Power Electronics Report

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1 Introduction

Power electronics play a crucial role in photovoltaic (PV) systems by enabling efficient conversion, control, and delivery of solar energy. As the output from PV modules is inherently variable and DC in nature, power electronic converters—such as inverters, DC-DC converters, and maximum power point trackers (MPPTs)—are essential for transforming this energy into usable AC power and optimizing energy harvest under changing environmental conditions. Their integration not only maximizes system performance and reliability but also supports grid compatibility and advanced energy management, making them a vital component in the advancement of modern solar energy systems.

As can be seen from the figure below, the main components of the PV system are the PV panels (they include the bypass diodes) and the Balance of Systems (BoS). The last one includes the battery (if there is one), the charge controller (if there are any batteries), the DC-DC converter, the DC-AC converter or inverter, the mounting frames, cables, etc.

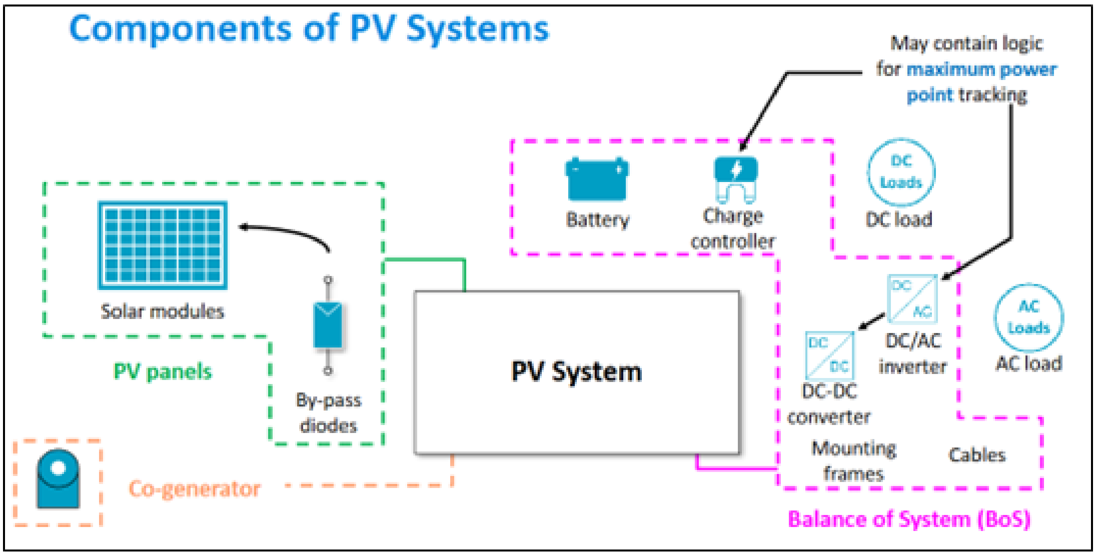


Figure 1: Basic components of a photovoltaic system [1].

2 Power Conversion Requirements for integrating solar PV, storage, and loads

Regarding the power conversion requirements, it is known that PV panels generate DC power, meaning that for AC loads, an inverter is required (DC to AC conversion). In case storage is also integrated into the PV system, then bidirectional inverters are essential. Battery storage stores DC power, which will need the bidirectional converters to convert it to AC to discharge into the household or grid. To add, when battery storage systems are necessary, eg, stand-alone PV systems, then another device named a Charge controller is essential. Its main purpose is to protect the battery from fluctuation in the PV system and prevent over-charging or over-discharging. The charge controller protects the battery, decoupling the PV array from the battery by stopping the battery from charging any further or discharging any further. The last one is achieved by disconnecting the battery from the load. Current regulation is another function of the charge controller, by maintaining current rates close to its C-rate. Imposing limits on maximum currents flowing. Another function is back charge regulation, which prevents the "charging" of PVs at low voltages. Useful when there are no blocking diodes on the PV system. When the charge controller includes MPPTs, the charge controller can act as a voltage regulator and ensure that the PV modules operate close to their Vmpp, while the battery operates close to its rated voltage range.
The figure below showcases a larger off-grid system where possibly 240 V AC appliances can be used. Here, the battery is connected directly to the inverter, which includes the battery discharge protection, handling the larger currents delivered by the battery to the inverter. The battery overcharging is prevented by the charge controller, while discharge protection is carried out by the inverter [1].

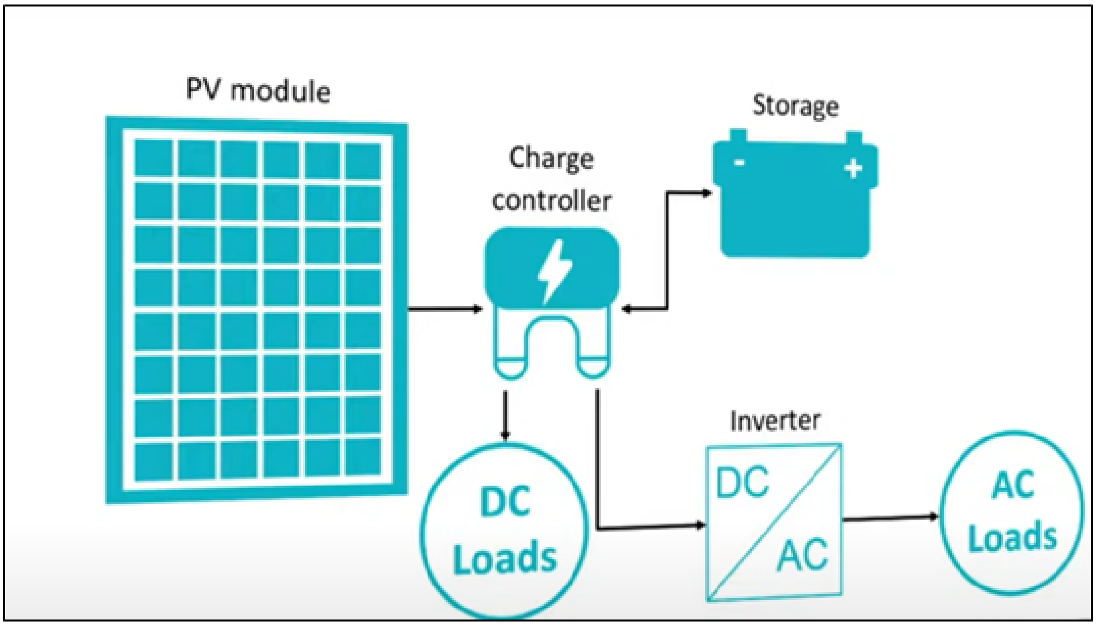


Figure 2: Schematic of an off-grid PV system [1].

3 Maximum Power Point Tracking (MPTT)

The typical structure and embodiment of the MPPT are presented below.

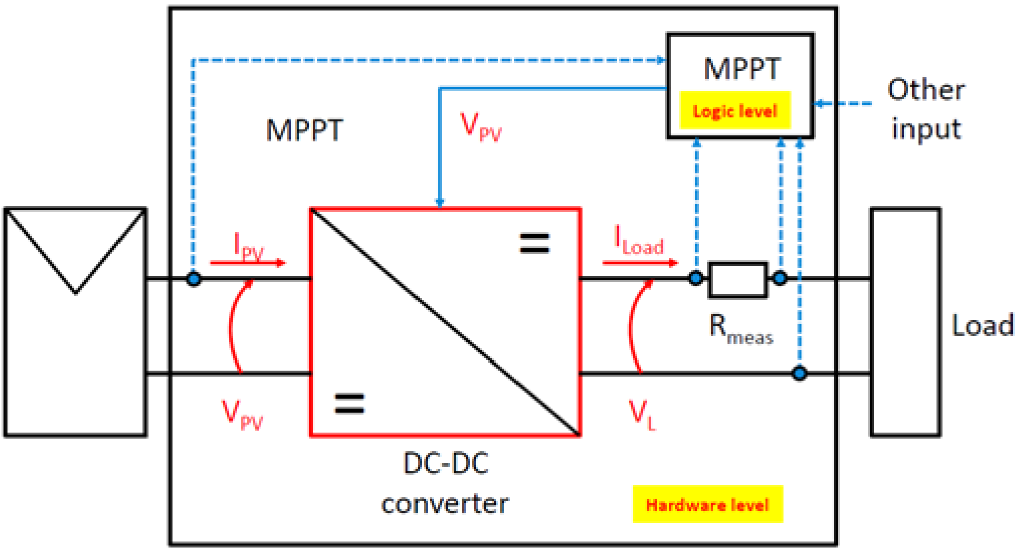


Figure 3: Example of integrated MPTT system working along with the DC-DC converter. [1].

The purpose of the MPPT algorithm is to find the voltage at the maximum power point (Vmpp) of the PV array, which is the voltage at which our PV delivers the maximum power. Then, by using power electronic converters, the PV output voltage is adjusted to match the system requirements. MPPT algorithms can be found either included inside charge controllers or inside inverters. There are 2 different MPPT tracking algorithm categories: Indirect and Direct. Indirect methods do not need an I-V curve to work, while direct ones do. Usually, indirect methods are not widely used since direct ones are much more efficient.

3.1 Indirect MPPT methods:

Some of the indirect methods are :

- **Constant voltage method**: Only STC settings are used, so the applied Vmpp equals the datasheet one. Of course, that's not ideal when conditions differ from STC [1].
- **Open Voltage Method**: A bit more robust compared to the Constant Voltage algorithm. This method approximates Vmpp by hardcoding a factor 'k' and using the formula Vmpp = k x Voc. For c-Si, usually k=0.7 or 0.9=8. Since the Voc changes are easy to track, this is a fairly easy method to implement. The downsides are, of course, that it is still an estimation because of the k constant. To add, for this measurement, the PV module needs to be open-circuited, and thus disconnected from the load for a bit, leading to reduced power output of the PV system [1].

