar energy capacity in the forthcoming years (Abdunnabi et al., 2023; Khaleel et al., 2022). Fig. 1, illustrates the distribution of cumulative electricity capacity across several technologies from the year 2010 to 2027. The projected growth of global installed storage capacity is anticipated to increase by 56% within the upcoming five-year period, resulting in a total capacity exceeding 270 GW by 2026 (Ahmed et al., 2023; Nassar et al., 2023). Fig. 2 illustrates the battery storage capacity of several countries in the years 2020 and 2026. The primary catalyst behind this phenomenon is the growing demand for enhanced system adaptability and storage on a global scale, to effectively harness and incorporate bigger proportions of variable renewable energy into existing power systems (Al-ammar et al., 2023; Khaleel et al., 2023; Ali, 2023). It is anticipated that utility-scale batteries will constitute the predominant portion of the global storage expansion.

LITERATURE REVIEW

The current article (Khaleel et al., 2023) presents an investigation that focuses on the modeling and simulation of PV systems connected to the distribution network through the utilization of the P&O algorithm. This study examines the effects of fluctuations in radiation from the sun on the reliability of a system and suggests the implementation of an energy storage system as a solution to address the PQ challenges arising from the intermittent nature of solar power. The efficacy of the proposed methodology was evaluated and contrasted with the fixed perturbation MPPT algorithm across several scenarios. The experimental findings provide empirical evidence that supports the viability and benefits of the proposed approach. The installed capacity is projected to experience a six-fold increase throughout the forecast period.



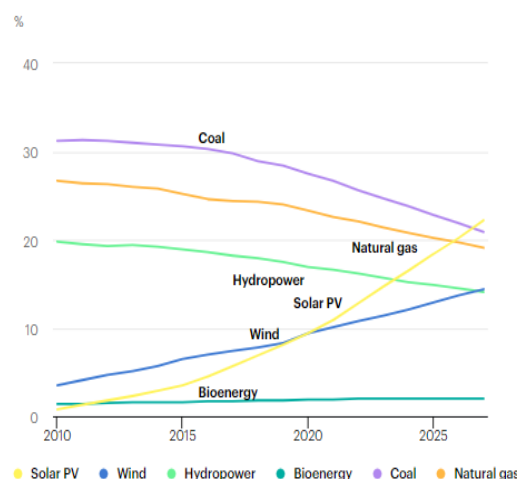


Figure 1. Distribution of cumulative electricity capacity across several technologies from the year 2010 to 2027.

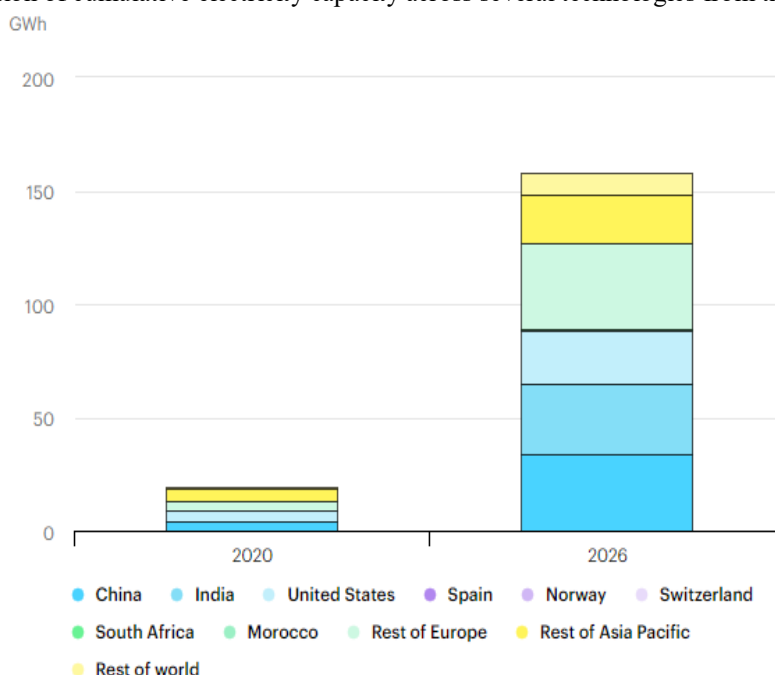


Figure 2. The battery storage capacity of several countries in the years 2020 and 2026.

