***Original Research Article***

Design and Performance Analysis of a Hybrid Grid-Connected PV System: A Case Study of Wakanda Estate's 1.5MWh Solar Installation

**Abstract**—

Due to technological advancements, there are efforts globally to lessen the generation of carbon dioxide, one of the gases responsible for the greenhouse effect. Renewable energy has seen tremendous growth in recent years. In order to protect the environment from pollution and provide electricity from an endless source for future generations, renewable energy sources, particularly solar energy via photovoltaic systems have come to stay.

This paper simplified the process, control mechanism and cost benefit of connecting solar farm (Wakanda estate as case study) for hybrid applications, directly connected to the grid with an inverter during high power demand or as standalone off grid system using batteries for energy storage when supply to the grid is not needed. Due to the intermittent nature of solar irradiance, an MPPT (Maximum Power Point Tracking) is applied to the topology. The MPPT algorithm must strike a compromise between maximizing power extraction and power quality issues, especially harmonic distortion brought on by switching elements, when interacting with the grid to dynamically modify the operating voltage to harness the most power possible under a variety of environmental conditions. The control mechanism commonly adopts a cascaded structure where the MPPT determines appropriate voltage references while an inner current control loop manages grid synchronization.

Filters play a dual role in the management of harmonics in solar PV system. Despite its usefulness in removing chopped signals, Filter dynamics (usually LCL configurations) must be taken into consideration since they can present resonance issues that have the potential to also destabilize the system if not well managed, particularly when irradiance changes quickly. In order to preserve stability during grid disruptions and guarantee that power quality criteria are fulfilled by adaptive filtering, advanced MPPT implementations and include anti-islanding protection, low-voltage ride-through capabilities, and dynamic impedance matching.

The process was investigated by modeling and simulating photovoltaic arrays in MATLAB-Simulink using solar cell block from SimElectronics where influence of variable elements such as solar radiation was checked against performance of photovoltaic cells.

**Keywords:** **Modeling, Solar cell, photovoltaic array, MPPT, Filter, MATLAB/Simulink, Solar Cell block, Grid**

# **Introduction**

Energy is recognized as the primary driver of economic development on a global scale (Laura Cozzi, 2024) and an essential pillar of socioeconomic growth that has propelled advancement for millennia (Amir Shahsavari et al.., 2024). According to BBC's research (www.bbc.co.uk) on ‘Issues of fossil fuels’, in addition to drawing attention to the challenge of pollution and carbon emissions, the estimates from international organizations indicate that oil and gas reserves may run out within our lifetimes if the world's demand for energy from fossil fuels continues at its current rate. Due to rising energy demand, the majority of currently used energy sources are finite and will eventually run out (Zoghi et al., 2017).

Hence, there is a paradigm shift for new energy sources to suit the current energy needs because of the rising demand. This has led to innovative solutions with desirable characteristics, such as greater efficiency, more power, and less pollution when generating energy, ability to recover, use and reuse energy sources without depletion. The form of energy that fits these characteristics are Renewable energy sources which include wind, sun, geothermal, ocean, hydropower, biomass, and biogas, etc.(Sholikha, 2019).

For a cleaner solution, different world powers, Government and private bodies have individually and jointly participated significantly in different global projects. For instance, the international renewable energy agency's (IRENA 2019) energy transformation roadmaps and in showcasing her commitment placed a strong emphasis on decarbonizing the energy industry and lowering carbon emissions to drastically slow down climate change. These roadmaps explore a bold, yet technically and financially viable approach for implementing low-carbon technology in the direction of a clean and sustainable energy future. In the 2019 edition of its global energy transformation study, IRENA examined two alternatives for energy production to 2050. The first is a path towards sustainable energy commitment established by both present and future policies. The second is a cleaner climate-resilient pathway that keeps global warming to well below 2 degrees and closer to 1.5 degrees, which is in line with the envelope of scenarios provided in the 2018 report of the Intergovernmental Panel on Climate Change (IPCC). It is primarily based on more ambitious but doable adoption of renewable energy and energy efficiency measures (Remap Case).