- **Short Current Pulse method**: Similar to the Open Voltage method, but for current. Uses Impp = k x Isc formula, using the short-circuit current. Again, the same disadvantages hold, with the only difference being that for the Isc measurement, the PV module needs to be short-circuited [1].

Other methods of indirect MPTT algorithms are available too, but direct methods are more involved and to the point.

3.2 Direct MPPT methods:

- **Perturb and Observe (P&O)**: In this method, small incremental changes in the voltage are taking place, and the power is monitored after every change. Every perturbation will lead to a power change. If an increase in the voltage leads to an increase in the power, then it means that the operating point is lower than the MPP and therefore, a positive (higher voltage) perturbation is needed. When the opposite holds, eg, decreasing voltage leading to decreasing power, a negative (lower voltage perturbation) is needed. Eventually, the algorithm will converge at the MPP. A disadvantage of this method is that the system doesn't recognize is the actual MPP is reached, and therefore it oscillates around the value, not leading to a steady value. The smaller the voltage steps, the less the meandering around the MPP. Another disadvantage is that in case of irradiance changes during the perturbation, the algorithm will fail to converge. Eventually, it will correct itself (TU Delft, PV Systems Course, 2023-2024)

- **Incremental Conductance Method**: We call $\frac{\Delta I}{\Delta V}$ the incremental conductance and $\frac{I}{V}$ the instantaneous conductance. Then:
  - $V = V_{mpp}$ if $\frac{\Delta I}{\Delta V} = -\frac{I}{V}$
  - $V > V_{mpp}$ if $\frac{\Delta I}{\Delta V} < -\frac{I}{V}$
  - $V < V_{mpp}$ if $\frac{\Delta I}{\Delta V} > -\frac{I}{V}$

  The main downside of this algorithm is that it's complicated, and therefore lots of measurements and calculations are needed. On top of that, in general for direct MPTT methods, when shading takes place, the I-V curve might have different local maxima, which can confuse the algorithm, leading to not finding the global maximum, which is the global MPTT [1].

4 DC-DC converters

The purpose of DC-DC converters is to decouple the PV voltage from the load voltage, so the PV works at its optimum and the load is supplied with its rated voltage. That is because the voltage at which PV power is generated differs from the operational voltage of the loads. Additionally, if there is MPTT logic included, the voltage at the maximum power point of the PV modules changes during the day, the system needs a converter to adjust the PV output voltage and current to match the requirements of the rest of the system; this is where the DC-DC is needed. To add, the DC-DC is needed to take the variable output voltage of the module and transform it into a constant voltage seen by the inverter. The main requirement for a PV system DC-DC converter is to draw the maximum power from the PV panel and supply it to the load. The most used DC-DC converter topologies in PV systems are:

- **Buck converter (step-down converter):**

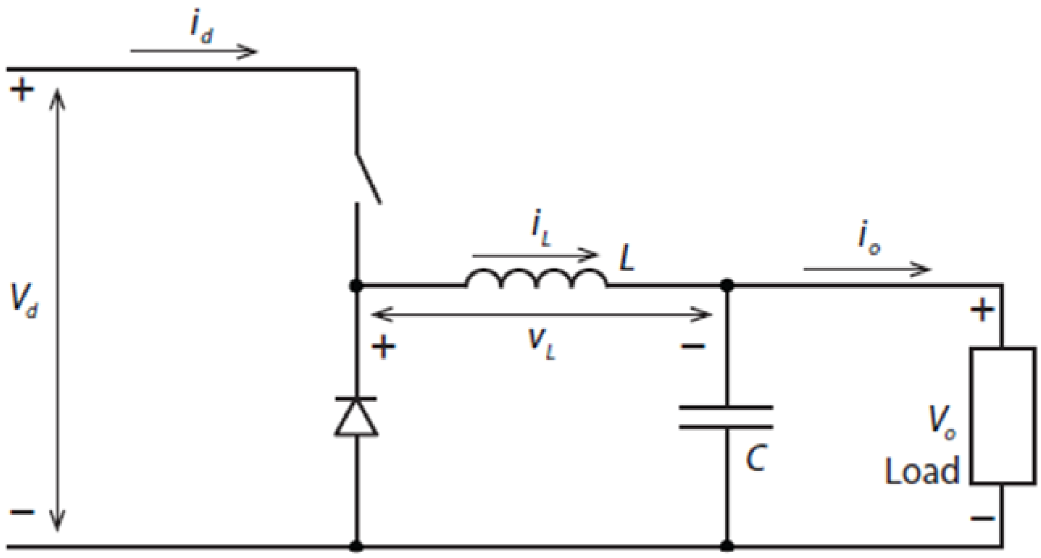


Figure 4: Buck DC-DC converter [2].

- **Boost converter (step-up converter):**

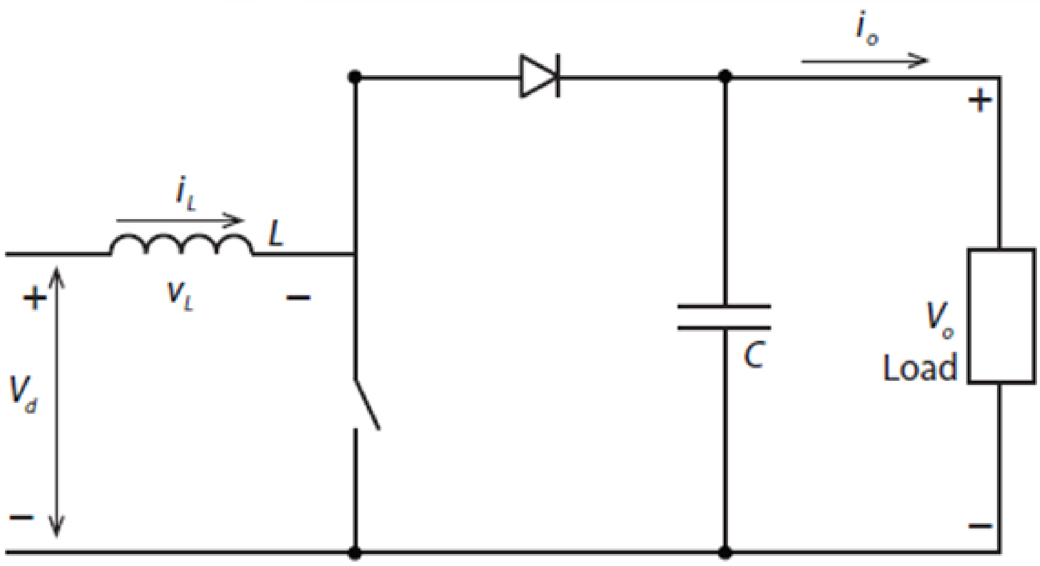


Figure 5: Boost DC-DC converter [2].

- **Buck-Boost converter (both step-up and step-down):**

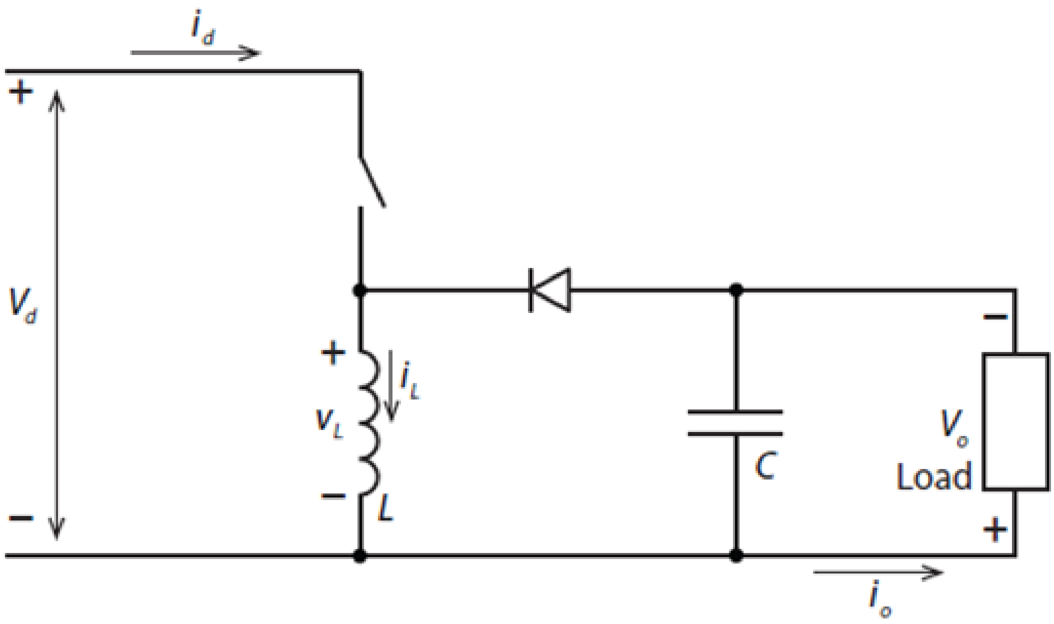


Figure 6: Buck-Boost DC-DC converter [2].

A comparison of the 3 different types is presented below. For DC-DC converters, the duty cycle (D) is the ratio of the switch ON-time to the total switching period, and it determines how much the input voltage is transformed into the output voltage.

	$V_{out} = D \cdot V_{in}$	$V_{out} = \frac{V_{in}}{1-D}$	$V_{out} = \frac{D}{1-D} V_{in}$
	Buck	**Boost**	**Buck-Boost**
D = 0	$V_{out} = 0$	$V_{out} = V_{in}$	$V_{out} = 0$
D = 1	$V_{out} = V_{in}$	$V_{out} = \infty$	$V_{out} = \infty$

	$V_{in} = \frac{V_{out}}{D}$	$V_{in} = V_{out}(1-D)$	$V_{in} = \frac{1-D}{D} V_{out}$
	Buck	**Boost**	**Buck-Boost**
D = 0	$V_{in} = \infty$	$V_{in} = V_{out}$	$V_{in} = \infty$
D = 1	$V_{in} = V_{out}$	$V_{in} = 0$	$V_{in} = 0$

Figure 7: Comparison of Buck, Boost and Buck-Boost DC-DC converter topology [1].