This growth can be attributed to various factors, including subsidies and a growing demand for system flexibility. Moreover, this demand is particularly evident in situations where the proportion of variable renewable energy sources meets nearly all of the electricity demand during specific hours of the day (Alsharif et al., 2022; Alsadi et al., 2017; Almagrouk et al., 2023; Ajendy et al., 2019; Boopathi et al., 2023). However, hybrid auctions that integrate wind or solar PV technologies with energy storage have recently surfaced in India and Germany. These auctions have resulted in contracts priced between USD 40-60/MWh during the past year. The rise of battery storage is being propelled by a combination of federal tax incentives in the United States and high peak prices in many markets. Additionally, the Chinese government has set long-term plans that aim to increase battery storage by five times between 2021 and 2026.

POWER QUALITY

According to the International Electrotechnical Commission (IEC) 61000-4-30, power quality refers to the attributes of electrical energy at a specific location within an electrical system, which are assessed in comparison to a predetermined set of technical parameters (Hafez et al., 2020; Khaleel et al., 2022; Gao et al., 2023; Nassar et al., 2023; kumar et al., 2023; Khan et al., 2020). In order to ensure the integrity of PQ in grid-connected solar PV systems, many power quality standards have been developed. The monitoring of power quality plays a crucial role in identifying and addressing diverse power quality issues that may arise within the system. Table 1, illustrates the PV capacity standard, publication, nature, and capacity (El-khozenadar et al., 2023; Elweddad et al., 2022; Fazal et al., 2023; Das et al., 2023;

Khaleel et al., 2021; Colrick et al., 2023; Choudhury et al., 2023).

TABLE 1. THE PV CAPACITY STANDARD, PUBLICATION, NATURE, AND CAPACITY

Publication	Standard	Capacity	Nature
IEEE	IEEE Std. (929)	<10KW	PV only
IEC	IEC (61727)	<10KW	PV only

An increased level of Solar PV integration within a grid infrastructure leads to an elevated amount of harmonic distortion within the network, thereby resulting in substantial losses in equipment efficiency. The monitoring of power quality is a crucial aspect of safeguarding the integrity of the overall power system. In addition, it is advantageous to carefully choose appropriate equipment for PQ monitoring and to establish a proactive timetable for conducting predictive maintenance. The variability of solar PV yield can be primarily attributed to its reliance on factors such as irradiance, temperature, and meteorological conditions. The integration of this technology with a power grid might exacerbate PQ issues, necessitating the implementation of measures to reduce these disturbances in order to maintain grid stability and assure seamless synchronization. The proliferation of PQ issues is expected to increase as the level of penetration advances. The subsequent sections include a comprehensive examination of PQ concerns linked to grid-connected Solar PV systems (Yusupov et al., 2023; Xu et al., 2023; Lavanya et al., 2023; Mishra et al., 2023; Makhzom, 2023; Miskeen et al., 2023; Pathak et al., 2023; Yusupov et al., 2023; Tabak et al., 2022).

Voltage sag

Voltage sag is an occurrence characterized by a reduction in the root mean square (RMS) level of the voltage, causing it to decline from 10% to 90% of the nominal amount. Voltage sag is a highly significant PQ concern that is prevalent in both industrial and power sectors. Figure 3, demonstrates the voltage sag event. The stability of the electrical grid is influenced by voltage sags occurring inside the network. The connection of solar PV systems to the electrical grid results in the injection of a significant amount of current into the grid, which subsequently leads to a decrease in voltage known as a voltage sag within the network. Voltage sag mostly affects industrial sectors as it accelerates the deterioration of electrical machinery, leading to substantial cost repercussions. Voltage sag can lead to several consequences, including system shutdown, decreased performance of the system, and unreliability (Nassar et al., 2024; Khaleel & Farag 2014; Ghayth et al., 2023; Hajibabai et al., 2023; Abdulwahab et al., 2023).