However, the IRENA report in 2024 reflect a concern that despite the commitment that was made by G7 and G20 at COP28 (2023) held in Dubai, we are still not on track on renewable energy generation as a result of the continuous clinch to fossil fuels by major economics who emits the highest amount of CO2 and hence making the attainment of the ambitious goal increasingly difficult. More also, even if the generation is drastically improved, there is the problem of stability of the transmission systems, this stability issue limit the efficiency and transmission capacity (Surya Prakash et al.., 2023)

The present report outlines the role of solar photovoltaic (PV) power in the transformation of the global energy system based on IRENA’s climate-resilient pathway (remap case). In 2019, IRENA highlighted the growth in solar PV power deployment that would be needed in the next three decades to achieve the Paris climate goals.

Solar Photovoltaic (PV) systems converts daylight into electricity which can be connected to the National Grid to export (sell) electricity to energy companies. Alternatively, the electrical energy produced which is in itself from a sustainable source can be fed directly into the property's power supply. When power is produced off the grid, it is stored in batteries for local consumption. The following is a summary of the various popular PV systems:

## Grid-Tied Solar Photovoltaic (PV) Systems

This include Cables & Accessories such as Generation Meter, Mounting System, isolators (for disengaging parts as well as all of the system for the purpose of maintenance and could also be helpful during emergencies), Solar PV Panels / PV Modules for generating the power required for the process and Grid-Tie Inverter converts the DC power into AC power which is then ready for use locally and for export to the grid when required (Ahmad Maliki el al..,2021)

## Off-Grid Solar Photovoltaic (PV) Systems

When the solar PV panels aren't generating power, as at night, an off-grid system uses batteries to store and release electricity or when there is no power supply from the grid. It can be referred to as self-contained. The major components include PV panel, Cables & Accessories such as Generation Meter, Mounting System, isolators etc. However, the main parts of off-grid systems are batteries, which store and release power, and a charge controller, which reverses current and prevents overcharging. Overcharging has potential to damage batteries degrading the capacity and cause higher internal resistance. (Peifeng Huang et al..,2023).

## Hybrid Solar Photovoltaic (PV) Systems

All the advantages of both systems are combined in a hybrid system, which also offers protection against power interruptions and cuts (from either solar or mains).

As with all grid-connected PV systems, hybrid systems must be protected against islanding, which occurs when the PV system keeps producing and exporting power to the grid even when the mains power is out. In the event of a power outage, hybrid systems will keep the property powered while photovoltaic systems will disconnect from the grid for safety reasons. (IRENA 2019).

# **PV system main components**

It’s designed to capture energy from the sun and transform it into electricity by using photovoltaic/solar panels, an incredibly safe system to use if the safety rules are not compromised, as well as low maintenance. The PV system component is summarized below

## Solar Array.

Solar cells, also known as photovoltaic cells, are the building blocks of a solar array. These cells are subsequently assembled to form solar panels. Arrays are collection of solar panels. About 0.5 V is produced by a single PV cell (M.Vivar et al.., 2024). With this little voltage, what can we do? The PV module, which is made up of many cells, is the fundamental building component for PV applications. Modules can be arranged in parallel or series to create a PV array, which can then add up the little voltage created to a value that can be used to generate the necessary amount of power.

## Inverter

The variable direct current (DC) output of a photovoltaic (PV) solar panel is converted into utility frequency alternating current (AC) by a solar inverter. This AC can then be used by a local off-grid electrical network or fed into a commercial electrical grid.

Temperature plays a significant role in inverters. As temperature rises above optimal, the inverter's power output may continue to drop. The solar panels are composed of semiconductors, whose efficiency declines as the temperature rises. At a certain temperature, when the cells are hot, the flow of electrons within them becomes less effective at converting sunlight into electricity, which lowers power output (Eustache Hakizimana et al.., 2024).

PV arrays' multi-peak partial shading output curves are constantly changing, therefore, a technique for accurately tracking the actual output curve must be developed. Solar inverter uses Maximum Power Point Tracking (MPPT), to extract as much power as possible from the PV array. The intricate interplay of temperature, total resistance, and solar irradiation in solar cells results in a non-linear output efficiency can be illustrated by the I-V curve (Ward et al.., 2023). The MPPT is designed to sample or analyse the cells' output and determine a resistance (load) to get the most power under any given set of environmental variables (Adamu et al 2024).