5 DC-AC converters (inverters)

Since many electrical loads are designed for standard AC grids, most PV installations require an inverter to convert the DC output from solar panels into usable AC power.

At this point is should be mentioned that in PV systems an inverter can be either the stand alone device that converts DC to AC, or to the overall power electronic device that includes also other components such as the MPTT, the DC-DC converter, the inverter and the charge controller in case of stand alone PV systems but still connected to AC loads. In general, inverters must be built to withstand varying environmental conditions, such as temperature fluctuations and humidity, and should comply with standards like IP45 for protection. Additionally, they should be designed for long-term reliability—ideally exceeding 20 years of operation—and operate silently to ensure suitability for residential or sensitive environments. Inverters can be either Single-phase or Three-phase. Single-phase inverters are connected to one phase of the grid. They are generally ideal for low-power systems and stand-alone PV systems. A three-phase inverter is used when a threshold of 5 kWp is reached, making it essential for larger applications. Three-phase inverters ensure balanced current flow, which is one of the disadvantages of single-phase inverters when power is injected to only one phase, is too high [2].

5.1 Bi-directional inverters:

This equipment can work both as an inverter, meaning to convert DC to AC, but also as a rectifier, converting AC to DC. These 2 power modes make these devices more efficient than regular inverters, while having the bidirectional capability makes the system more compact and cheap, since less power electronics are used for more functions. For the DC to AC conversion (battery-to-grid, or battery-to-load modes), the inverter uses PWM techniques for the conversion, while voltage and frequency regulations are also used to match either the grid or the load requirements. Sine wave generation is also used to make sure that a pure sine wave output comes on the AC side, increasing efficiency. The grid-to-battery mode (AC to DC conversion) works the other way around. In this rectification mode, AC is converted to DC, and the battery is being charged. Some bi-directional inverters use Power Factor Correction (PFC). Power Factor Correction means configuring the inverter to inject or absorb reactive power (Q) as needed, and bring the power factor closer to 1. During low-solar periods, the inverter can charge the battery from the grid, ensuring energy availability. In that way, when energy generation from solar is not available, the grid can charge the batteries when electricity is cheaper (at night) and use it (discharge) when it's expensive. To add, when there's surplus energy, it can feed power back to the grid, supporting grid stability and potentially earning revenue [3], [4], [5].

5.2 Modes of operation of Bi-directional inverters:

Many rural PV systems highly depend on the grid availability and reliability to be grid-connected or fully stand-alone. According to [6], there are different modes of bidirectional inverter operation. There are the battery charge and battery discharge modes. The battery charge mode takes place when the inverter acts as a rectifier, charging the battery from an AC source, which is usually the grid. On the other hand, battery discharge mode happens when the battery is supplying the AC load. The bidirectional inverter of this paper includes a bidirectional buck-boost DC-DC converter and a single-phase inverter. In this simulation, the bi-directional inverter successfully worked in stand-alone (battery discharge), battery charge, and transition mode. In these inverter circuits, no transformers are used (transformer-less design), which reduces the total system's losses and cost, making it suitable and feasible for rural area energy applications.

5.3 Control systems in bi-directional inverters:

According to [6], the DC-DC converter uses a double-loop control. This control strategy ensures effective closed-loop performance. The outer loop is responsible for regulating the voltage of the intermediate DC-link capacitor (VH). In boost mode, when the battery is discharging to supply AC loads, this voltage is maintained at 390 V. However, if excess power causes the capacitor voltage to rise and reach a predefined threshold (e.g., 420 V), the system switches to buck mode, where the voltage is then stabilized at the higher level. Meanwhile, the inner loop controls the inductor currents in each phase to ensure balanced current sharing among them. This inner current loop is designed to respond faster than the outer voltage loop, allowing the two loops to be analyzed independently. Mode switching between boost and buck operation occurs automatically based on the capacitor voltage level and is coordinated by an integrated power management and control logic. The inverter operates using a double-loop control system and functions as a stand-alone, full-bridge, single-phase inverter with pulse-width modulation (PWM). An LCL filter is integrated at the output to effectively suppress harmonics and ensure clean power delivery. The outer control loop is responsible for voltage regulation and employs a PI (Proportional-Integral) controller in combination with an unbalanced dq transformation. The inner loop manages current control and typically uses a simpler compensator, such as a P or PI controller. Errors in the transformed dq channels include both a DC component and a frequency-dependent oscillation. By applying a single PI controller to correct the DC error, the oscillatory component is inherently suppressed as well, ensuring stable current control. This integrated control approach enables the single-phase inverter to operate reliably across various modes: stand-alone mode (battery discharging), charging mode (battery charging), and seamless transitions between these states.

6 Comparison of Inverters with or without transformers

By taking a look at the comparison table below (Figure 8), it is clear that each inverter technology has its advantages and disadvantages. However, given the high efficiency, low cost, and compact size of transformer-less inverters, most PV systems use them, while they are also more appealing for stand-alone and rural area applications. Figure 9 below shows a schematic of a transformerless inverter used for residential PV systems. Besides the actual DC-AC converter, which is realised as an H-bridge, it also contains a DC-DC boost converter and an MPPT that uses the voltage and current measured on the PV side as input. The system sketched also contains several electronic components for increased safety: a residual current measurement to detect leakage currents above a certain threshold and to shut down the inverter if these currents appear. Further, a grid-monitoring unit is needed to prevent islanding.

Features	Inverter with main transformer	Inverter with HF transformer	Inverter without transformer
Galvanic isolation	Yes	Yes	No
Residual current monitoring	No	No	Yes
EMI	Little	Little	Possibly high
Usage with thin-film modules	Yes	Yes	Possibly
Size and weight	Large	Medium	Low
Efficiency	Poor	Medium	High

Figure 8: Comparison of inverters with main transformer, with High Frequency transformer and transformer-less [1].

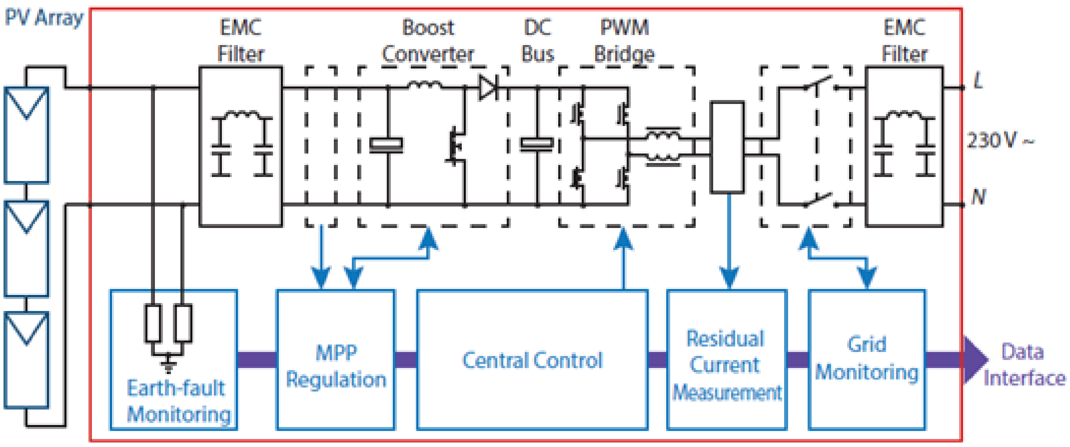


Figure 9: Transformer-less inverter unit [2].

7 Importance of PV islanding detection

Photovoltaic islanding takes place when the PV system keeps generating electricity even when the grid is shut down (eg, when a power outage occurs or after an intentional disconnection of the PV system). This can be very dangerous since utility workers might be working on restoring the utility grid, and thus they might get hit by the current. Therefore, a local "island" of electricity is created that is disconnected from the grid. It goes without saying that the detection of such an event is of great importance [7].

The detection of PV islanding has to do with the inverter type that is used in the system as well as with the presence or not of other distributed energy resources (DERs) that might also cause islanding. The larger the PV system, the more electricity is produced and therefore more likely to cause islanding conditions.

Inverters' behavior during islanding can be categorized into grid-forming and grid-following. For the local islanded system, grid-forming inverters can produce a steady voltage and frequency and can function independently of the utility grid. These inverters are usually utilized in off-grid locations without access to the utility grid, including isolated communities or military installations. In contrast, grid-following inverters are not able to produce a steady voltage and frequency when in islanded mode because they are made to synchronize with the utility grid. Usually, these inverters depend on the utility grid to supply a steady reference for the frequency and voltage of their output. These inverters may continue to produce energy in the event of a grid outage, but they are unable to maintain a steady voltage and frequency, which might cause instability and system damage. Several steps can be taken to guarantee the safe operation of PV systems when islanding. These include the use of energy storage devices to supply backup power during islanding, the deployment of islanding detection techniques to promptly shut down the system if an islanding scenario is discovered, and the use of grid-forming inverters for off-grid applications [7].

Techniques for islanding detection can be broadly divided into three groups: remote, active, and passive. In order to identify an islanding condition, passive techniques depend on variations in system characteristics like voltage or frequency. On the other hand, active procedures send a signal into the system and track its reaction. Lastly, to monitor the system from a distance and identify islanding based on the lack of communication signals from the utility grid, remote techniques employ communication technologies [7]. The following three figures showcase the above-mentioned detection techniques.