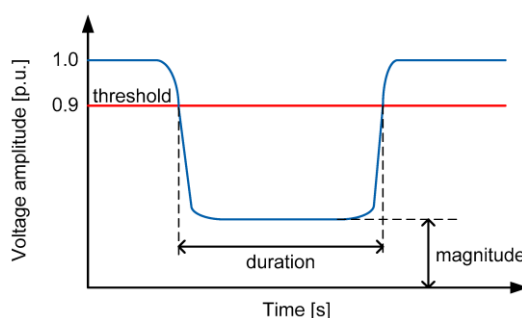


Figure 3. The voltage sag event.

Voltage unbalance

The definition of voltage unbalance, as stated in the IEEE 112-1991 standard, refers to the percentage divergence between the highest possible phase voltage and the average phase voltage. The precise characterization of the imbalanced voltage is commonly referred to as the percentage that constitutes the voltage unbalance factor.

Voltage Flicker

Flicker refers to the variation in irradiation caused by fluctuations in the power supply. The fundamental constituents of the flicker phenomenon encompass the amplitude and frequency characteristics of a signal. Solar irradiation experiences ongoing fluctuations, which consequently lead to voltage flickering when the system is connected to the grid. Based on the IEEE 1547 standards, it is recommended that the amplitude of undesirable flickers originating from distributed electricity generation be restricted to 0.6 and 0.9 per unit (pu) for short-term and long-term probabilities, respectively. Figure 4, shows the voltage flicker event.

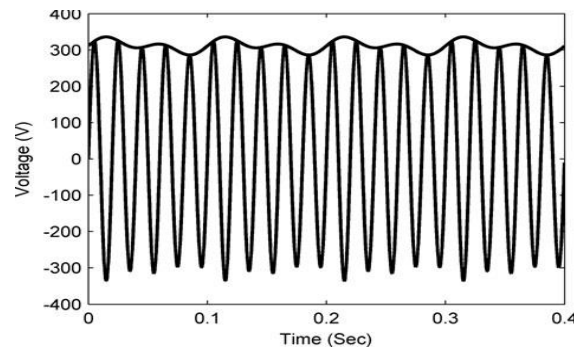


Figure 4. The voltage flicker event.

Total harmonics distortion

The phenomenon of Total Harmonic Distortion (THD) is considered to be the most prominent of all power quality concerns. The regular alternation of solar PV inverters, as well as additional power electronics converterto, in response to varying irradiance and temperature fluctuations, leads to the generation of harmonics in the load currents. As per the IEEE standard 519-1992, it is recommended that the total harmonic distortion remains within a threshold of 5%. Current as well as voltage harmonics are often encountered power quality disturbances (PQDs) in electrical distribution networks. Typically, these events manifest themselves in the context of short circuits, grounding anomalies, and the functioning of switching mode power supply (Sahoo et al., 2023; Rajesh et al., 2022; Rahmani et al., 2023; Khaleel, 2014; Noroozi et al., 2023; Alsali et al., 2023; Alsharif et al., 2023; Castellanos et al., 2022; Budiman et al., 2024; Ali, 2023; Benbouhenni et al., 024; Khaleel, 2015; Aljendy et al., 2019; Andeef et al., 2023. As a result, in order to mitigate the impact of these harmonics, it is necessary to make adaptations to formulae (1) and (2).

$$u_{\alpha + \alpha h}(t) = u \cdot \cos(\omega t) + \sum_{h=2}^{\infty} u_{\alpha h} \cdot \cos(h\omega t) \quad (1)$$

$$u_{\beta + \beta h}(t) = u \cdot \sin(\omega t) + \sum_{h=2}^{\infty} u_{\beta h} \cdot \sin(h\omega t) \quad (2)$$

Where $u_{\alpha h}$ and $u_{\beta h}$ represent the values of the magnitudes of the u_{α} and u_{β} harmonics, correspondingly, while h denotes the harmonic index.

METHOD

The methodology employed in this study involves the systematic organization of the photovoltaic (PV) array into 86 parallel strings. Each of these strings is carefully constructed, comprising a sequence of seven SunPower SPR-415E solar modules that are intentionally interconnected. This configuration is designed to address the challenges arising from a weak electrical infrastructure, particularly focusing on power quality (PQ) issues associated with low capacity or limitations within the AC grid.