There are various classifications for solar inverters. Converters can be a Stand-alone, Grid-tied (which match phase with a utility-supplied sine wave), Battery Backup (which can supply AC power to specific loads during an utility outage and must have anti-islanding protection), and Intelligent Hybrid (which control a photovoltaic array, battery storage, and utility grid) which are all directly connected to the unit. Inverters can also be classified based on switches; the eight-switch inverter, the traditional six-switch inverter and the four-switch inverter with fewer switches. For the eight-switch inverter, when one inverter leg fails, the subsequent inverter can be redesigned as a neutral-point diode-clamped inverter, However, in comparison, the six-switch inverter has exceptional performance, and is widely used in applications such as active power filters, renewable energy systems, electric vehicles, and high-power variable speed drives (Abdel-Aziz et al..,2023)

## Filter

For grid connected PV system, power quality is a significant problem that is impacted by the increasing usage of nonlinear loads by commercial, industrial, and residential users. All users connected to the same point of common coupling (PCC) are impacted by the harmonic voltages created by these loads' high harmonic currents interacting with the grid impedance. A multi-inverter grid-connected system's resonance characteristics become more intricate and challenging to forecast when it is affected by the parasitic parameters of LCL-type inverters and the impedance of the lines connecting the system (Tianhao Hou et al.., 2024.). However, with the right algorithm, the LCL grid connected inverters can eliminate the problem of resonance (Danyun Li et al.., 2024)

Active damping technology uses auxiliary devices which include active power filters to intervene in the system and suppress resonance by dynamically adjusting grid impedance characteristics (Hou et al.., 2024).

The power filter is necessary to remove undesirable harmonics while preserving the essential components.

There are different groupings of filter in relation to design which are;

L-Filter - First order

LC–Filter - Second order

LCL-Filter – Third order

In order to select the right filter, we can apply the equation below to determine the inductance, capacitance and switching frequency required for the right control and ripple reduction.

=

𝐿1= / Δ𝐼𝐿\_𝑚𝑎𝑥 =10%\* /,

L2=𝐿1 /𝛼, 𝛼 ∈ [3,7]

C= , 10 ∗ 𝜔𝑜 < 𝜔𝑟𝑒𝑠 < 𝜔sw

(Jegadesan Subbiah ‘2018)

## Other components

There are other components that make up a PV system not mentioned above. This include;

Controller Stage (Converter/ MPPT Algorithms): Solar PV Charge Controllers protect batteries by blocking reverse current and preventing battery overcharge (Bathirappan et al.., 2024).

Cables & Connectors: For connecting the various components, usually a bare copper, tinned, finely stranded according to DIN VDE 0295 class 5 and IEC 60228 class 5, and could be double insulated. Other properties to be checked before its usage include temperature range (e.g C- C), nominal voltage (e.g., 1800 V DC), AC test voltage (e.g., 10,000v), minimum bending radius of the wire etc. (Solar Cables www.topcable.com)

Mounting Structure: Depending on the number of PV units or types, whether roof mounting or ground mounting are to be used, there are some basic properties of the mounting structure that needs to be taken into account. This inexhaustibly include mechanical properties, strength, corrosion properties, rigidity & maneuverability. To make the most from the available space, the tilt angles can be optimized i.e carefully placed in order to avoid solar panels shading each other.

There are also components that include switches, fuse box to control amount of voltage and current delivered to the circuit etc.

## Summary.

PV Component summary

Table 1: PV Component Summary

|  |  |  |
| --- | --- | --- |
| PV Component | Function | Placement |
| PV Module (Array) | To capture the energy from the sun | Installed on a mounting structure connected to the DC isolator with a cable & connector |
| Inverters | To transform DC current into AC currents | Placed between battery blank and load if a battery is used |
| Battery Bank | To store energy mostly in standalone application | Connected to the charge controller and placed in between PV array and inverter |
| Charge controller | Rely on solid state technology in order to control current flowing into the battery bank | Connected to the battery and placed in between PV array and inverter |
| Filter | To filter unwanted harmonics. | Between inverter output and grid |
| DC Isolator | System & Human Safety | Between Inverter and PV Array |
| AC Isolator | System and Human Safety | Breakers and switches –Between inverter and grid generation meter |
| Cables & Connectors | For connecting components | Connecting various component of the system |
| Generation Meter | For reading circuit elemental values | Between AC isolator and grid or another isolator before the grid |
| Lighting Arrestor | System & Human Safety | Topmost point in the location where the solar energy system is installed |

## Grid-Connected PV Array

An example of comprehensive model architecture of a photovoltaic array connected to the grid through a three-phase converter is displayed below