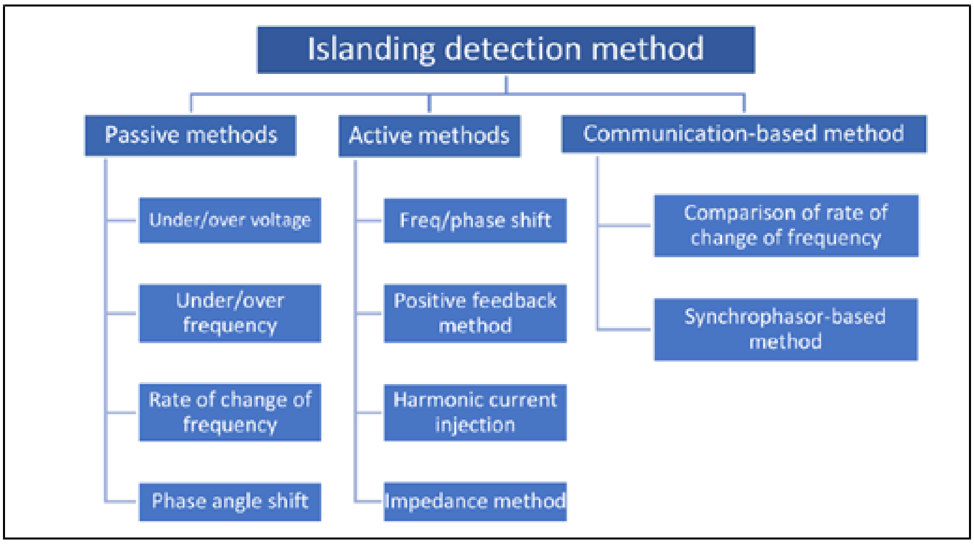


Figure 10: Islanding Detection Solutions [7].

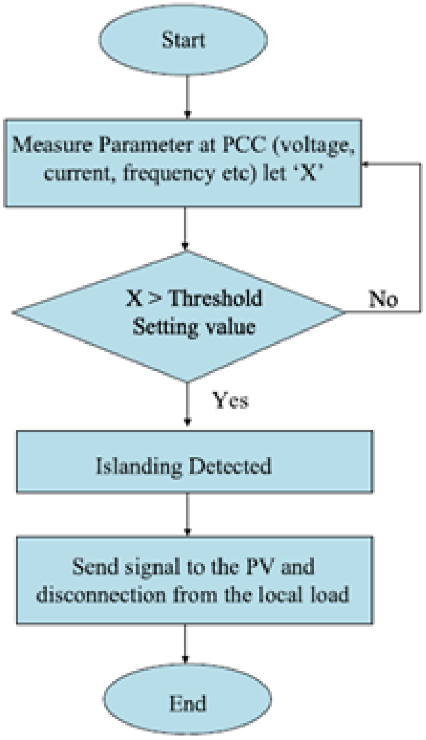


Figure 11: Passive Islanding [7].

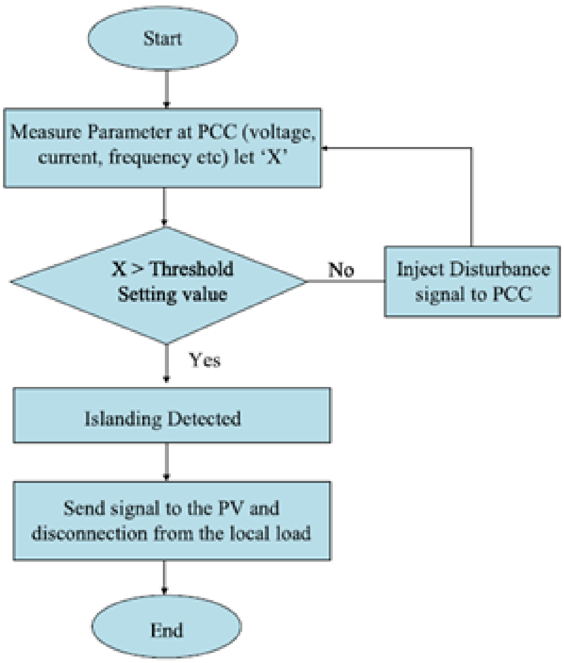


Figure 12: Active Islanding [7].

7.1 Islanding detection standards

According to [7], the detection of islanding in photovoltaic (PV) systems is defined by several international standards. These standards offer specifications and instructions for developing and putting into practice islanding detection techniques in grid-tied photovoltaic systems. The International Electrotechnical Commission IEC 62,116 standard, which specifies specifications and testing methods for grid-connected PV inverters and associated equipment, is one of the important standards. This standard specifies standards for islanding detection techniques, such as the use of voltage and frequency measurement techniques and the assessment of the reliability and effectiveness of such techniques. The IEEE 1547 standard, which offers rules for linking distributed resources, including photovoltaic systems, with electric power systems, is another significant standard [7].

NOTE: The choice of an inverter is highly connected to the area of the interconnected PV installation. Most grid-tied inverters have already been programmed, designed, and manufactured according to the grid, the standard, and safety measures that the specific country and its grid operate with. That includes anti-islanding features.

Of course, in stand-alone PV systems, there is no need for grid-tied inverters and thus there is more freedom regarding the choice of the inverter.

The following are the primary requirements for islanding detection [7]:

- **Frequency**: The PV system's power generation frequency and the grid frequency should be closely aligned. An islanding condition might be indicated if the PV system's frequency differs noticeably from the grid frequency.
- **Voltage**: To guarantee safe and dependable operation, the voltage of the power produced by the PV system should be kept within a specific range. An islanding condition might be indicated if the PV system's voltage differs noticeably from the grid voltage.
- **Rate of frequency and voltage change**: Abrupt variations in the PV system's frequency or voltage may be a sign of an islanding condition.
- **Reactive power and active power**: Variations in the PV system's reactive and active power can also be used to identify islanding situations.
- **Islanding duration**: Another way to identify islanding situations is to measure how long the PV system keeps producing electricity after the grid is cut off.

8 Grid Synchronization

Another function of the grid-tied inverter is grid synchronization. This is the process of aligning the output of the inverter with the grid so it is fully synchronized, safe, and efficient. This helps the seamless integration of the PV system to the grid. Grid sync is therefore essential for grid stability, safety, and efficiency. By synchronization, we mean 3 main things. The most important features of grid sync are: Voltage matching, phase matching, and frequency matching of the inverter and the grid. According to [8], there are different methods to achieve that. Some of them are:

- **Synchroscope Grid Sync method**: A tool known as a "synchroscope" helps in the solar inverter's synchronization with the grid in this technique. The synchroscope displays the phase difference between the solar system and the grid. A rotating disk on the synchroscope aligns with a fixed reference mark when both systems are in phase, or synchronized. The inverter can modify its output to preserve phase alignment with the grid by keeping an eye on this disc position.

- **Two bright, one dark Grid Sync method**: This method connects three lights in series and interprets their brightness to assess phase alignment. The inverter slowly modifies its output voltage until two lights shine brightly while one remains dim, a pattern that signifies the inverter's output phase is nearly in sync with the grid.

- **Three dark lights Grid Sync method**: This method connects three lights in parallel, and the inverter adjusts its output until all the lights turn off. This occurs when there is no phase difference between the inverter and the grid, meaning the current is balanced, indicating that synchronization has been achieved.

On top of these methods, some Synchronization Control Algorithms are a bit more advanced and achieve and maintain grid synchronization.
Some of them that work together are:

- **Proportional-Integral-derivative (PID) control**: PID control algorithms regulate the inverter's output voltage and frequency by minimizing the error between actual grid parameters and target values, offering stable and precise synchronization even as grid conditions change [8].

- **Phase-Locked Loop (PLL)**: PLL algorithms measure the phase difference between the inverter's output and the grid voltage, then adjust the inverter's phase angle to reduce this mismatch, offering fast and reliable synchronization commonly used in grid-connected inverters [8].

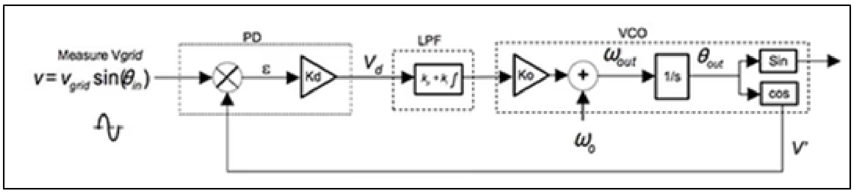


Figure 13: PLL block diagram [8].

- **Droop Control**: Droop control algorithms modify the inverter's output frequency in response to deviations in grid frequency, mirroring the behavior of synchronous generators to help maintain grid stability [8].

- **Virtual Synchronous Generator (VSG) Control**: Virtual Synchronous Generator (VSG) control is a modern synchronization approach that replicates the operation of conventional synchronous generators in solar inverters connected to the grid. VSG algorithms mimic the inertia and damping properties of traditional machines, allowing inverters to deliver inertial support and frequency regulation like those provided by conventional power plants [8].

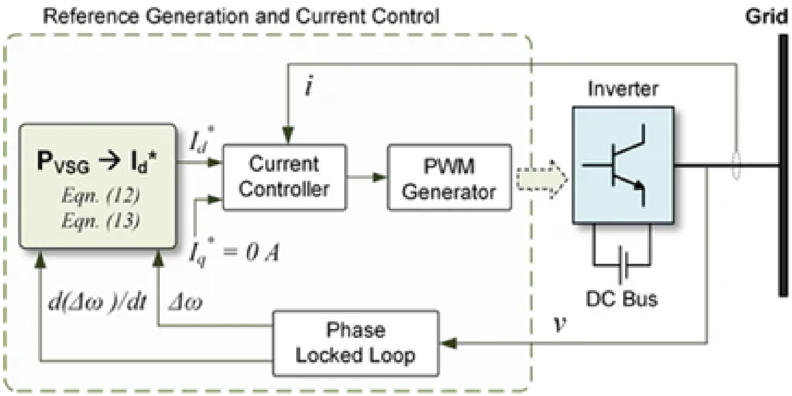


Figure 14: VSG block diagram [8].