RESULT

The article investigates the simulation parameters of a PV array integrated with a power grid utilizing the MPPT control technique including a PV Array, DC-DC converter, DC-AC inverter, and 3-phase transformer. The PV Array parameters can be seen in Table 2 which is implemented parameters in the MATLAB simulation software

Table 2. The parameters, units, and value of the PV array integrated with the power grid

	Parameters	Unite	Value
Power Grid	Distribution grid	kV	120
	Maximum Power (W)	kW	414.801
	Sun irradiance	W/m ²	1000
PV	Cells per module (Ncell)	-	128
	Short-circuit current Isc	Amps	6.09
	Open Circuit Voltage (Vmp)	Volts	72.9
	Parallel strings	-	88
	Operating Temperature	°C	25-45
	Light-generated current Il	(A)	6.0978
	Shunt resistance (Rsh)	ohm	419.7781
	Series resistance (Rs)	ohm	0.5311

DC-DC Converter	Voltage level	V	500
	Nominal Maximum voltage	V	260
Inverter	Efficiency	%	95
	-	kVA	400
Three-phase transformer	-	V	260

SIMULATION PARAMETERS

This section discusses the interconnection of the PV Array with the power grid. To emphasize, the power grid simulation consists of representative 120.0 kV distribution grid feeders. Figure 5, illustrates the modeling of PV interfaced with the power grid. Figure 6, presents a simulation diagram PV-array. Figure 7, depicts the Modeling of inverter control using Perturbe & Observe technique. The PV array configuration is a pivotal aspect of solar energy systems. In the presented setup, the PV array is meticulously organized into 86 parallel strings. Each of these strings is meticulously constructed, featuring a sequence of 7 SunPower SPR-415E solar modules that are thoughtfully interconnected in series. This arrangement effectively harnesses the electrical potential of these modules, ensuring efficient energy conversion. Furthermore, it's worth highlighting a noteworthy feature of the system the model menu's capabilities. This menu empowers users to perform in-depth analysis and visualization of the PV array's performance characteristics. Specifically, it offers the flexibility to plot the current-voltage (I-V) and power-voltage (P-V) curves.

The converter employed in this system is meticulously characterized by a 3-level Insulated Gate Bipolar Transistor (IGBT) bridge, expertly controlled via Pulse-Width Modulation (PWM) techniques. The utilization of a 3-level IGBT bridge reflects a deliberate choice in favor of enhanced power quality, lower switching losses, and minimized harmonics. This is vital in maintaining the quality of power generation and distribution within the system. To further refine the converter's performance and ensure compliance with stringent harmonic standards, specific components are thoughtfully integrated. An inverter choke with a series resistor is judiciously incorporated, serving the crucial role of filtering and attenuating any harmonics generated during the operation of the IGBT bridge.

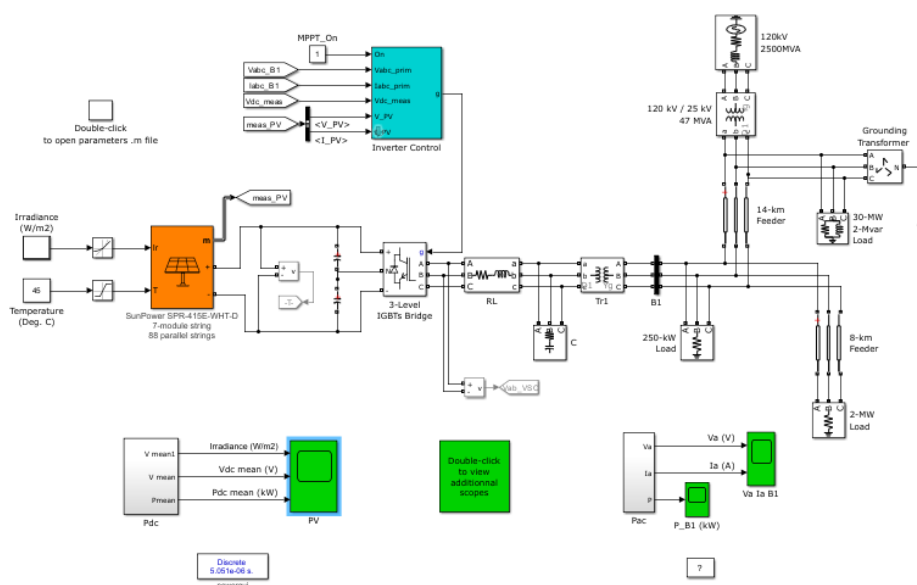


Figure 5. Modeling of PV interfaced with the power grid.