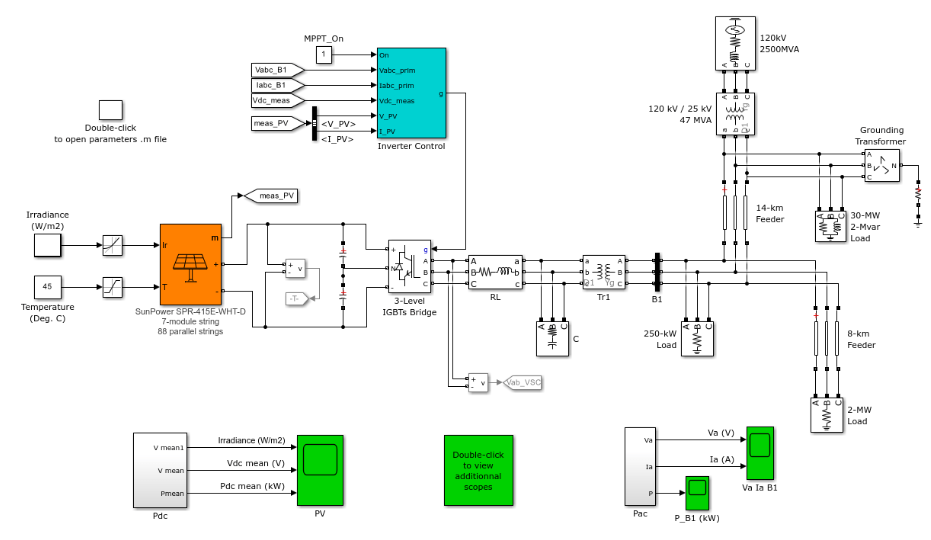


Figure 1: Grid connected PV Array

https://uk.mathworks.com/help/physmod/sps/examples/250-kw-grid-connected-pv-array.html

# **PV system design**

## **Load- Power Demand for Wakanda Estate**

I shall be considering the below hypothetical figures of daily sun hours from a fictional location in Table 2 taken to represent an unknown location ‘Wakanda’ in Europe.

Table 2 Average daily sun hours

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Calendar  Period/Daily Sun Hours | 20-Year mean | 2020- Average | 2021  Average | 2022  Average  provisional | No-Days |
| Jan | 1.6 | 1.8 | 1.4 | 2.5 | 31 |
| Feb | 2.7 | 2.7 | 2.6 | 3.1 | 28 |
| Mar | 4.5 | 5.2 | 3.8 | 5.7 | 31 |
| Apr | 7.7 | 7.8 | 7.6 | 6.3 | 30 |
| May | 7.6 | 9.7 | 5.6 | 5.6 | 31 |
| Jun | 6.3 | 6.2 | 6.3 | 7.7 | 30 |
| Jul | 5.9 | 5.6 | 6.1 | 7.2 | 31 |
| Aug | 4.8 | 5.2 | 4.4 | 7.8 | 31 |
| Sep | 5.0 | 5.4 | 4.6 | 4.3 | 30 |
| Oct | 2.6 | 2.2 | 3.0 | 4.1 | 30 |
| Nov | 2.2 | 2.1 | 2.4 | 2.1 | 30 |
| Dec | 1.3 | 1.6 | 1.0 | 1.3 | 31 |

The project is to design an energy value of 1.5mwh solar systems to power an estate of 150 blocks with three flats per block on a 24hour basis all year round while feeding the grid with the excess generated energy.

Table 3 DC Energy Consumption Component

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Cumulative Appliances | Power rating (W) | No (In estate) | P avg. usage | Hours of use | Energy Consumption/day (Wh) |
| Rechargeable Lamps | 50 | 30 | 1500 | 24 | 36000 |
| Radios | 48 | 20 | 960 | 24 | 23040 |
| Phones/Adaptors | 10 | 50 | 500 | 24 | 12000 |
| Lamps(Total) | 50 | 25 | 1250 | 24 | 30000 |
| Television | 220 | 60 | 13200 | 24 | 316800 |
| Total Power (W) & Energy consumption (Wh) |  |  | 17410 |  | 417840 |