There are, of course, more grid synchronization techniques, a comparison of which can be found in Figure 15:

S No.	Synchronization methods	Merits	Demerits
1.	Zero crossing detection (ZCD)	• Used for both single and three-phase. • Easy to implement. • Robust to frequency variations	• Poor performance in the presence of harmonics. • Noise sensitive
2.	Discrete Fourier transform (DFT)	• Utilized for both single-phase and three-phase • Used for harmonics detection • Stable in distorted environment. • Immune to noise	• Not suitable for unbalanced condition.
3.	Kalman-filter (KF)	• Utilized for both single-phase and three-phase. • Accurate during variation in frequency.	• Not used for harmonic detection. • Complex structures • Complex calculations
4.	Weighted least square estimation (WLSE)	• Measure time varying frequency • Easy implementation • Fast and robust	• Do not detect harmonic
5.	Adaptive notch filter (ANF)	• Used for both single phase and three phase. • Used for harmonic detection. • Easy to implement • Fast transient response	• Slow adaption process
6.	Phase-locked loop (PLL)	• Used for both single and three phase. • Used for harmonic detection. • Easy to implement. • Very accurate.	• Not accurate in unbalanced condition.
7.	Frequency locked loop (FLL)	• Used for three phase. • Used for harmonic detection and harmonic elimination. • Reliable to variation in frequency, voltage and harmonics.	• Not used for single phase • High computation • To the phase error signal, double frequency oscillations are introduced.

Figure 15: Grid Synchronization methods comparison table. [9].

Grid synchronization and anti-islanding protection are vital components in decentralized photovoltaic (PV) systems, and their importance is even greater than in centralized systems. Grid synchronization ensures that each inverter's output matches the grid's voltage, frequency, and phase. In decentralized systems, where multiple smaller inverters are on rooftops and buildings, maintaining synchronization is more challenging due to the lack of centralized control and the electrical sensitivity of local grid segments. Poor synchronization can lead to voltage instability, power quality issues, and grid disturbances. Equally, anti-islanding protection is also critical, which detects when the grid is down and disconnects the PV system to prevent it from unintentionally powering a local portion of the grid. This function is crucial in decentralized systems because each inverter operates independently, and failure to disconnect can pose serious safety risks to utility workers and threaten system stability. In contrast, centralized systems can manage these tasks more easily through centralized coordination and single-point control, making decentralized protection strategies more demanding and complex but essential.

9 Relevance for PV Smart Box

Most of the abovementioned techniques and controls could be either implemented separately or are already included in components like the inverter. For example, most grid-connected inverters like the ones from Sunsynk [10] already include components such as DC-DC converters and MPPT logic. However, since these are nothing but software and hardware combinations, most of them could be implemented separately. For example, in the paper of [11], a microcontroller-based islanding detection system was developed in a laboratory. Figure 16 shows the system block diagram of the whole system, while Figure 17 exhibits the actual components and circuitry of the system.

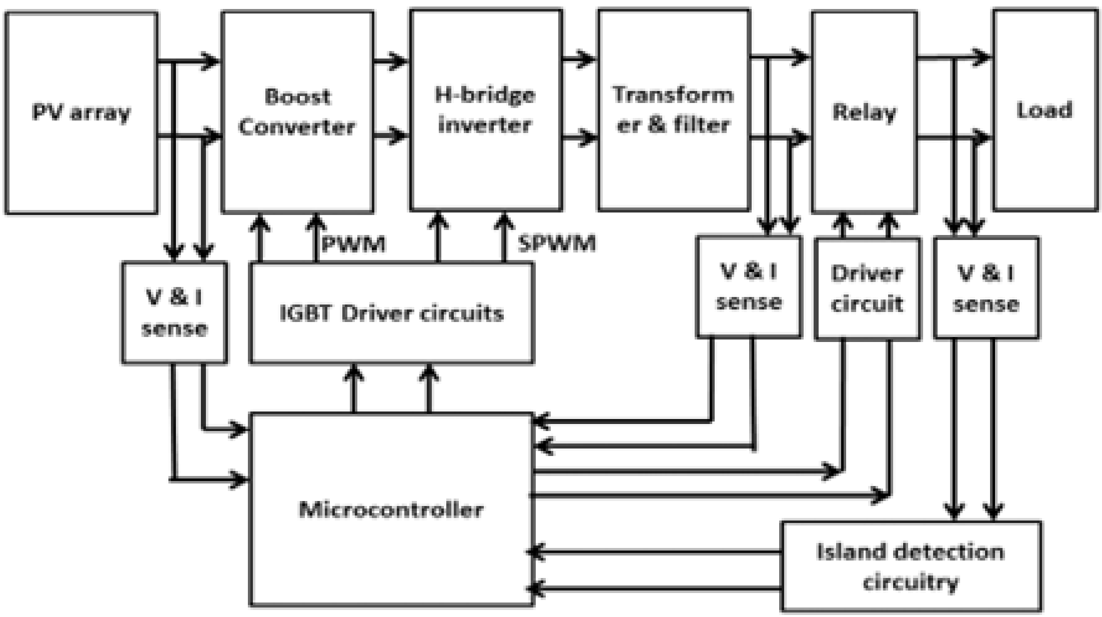


Figure 16: Islanding system block diagram [11].

Most of these components, such as the Boost converter, the inverter, etc, are already discussed in the research section above. Therefore, such controls and algorithms could be implemented in our PV smart box vision. However, as shown in Figure 17, such implementations could be complex and take a lot of space, meaning that the size of the box automatically will need to increase. Also, in case of self-implementation of such systems, it is clear from Figure 16 that the circuitry will need to be wired to different sensors (eg, V, I) and components (PV Array) and therefore located close to them and not inside the house. The flow chart of the software logic is shown in Figure 18.

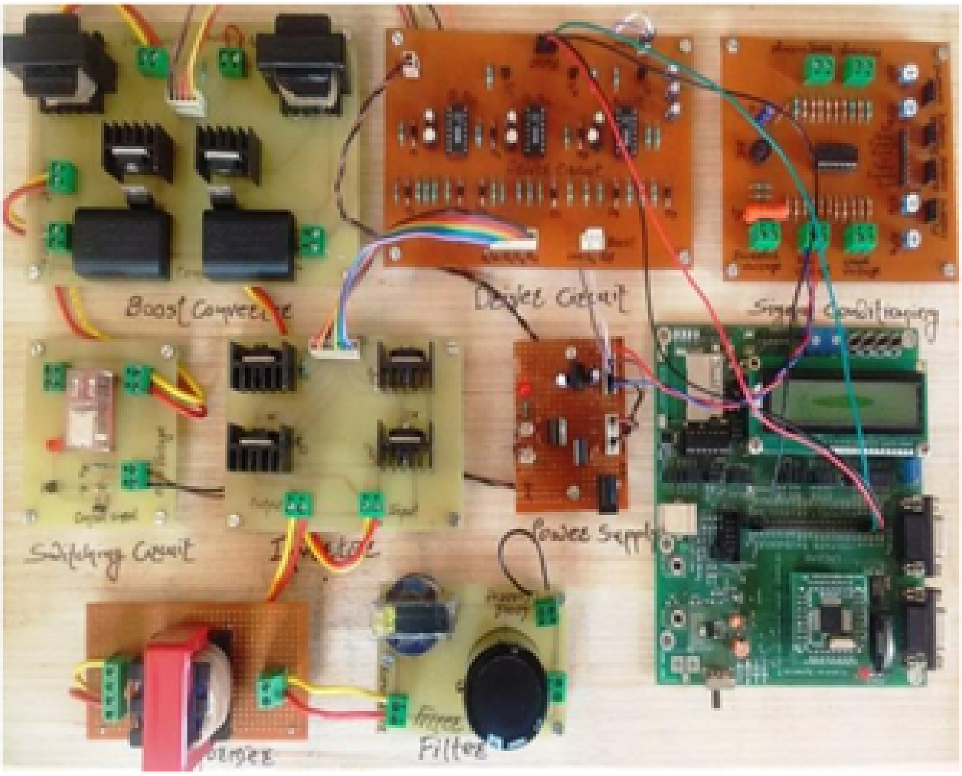


Figure 17: Islanding system block diagram [11].

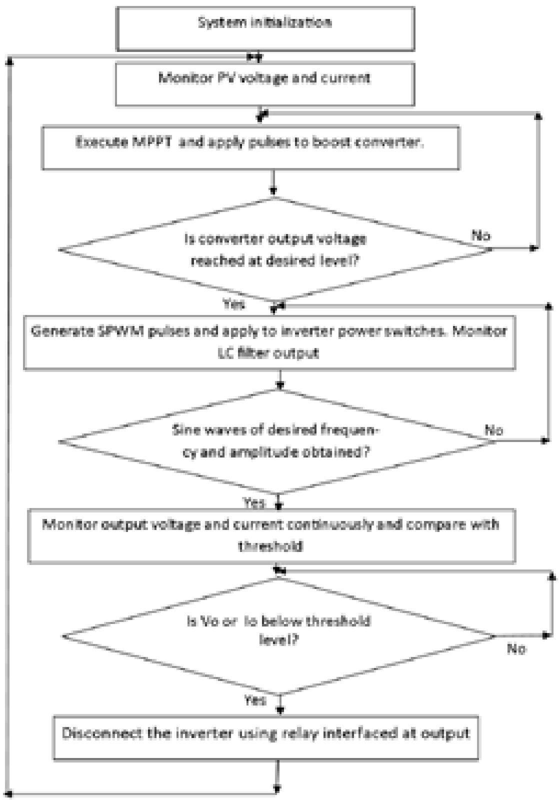


Figure 18: Islanding software implementation [11].