Implementing the Maximum Power Point Tracking (MPPT) controller within this system is a noteworthy academic and engineering achievement. It is built upon the well-established 'Perturb and Observe' technique, a widely recognized and effective method for tracking the maximum power point of a PV array. The core functionality of the MPPT controller revolves around its ability to dynamically adapt the VDC reference signal for the inverter's VDC regulator. This adaptation is executed in a manner that consistently seeks to optimize the DC voltage generated by the PV array, effectively extracting the maximum available power. This intricate control mechanism is pivotal in ensuring that the PV system operates at its peak efficiency and harvests the greatest possible energy from the solar source.

By incorporating the 'Perturb and Observe' technique into the MPPT controller, the system autonomously adjusts the VDC reference signal, subjecting it to incremental perturbations, and subsequently observes the resulting power output. The controller continues to perturb the signal until it detects a decline in power production, at which point it can

accurately pinpoint the maximum power point (MPP). This dynamic process of tracking the MPP ensures that the system's energy conversion remains consistently efficient, even in the face of changing environmental conditions. Figure 8, shows the Modeling of the 3-Level IGBT Bridge. Figure 9, illustrates the output of PV including irradiance, voltage, and power. Figure 10, illustrates the output of PV including voltage and current.

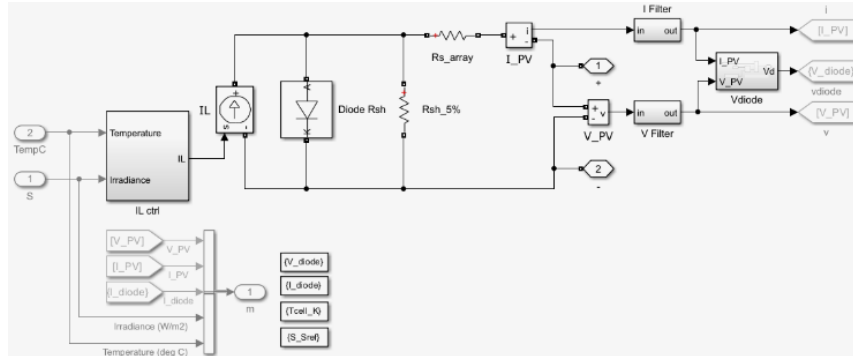


Figure 6. Simulation diagram PV-array

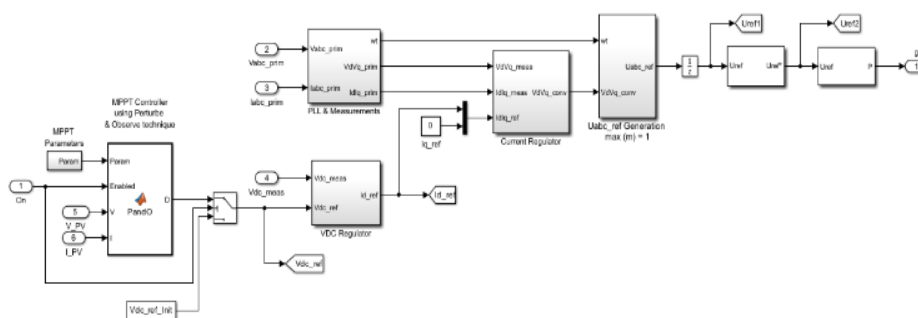


Figure 7. Modeling of inverter control using Perturb & Observe technique.