Table 4 AC Energy Consumption Component

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| AC devices | Power rating (W) | No (In estate) | P avg. usage | Hours of use | Energy Consumption/day (Wh) |
| Central gas heater | 250 | 70 | 17500 | 24 | 420000 |
| Television | 200 | 25 | 5000 | 24 | 120000 |
| Vacuum Pump | 120 | 60 | 7200 | 24 | 172800 |
| Microwave | 350 | 10 | 3500 | 24 | 84000 |
| Fridge | 250 | 50 | 12500 | 24 | 300000 |
| Total Power (W) & Energy Consumption (Wh) |  |  | 45700 |  | 1096800 |

Total Maximum Power demand = 17410 + 45700 = 63110W

Total Maximum Energy demand = 417840 + 1096800 = 1514640Wh = 1.5mwh

For generation, assuming 10% system losses, then actual generation targeted =

The total sun hours per year using 20-year mean average: 1.6\*31+2.7\*28+4.5\*31+7.7\*30+7.6\*31+6.3\*30+5.9\*31+4.8\*31+5.0\*31+2.6\*30+2.2\*31+1.3\*31

=1,553.2 hours/year

## **PV array (The module, number of modules, series-parallel arrangement,)**

Average Sunny hours per day is calculated as follows 1553.2/365 = 4.26hrs/day

The PV array power to be installed will be = =395kw

The total number of PV modules =

The total number of PV modules = = 952.4 = 953 modules

## **Inverter (Selection)**

The inverter selection is to ensure that there is frequency/voltage & current matching which refers to the necessity of a grid tied inverter to match the speed (frequency) of the AC wave that it generates to that of the mains power that it is trying to connect to. When the inverter matches the frequency and synchronizes with the mains, it’s then electrically “locked” with the mains

Inverter sizing

Note that the PV array power to be installed is =395kw

Our selected inverter is 98.6 % efficiency, we will require

For safety, the inverter should be considered 20- 25% bigger size.

The inverter size should be about kw. In my model the inverter has a maximum input power of kw which is fantastic

The selected Inverter model no is PVS800-57-0500kW-A

<https://new.abb.com/docs/librariesprovider22/technical-documentation/pvs800-central-inverters-flyer.pdf?sfvrsn=2>

Table 5 Inverter model no- PVS800-57-0500kW-A

|  |  |
| --- | --- |
| **Inverter** |  |
| Maximum input power (kW) | 600 |
| Full power MPP range (V) | 450-750 |
| Maximum Voltage (V) | 900V |
| Max. current (A) | 1145 |
| Nominal AC current (A) | 965 |
| Efficiency (%) | 98.6 |

Table 6: PV Module SPR-415E-WHT-D Details

|  |  |
| --- | --- |
| **PV Module** |  |
| Output Power (W) | 415 |
| VOC (V) | 85.3 |
| ISC (A) | 6.09V |
| Vmpp (V) | 72.9 |
| Impp(A) | 5.69 |
| Efficiency (%) | 16.5% |

Number ( #)of modules in series

Average voltage of the inverter= V

Vmpp (inverter-average) / Vmpp (module) = = 9 modules in series

Which means the maximum voltage will be;

which is lower than inverter max. DC input voltage (900V)

# of modules in parallel:

Average Sunny hours is 4.26hrs/day

Line chart

Description automatically generated with medium confidenceThe total energy generation per year 365\*4.26\*395 kW = 614,955,175.5 Wh/year =615MWh/year

From the section above, Total maximum Power requirement and energy demands are 63kW and 1.5MWh

## **Battery (Battery sizing for off-grid PV system)**

17410(DC) + 45700(AC) = 63110W =63kw

## **Control**

There are several MPPT algorithms that can be used for the converter (ac to dc & vice versa). A classic perturb and observe (P&O) method has been used in this work due to its simplicity (Krim Salah et al.., 2024) . The main components of the Inverter Control are: PLL & Measurements, Maximum Power Point Tracker System (MPPT) using a Perturb & Observe algorithm, DC Voltage Regulator, Current Regulator and PWM Modulator. For the proper operation of the system, other important control blocks must be taken into account, that is, the MPPT algorithm, the grid synchronization algorithm, and the voltage reference generator. The simulation using math lab simulink from topology in figure 1 for this project is displayed in figure 2 below