Similarly, a grid synchronization example is explained in [12], the lab prototype of which is seen in Figure 19. In this control implementation, the PLL and PID controls that were mentioned in the grid-synchronisation section are used.

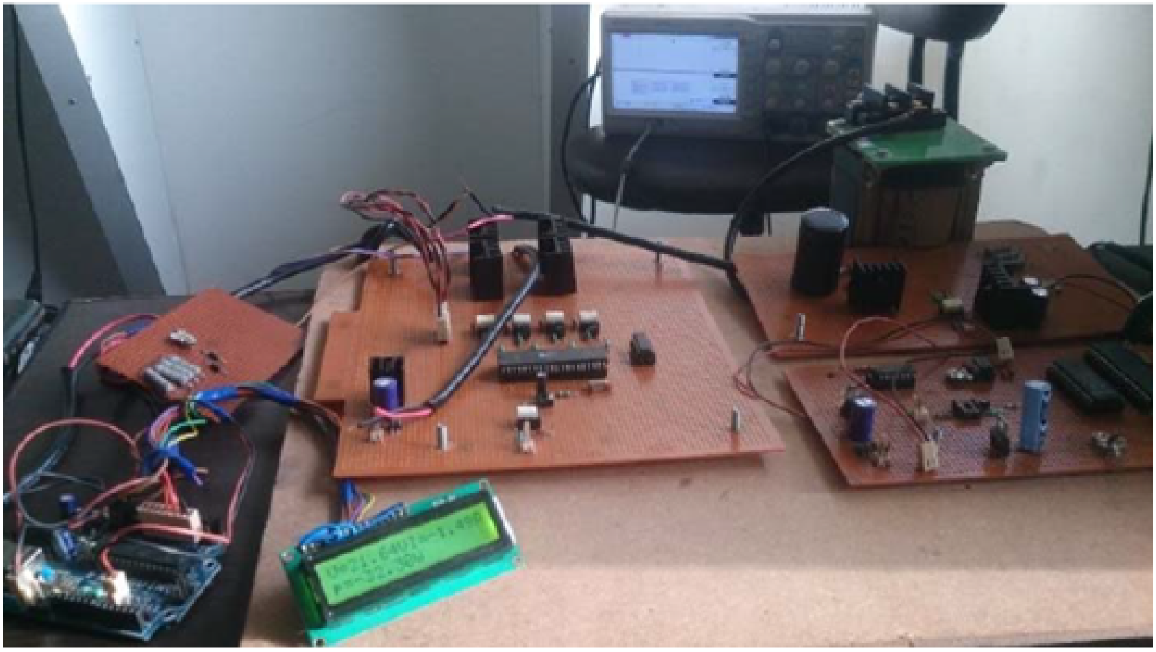


Figure 19: Grid synchronization in-lab prototype [12].

These techniques could be developed fully by Biosphere Solar's Product Development group by choosing the right components and control strategies. However, from Figures 17 and 19, which include only controls related to power electronics (so not including congestion management techniques or battery management) the implementation in a domestic box will be bulky. Therefore, my proposal, being also influenced by [13], would be to keep the microcontroller that is going to take sensor data from the PV system close to the battery, PV panels, inverters, etc. This microcontroller will also be an MQTT client that will communicate with our MQTT broker (software-based). After that, a better-looking, more compact smart PV box could be used inside the house to facilitate monitoring of the whole system and even serve other functions, such as a home assistant or speaker. Since our vision includes Peer-to-peer Energy trading using blockchain technology, the data from the microcontroller will be sent to the cloud backend, where the blockchain smart contract handles the peer-to-peer trading logic. This cloud server acts as the MQTT broker that will receive the messages (sensor data) with a certain topic and publish them to any other MQTT client that is subscribed to that topic (including the Raspberry Pi itself, included in our domestic PV smart box).

10 Key takeaways for PV smart box project

In our design, we'd consider using a Buck-Boost topology since these converters are commonly used in photovoltaic (PV) systems due to their ability to efficiently handle the variable voltage output of solar panels, which changes with environmental conditions. Their key advantage is the capability to both increase and decrease voltage, enabling the system to deliver a consistent output regardless of whether the panel voltage is above or below the load's requirement. To add, a buck-boost converter is a highly suitable choice for rural photovoltaic systems in the Global South. Due to frequent fluctuations in solar panel output caused by environmental factors like dust, shading, and weather variability, the ability to both step up and step down voltage ensures a stable and reliable power supply. This is especially important in off-grid areas where consistent energy delivery is critical. Buck-boost converters also support flexible integration with different PV and battery configurations, making them ideal for low-cost, modular systems. Their efficiency and adaptability enhance system resilience and help maximize energy harvesting even under non-ideal conditions.

Regarding the inverter, our options vary since the exact inverter and its technology depend on each PV system and application. As shown in Figure 20, we could have central inverters, Micro inverters, string inverters, inverters with optimizers, and more. Having in mind that central inverters and central inverters with optimizers are usually ideal for large applications, at least for the first stage of the project, and the testing, we won't need them. On the other hand, microinverters have many advantages since they operate directly at each module, and one of their main features is the "plug and play" characteristic. However, since most of the time these inverters are expensive and since they are usually located very close or even on the module itself, it's not always easy to replace them in the field in case of need. Given the above, string inverters could be ideal for our project since we are considering still being connected to the grid (string converters are not compatible with off-grid systems since they detect the grid to work. They work in 1-phase configurations for small applications close to 6kW, which will be more than enough in a rural area house. Other than that, although shading part of the string affects the system's total efficiency, each string can independently be operated at its MPP. To add, ideally for our project, we will need bidirectional inverters (sometimes mentioned as hybrid). That is because bidirectional inverters play a key role in enabling energy trading in rural areas. By allowing two-way power flow, they let users not only consume but also export surplus energy to neighbours or the grid. This is essential for peer-to-peer energy trading systems, where households act as both producers and consumers. When combined with smart meters and blockchain, bidirectional inverters support real-time energy exchange, automated transactions, and better use of local renewable resources, making rural energy systems more flexible, reliable, and economically feasible.

As for the microcontrollers used, we will need one working as an MQTT client on the field side that will be capable of operating at harsh environments and connecting directly via the sensors to the panels and batteries, and another one that could communicate with the first one via MQTT and will act as both an MQTT broker and an MQTT client. The last one will be receiving data and monitoring the PV system. The microcontroller that will read sensor data should have a Wi-Fi capability to publish data over MQTT. Therefore, Raspberry Pi or ESP32 microcontrollers can be used [13]. To add, along with a proper casing at least IP65 and a cooling fan, ESP32 seems like a good option since it can operate between -40 °C and 125 °C according to their website. Since Wi-fi capability will also be needed for the microcontroller in the domestic PV smart box, again, we could use one of the two. Since ESP32 has lower power consumption, this could be the choice, especially if we want our domestic PV smart box to be wireless and rechargeable. However, since the domestic node will run both as MQTT broker and MQTT client controling and monitoring (or home assistant/speaker), we do not need to make the most robust choice, but the one with the best user interface and lowest cost, which, given the online documentation and the numerous projects available online, can be a Raspberry Pi board.

Therefore, in the proposed IoT architecture for PV system monitoring and the PV smart box, the ESP32 microcontroller is suggested as an MQTT client to collect real-time sensor data, such as voltage, current, and temperature. The ESP32 reads these values using connected field instrumentation devices and transmits the data using the MQTT protocol. A Raspberry Pi is suggested as the unit that will directly connect to the MQTT broker, using a lightweight broker such as Eclipse Mosquitto. Raspberry Pi will also act as a client that will be subscribed to certain topics that the ESP32 will publish, and therefore, monitoring via LEDs on the box will take place. This configuration provides a stable, local, and energy-efficient solution for managing MQTT topics and routing messages between devices. The Raspberry Pi offers sufficient computational power, runs a full Linux OS, and supports integration with dashboards (e.g., Grafana), making it ideal for acting as a local server in a PV monitoring environment. To add, Raspberry Pi handles great home assistant tasks and could easily connect the the LED bars that will be showcasing/monitoring the battery of the PV system. The PV smart box can be found on Figure 21

This separation of roles, where the ESP32 handles sensor-level acquisition and the Raspberry Pi handles MQTT messaging and system coordination, improves modularity, scalability, and resilience of the system, particularly in off-grid or remote deployments.

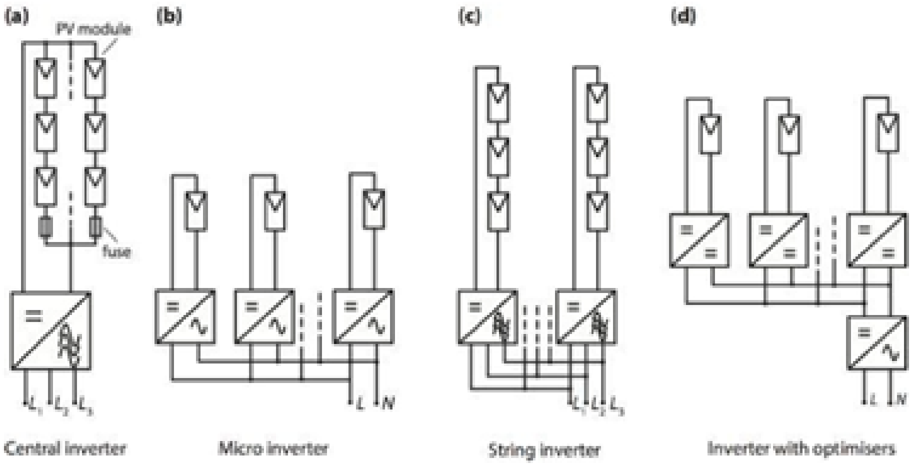


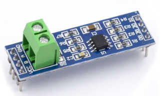
Figure 20: Different inverter system applications [12].