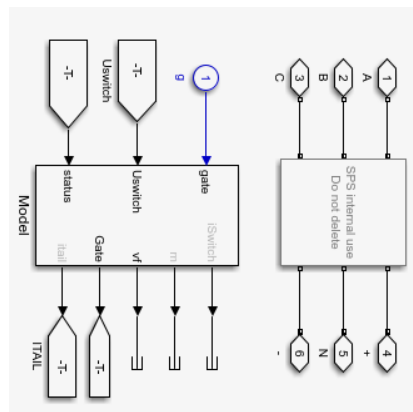
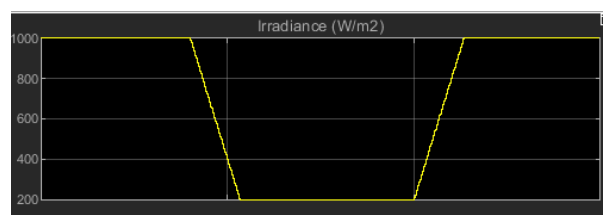


Figure 8. Modeling of 3-Level IGBTs Bridge



(a) Irradiance (W/m2)

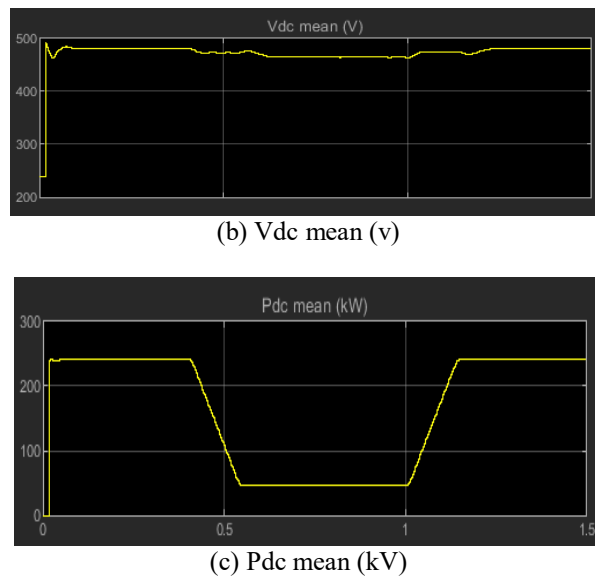


Figure 9. The output of PV including irradiance, voltage, and power.

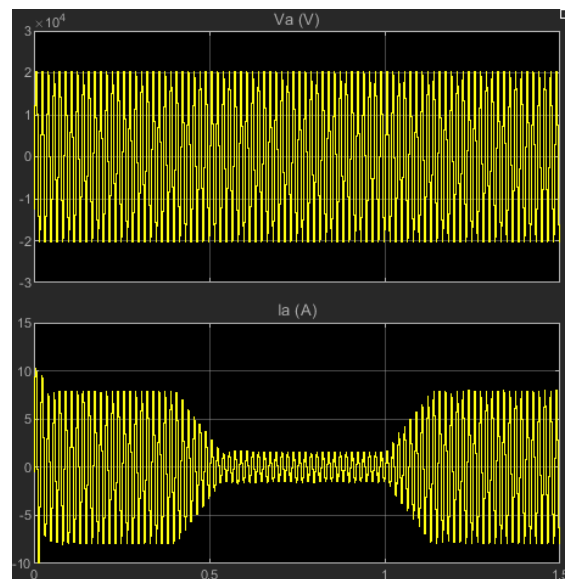


Figure 10. The output of PV including voltage and current.

CONCLUSION

A major highlight of this article is the focus on power quality enhancement. Power quality issues, such as voltage fluctuations and harmonics, can have detrimental effects on both utility grids and sensitive electronic loads. The research has delved into these issues and proposed strategies for enhancing the power quality of the integrated system. However, by applying advanced control techniques and harmonic filtering, the study has demonstrated how the adverse impacts of power quality disturbances can be mitigated effectively. Furthermore, the incorporation of battery storage into the PV system showcases the potential for load shifting and peak shaving, which can contribute to grid stability and reduce energy costs. As a matter of fact, this aspect is of paramount importance in the context of the increasing integration of renewable energy sources into utility grids. In this regard, the PV array is systematically arranged into 86 parallel strings. Thus, each of these strings is carefully assembled, comprising a succession of seven SunPower SPR-415E solar modules that are interconnected deliberately.

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