Figure 2: MPPT Tracking

In figure 2, P&O algorithm is applied to observe the difference between extracted power with and without the MPPT technique. The charts display the I V, P V, and solar irradiance curves. The MPPT algorithm is absent from the first operation. In order to maximize output power, the P&O algorithm introduces perturbations to the system's operational point, as illustrated in figure 2. Little increments are added to the PV array until the maximum power point is attained. The solar module's V1 and I1 readings are first measured in order to determine P1 (power output). Next, a slight perturbation in the form of ∆V is introduced. The revised values of V2 and I2 are then measured to determine P2. The system will continue to perturb in the same direction if the P2 value is positive. When the maximum power point is reached close to Pdc, the system operating point will start to oscillate constantly around that maximum power point. The controller will track this operating point and bring the V of the solar module to perform on this maximum power point.

## **Other components**

Major components have been covered. Other components may include transformer, feeder. This is beyond the scope of this study

## **Grid connection**

The Grid is 3-phase & IGBT switch with feeder of 14km where the power will be transmitted on high voltage and low current to minimize eddy current losses through a step up transformer in the transmission line. The PV is designed for 63KVA maximum domestic power consumption and PV Power generation is 395KVA .It’s only the excess that will be fed into the grid when in low demands

## **Design summary**

**Chart, line chart

Description automatically generated**

Figure 3: Module output when run on Simulink [a). I-V characteristic fixed temperature, varying irradiation. b).P-V characteristic, fixed temperature varying irradiation.

The aforementioned results demonstrate that as irradiation increases, the output voltage and current increases. The PV panel's power output rises as a result of these increases.

# **Cost benefit analysis**



# **PV system modelling and simulation**

## **PV system model**

The PV model selected is SunPower SPR -415E -WHT-D based on the power to be generated by PV (series and parallel) and simulated with different irradiation, temperature and MPPT etc

## **Harmonic analysis from simulation finding**

The harmonic distortion was initially high at about 24% just after the inverter

However, it was reduced to 2.5% after the first filter and finally to 0.16% after all the filter phases. Hence unwanted harmonics is greatly reduced at the grid connection

## **Power flow at different solar irradiation**

As shown below in figure 4, at a reduced irradiation value, the current, voltage and power is reduced.

I have implored MPP algorithm in this model using P&O method. The algorithms account for factors such as variable irradiance (sunlight) and temperature to ensure that the PV achieve a steady state and generates maximum power at all times depending on the time lapse. Please see below

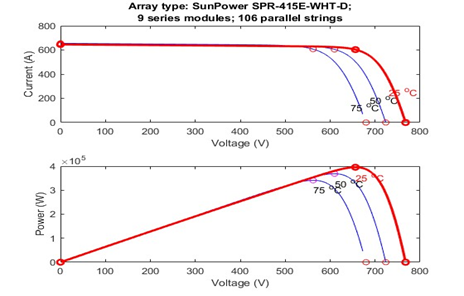
Chart, line chart

Description automatically generated

Fig. 4 PV output power for. -Achieving steady state with MPPT

## Impact of temperature

From the simulation result, Its shown that temperature deviation from STC value of , leads to reduced voltage and current and therefore power delivered as shown in the simulated graph above



# Fig. 5 PV Power Delivered To Circuit at Different Temperature

As the irradiation increases, the output voltage and current both rises, according to the results above. The power output of the PV panel rises as a result of these increments. However, as shown in the result, there is an optimal temperature () where power output is maximum. Meanwhile, if the temperature increases or decreases further, there is drop in power. Hence, solar module is designed to produced maximum power at the designed temperature

# **Conclusion**

The payback period in session IV shows that solar panels are a popular and expanding renewable energy source for both residential and commercial uses. In order to create a grid-connected solar system, it is first of all connected to the grid via a power converter. It is essential to incorporate a number of features, such as power factor correction and active power filtering into the power converter in order to optimise this system. The mains power quality deteriorates due to current harmonics produced by nonlinear loads connected to the grid which is one of the most significant issue with connecting renewable to the grid. Though, these current harmonics can be compensated by active power filters which are quite expensive. The simulation result showed that a photovoltaic system with additional harmonic compensation and power factor correction capabilities produced a respectably good output as demonstrated in the MATLAB-Simulink simulation. Beyond this journal, I look forward to researchers to resolving the issues with integrating the renewable energies to National grid and transporting energy to far distances (using HVDC technologies)

Disclaimer (Artificial intelligence)

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Details of the AI usage are given below:

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