11 Physical connectivity

The proposed main components of the PV system and the PV smart box are presented in Table 1.

Table 1: On-field and PV Smart Box Main Components

Component	Function	Justification
 **ESP WROOM 32**	Module that contains the ESP32 microcontroller responsible for IoT and data collection from sensors (Voltage sensors, Hall effect sensor, etc)	• Built-in Wi-Fi and Bluetooth • Low cost (15 euros) • Dual-core CPU @ 80–240 MHz • Multiple GPIOs for real-time sensing • PWM, I2C, SPI, UART, ADC, DAC • Supports MicroPython, C/C++ • Low power (μW range) • Good MQTT client support • Robust under harsh conditions
 **Raspberry pi 4/5**	Microcomputer running the MQTT broker service (Mosquitto), acting as a local server that receives and routes data from ESP32 clients. Also acts as an MQTT client subscribed to sensor data from the ESP32 via MQTT, interprets the incoming values, and uses them to control LEDs, display information, or log data to a file. Housed inside the PV smart box.	• Runs full Linux OS (Raspberry Pi OS) • Supports Eclipse Mosquitto, Node-RED, Grafana • Python support for local processing • Always-on stable operation • Can log locally or push to the cloud • Low power consumption for a full server (5W), but higher than ESP32
Voltage sensors	For measuring PV and battery voltage	Crucial for real-time power and SoC estimation
Hall effect current sensor	For measuring PV-side current	Crucial for safe and accurate power calculation

Component	Function	Justification
Bidirectional inverter (better to go with an off-the-shelf solution for this purchase - ideally string inverter)	DC-to-AC and AC-to-DC for grid feed-in and battery charge via the grid	• Consumption and injection of power to the local grid or peers • Convert solar-generated DC power to AC for household use • Export surplus energy to other users or the grid, and charge batteries when needed
DC-DC buck–boost converter (can be self-implemented but most of the time it's inside the MPPT charge controller, which can also be located inside the inverter)	Step-up and step-down voltage functions	Adjusts to variable voltage because of weather fluctuations
 **MAX485 TTL to RS485 Converter Module**	bi-directional logic level shifter so the Modbus logic pin (5V) matches the ESP32 logic pin (3.3V).	• easy to connect • low cost • necessary for industrial-type sensors
 **bi-directional logic level shifter**	used to safely shift voltage levels (e.g., from 5V to 3.3V or vice versa) between the ESP32 (3.3V logic) and RS485 modules or sensors (often 5V logic) to prevent damage and ensure reliable communication.	• Easy to connect • Low cost • Necessary for ESP WROOM 32 connection to Modbus devices

Note: In case we want to develop our own electronic components, such as DC-DC controllers, then a few things about the complexity need to be taken into account. To operate a buck-boost converter, additional components beyond the main circuit are required. A gate driver circuit is necessary to control the switching device, such as a MOSFET or IGBT, by supplying the appropriate voltage and current. A PWM generator or controller is used to create the pulse-width modulated (PWM) signal that governs the switch timing, and this can be implemented using either analog controller ICs or microcontrollers. A feedback control loop continuously monitors the output voltage or current and adjusts the duty cycle to maintain regulation, typically by comparing the output to a stable voltage reference. In many designs, a soft-start circuit is included to limit inrush current during startup by gradually increasing the output. Protection circuits, such as overvoltage, over-current, and thermal shutdown mechanisms, ensure safe operation. An oscillator, often integrated into the controller, determines the switching frequency. In some cases, current mode control is also used to enhance stability and dynamic response, requiring additional current sensing elements.

Since our product is mainly developed for residential applications in rural areas, it is best for component protection purposes to use Modbus RTU communication between the sensors and the ESP32 development board.

12 System schematic

Figure 21 showcases the block diagram of the whole system.

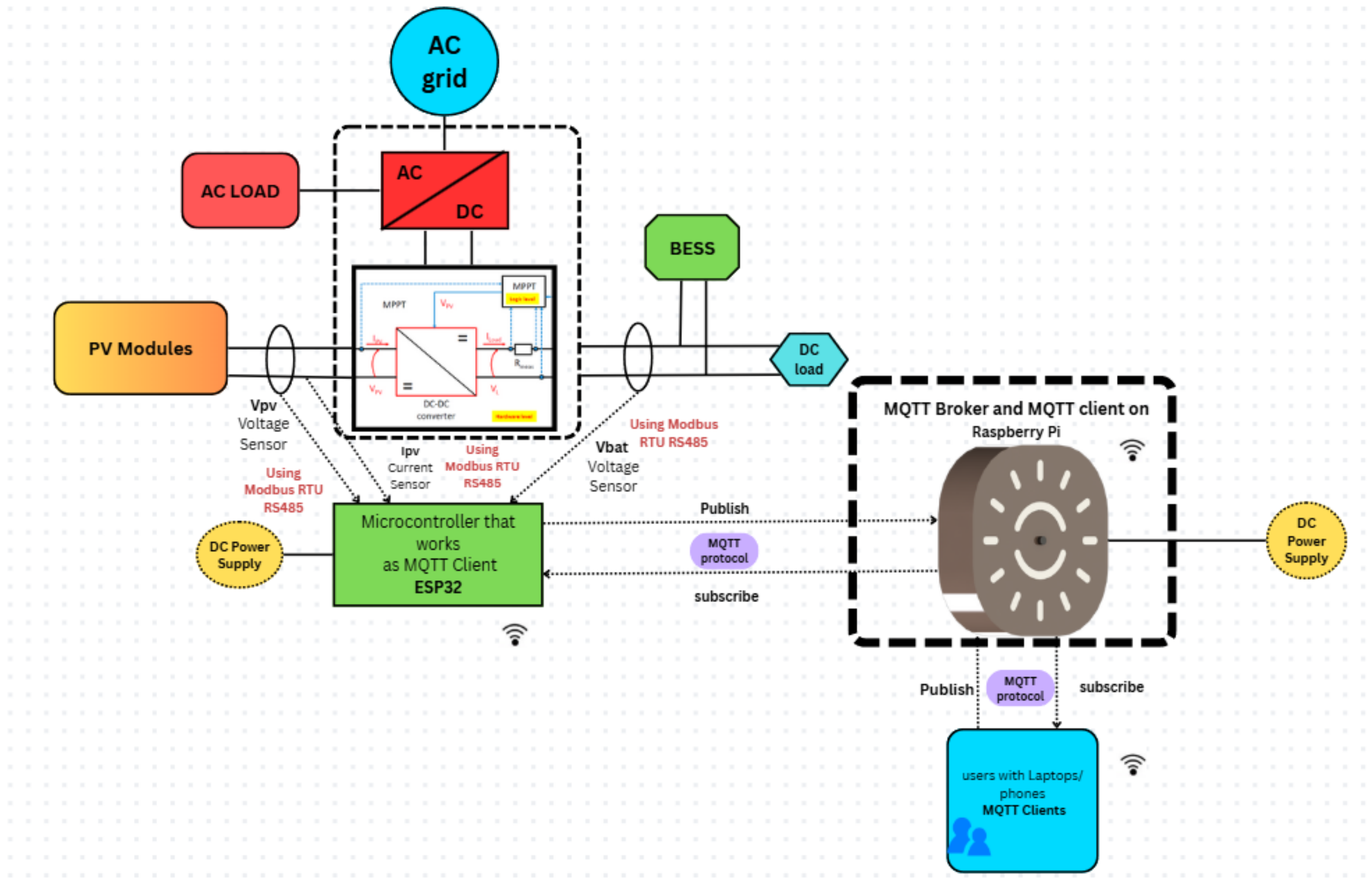


Figure 21: PV system schematic flowchart.

The physical connectivity between the sensors and the communication system is depicted in Figure 22. A MAX485 TTL to RS485 converter module is used to interface the RS485-based Modbus sensors, which normally run on 5V logic and employ differential A/B signal lines. The ESP32 microcontroller, which only supports ordinary UART communication, may connect to the RS-485 sensors thanks to this module. Because the ESP32 runs at 3.3V logic levels and the MAX485 utilizes 5V logic, a bi-directional logic level shifter is inserted between the two to provide a secure connection without causing harm to the ESP32. The ESP32 transforms sensor data into MQTT messages after it has successfully read sensor readings over the Modbus RTU protocol. The Raspberry Pi serves as the MQTT broker and MQTT client, while the ESP32 is set up to operate as an MQTT client. Raspberry Pi as an MQTT client will use its General Purpose Input/Output (GPIOs) based on incoming messages to control LEDs, trigger alerts, and more. The two devices interact wirelessly and will communicate using the MQTT protocol over Wi-Fi. All MQTT messages will be received by the MQTT broker in order for other devices that are subscribed to these topics to be able to access them. The Raspberry Pi serves as the backbone of the monitoring network and may be running an MQTT broker such as Mosquitto, while at the same time will act as an MQTT client to control actions.

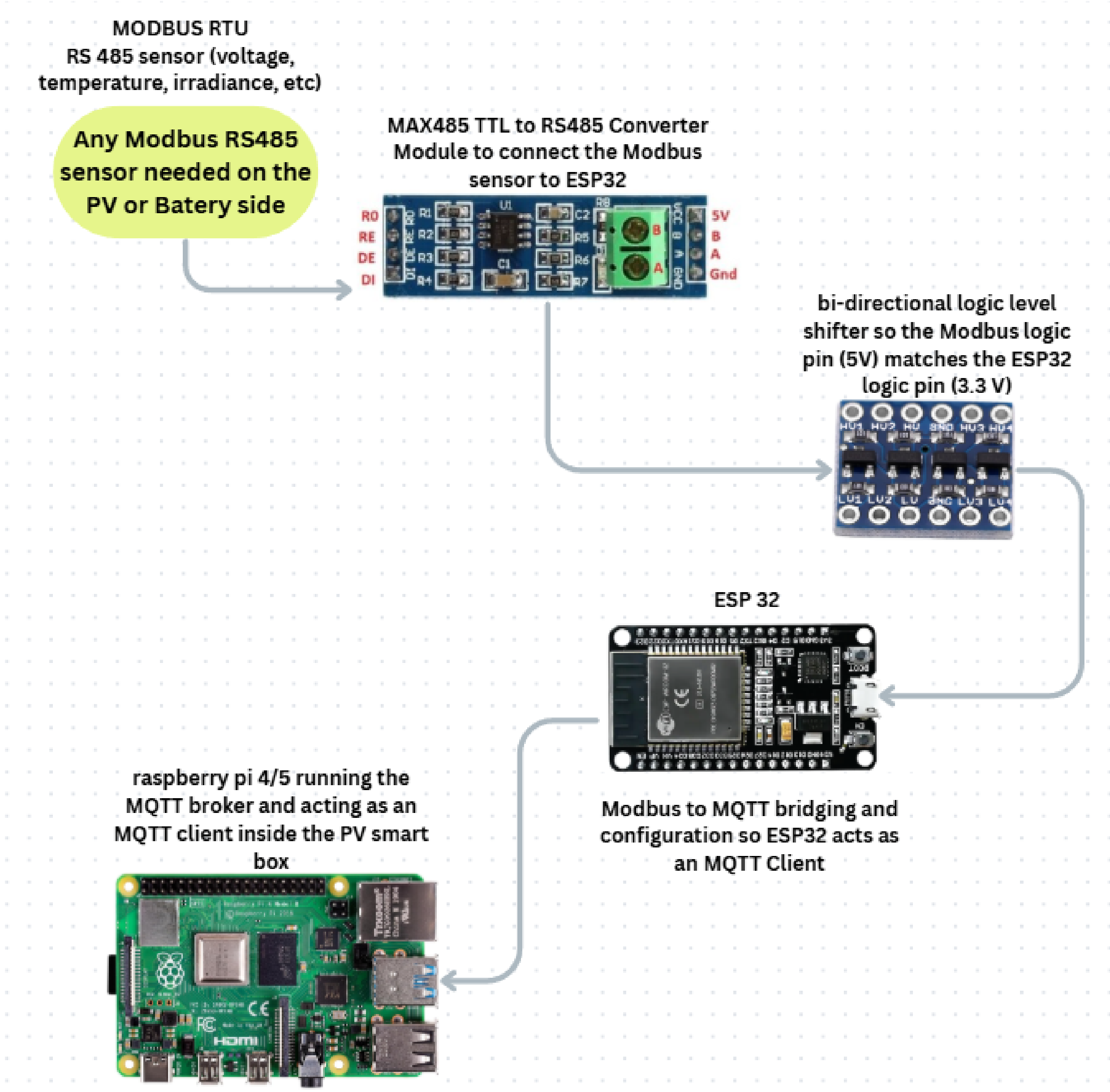


Figure 22: Modbus to ESP32 - Modbus to MQTT bridging.

12.1 MQTT publish-subscribe

The ESP32 reads values from connected sensors and, acting as an MQTT client, publishes messages to the MQTT broker running on the Raspberry Pi. The Raspberry Pi, which also functions as an MQTT client (e.g., using Python or Node-RED), subscribes to the same topic the ESP32 publishes to. This way, the Pi listens to the sensor data and, based on the received values, controls LEDs via its GPIO pins accordingly. Figure 23 presents how the MQTT publish-subscribe protocol works.

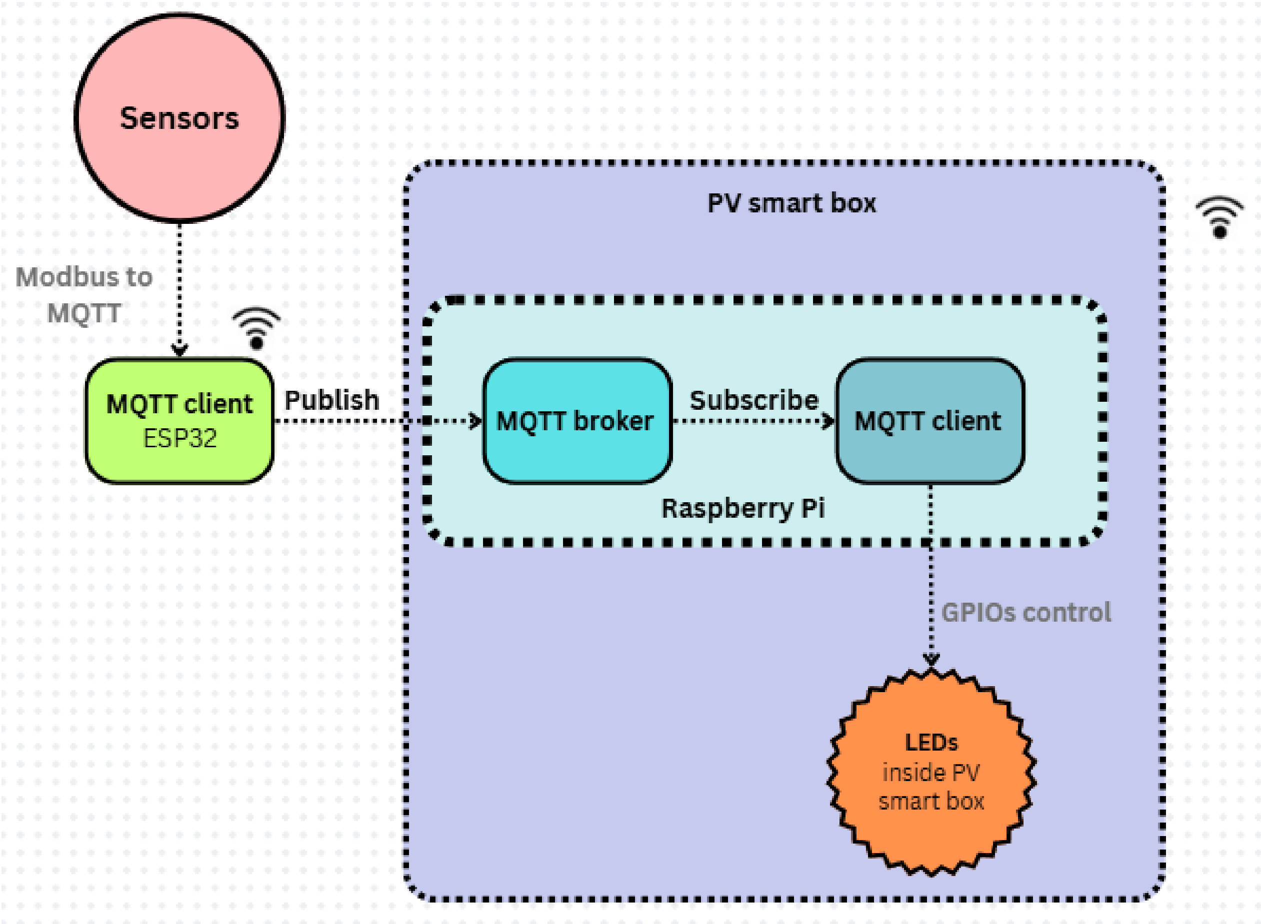


Figure 23: MQTT publish-subscribe protocol diagram.

12.2 MQTT publish-subscribe

The ESP32 reads values from connected sensors and, acting as an MQTT client, publishes messages to the MQTT broker running on the Raspberry Pi. The Raspberry Pi, which also functions as an MQTT client (e.g., using Python or Node-RED), subscribes to the same topic the ESP32 publishes to. This way, the Pi listens to the sensor data and, based on the received values, controls LEDs via its GPIO pins accordingly. Figure 23 presents how the MQTT publish-subscribe protocol works.

Every MQTT message has two important main components, which are the **topic** and the **payload**. The topic shows where the message is initially coming from and what it contains. E.g., PVsystem/voltage. Payload includes a string of characters describing what needs to be done for that specific topic. Given that, ESP32 will publish to a topic while being connected to the MQTT broker running on the Raspberry Pi. Then, the MQTT client (Raspberry Pi as MQTT client) that is subscribed to that message will "listen" to it and act accordingly [14].

12.3 OpenRemote integration

Higher-level system logic, including asset modeling, dashboard visualization, alerting, and maybe rule-based control, would be managed by OpenRemote once it is incorporated. Thus, although data coordination, monitoring, and user engagement take place in OpenRemote, sensor reading, edge computation, and actuation take place in real time on the device. This ensures fast response on the edge and centralized visibility in the platform.

13 Conclusion

From the analysis above, it is clear that many of the critical components and control strategies required for effective PV system operation—such as buck-boost conversion, MPPT algorithms, inverter functionality, islanding detection, and grid synchronization—can either be custom-developed or sourced from commercial solutions. While it is technically possible to build these power electronic systems in-house using microcontrollers and discrete components, doing so would significantly increase both complexity and development time. More importantly, the overall cost would become too high for a scalable and field-ready solution, especially considering the need for robust, compact, and long-lasting hardware suited to rural environments.

Therefore, it is more practical and cost-effective to use commercially available, integrated power electronics—such as bidirectional inverters and MPPT-enabled charge controllers—which already include many required functionalities in a reliable and compact form. Our efforts can be focused instead on developing the custom IoT-based monitoring and communication architecture (ESP32 and Raspberry Pi with MQTT), which adds flexibility and value without greatly increasing system cost or complexity. This balanced approach ensures that the PV Smart Box remains affordable, modular, and suitable for deployment in rural or off-grid areas.

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