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Professional paper

OPTIMIZING PHOTOVOLTAIC SYSTEM PERFORMANCE USING CT SENSORS WITH REAL-TIME MONITORING AND PI CONTROL

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Abstract

This study investigates the integration of current transformer sensors and Proportional-Integral control strategies to optimize the performance of grid-connected photovoltaic systems under regulatory power constraints. The system analyzed incorporates CT sensors to enable precise and real-time monitoring of currents in each of the phases, providing feedback for controlling energy flow. A Bluelog XC controller was used to implement a PI control algorithm and to maintain a fixed feed-in limit. Results from a real-world PV installation are shown in this paper and they demonstrate that the PI controller effectively regulated active power within ±1.5% of the target setpoint. Data analysis over daily and monthly intervals further confirmed precise system behavior. This work confirms the integration of CT sensors and PI regulation for enhancing energy management in PV systems offers a reliable approach to maintain performance and maximize self-consumption while staying within grid regulations.

Keywords: Photovoltaics, CT sensors, PID control, active power control, Bluelog XC, energy management.

1. Introduction

Photovoltaic systems have become a source of renewable energy solutions due to their ability to convert solar radiation into clean, sustainable electrical energy. Their adoption continues to rise globally as countries try to meet climate targets and reduce the use of fossil fuels and nuclear power plants. Despite their environmental advantages, PV systems present engineering challenges, particularly in maintaining operational efficiency and ensuring stable integration with the electrical grid.

Efficient energy management in PV systems depends on accurate, real-time information about the system's electrical behavior. For this purpose, Current Transformer sensors offer a practical and non-intrusive means of measuring alternating current in multiple points of the electrical infrastructure.

Active power control is one of the most important control strategies employed in grid connected PV systems. Its primary goal is to dynamically adjust the energy injected into the grid to maintain stability and meet regulatory rules. In many regions, regulatory energy authorities impose feed-in limits for prosumers. In the system analyzed in this study, a maximum grid feed-in power of 49 kW was enforced, requiring a control system capable maintaining such limits precisely and in real time (every 500 ms in our case). To achieve these requirements, this study utilizes a Proportional-Integral controller. This type of controller is a simplified variant of the more general PID controller but excluding the derivative term.

Electrical infrastructure is composed of KACO Siemens inverters, CT sensors and Bluelog XC controller and datalogger. Main objective of this work was to test integration of CT sensors and a PI closed control loop in maintaining system performance within regulatory feed-in constraints, while maximizing the use of locally generated solar power.This study demonstrates

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that sensors and monitoring, when combined with appropriately tuned PI controller, is a reliable strategy for optimizing the performance of photovoltaic systems.

2. Current Transformer Sensors (CTs)

2.1 Working principle: CT sensors work on the principle of electromagnetic induction and enable measurement of high current levels through safe and reduced signals rations. Their ease of installation, accuracy and robustness make them ideal for monitoring and feedback control strategies in electrical applications.

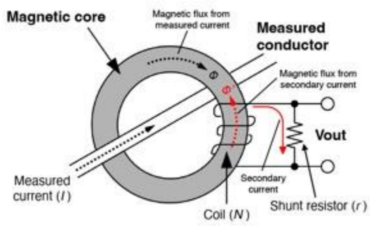

Figure 1. Working principle of CT sensors.

When current flows through a conductor, it creates a proportional magnetic field around the conductor. This is based on the principle of electromagnetic induction, more specifically with Farday's law of induction.

$$e = -N * \frac{d\phi}{dt}$$

e - Induced electromagnetic field (in Volts)
N - number of secondary turns (winding around the magnetic core), and
Φ - magnetic flux
Under ideal circumstances (lossless conditions), the current in primary and secondary windings follows this equation:

$$N_p I_p = N_s I_s \rightarrow I_s = I_p * \frac{N_p}{N_s}$$

Ip - primary current, Is - secondary current, Np and Ns - number of turns in primary and secondary coils.
In current transformers, since primary coil is actually the wire whose current is monitored, the number of coil windings is actually Np = 1. Considering the fact that most measurement devices that have analog inputs are only able to measure voltage and not current, we need a way to convert current into voltage:

$$V_{out} = I_s * R$$

Where R is the shunt resistor shown in figure 1.
2.2. CTs in our application: Since the case study of this paper is a three-phase system, each of the phases requires its own CT sensor to measure the current respectively. Below is attached a picture of these CT sensors that are used for this study.

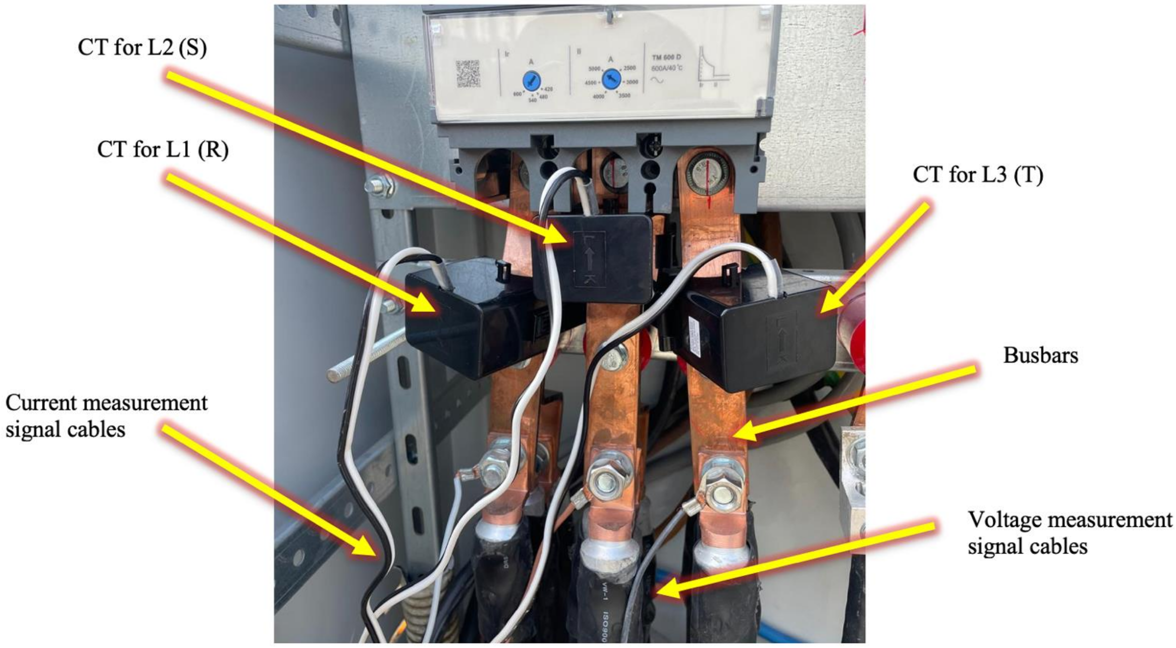

Figure 2. Current transformers in actual PV system.

3. Active power control in PV systems

3.1. PI vs PID in active power control: Proportional-Integral-Derivative (PID) controllers represent one of the most used strategies in modern automatic control systems. Their application ranges from temperature regulation and industrial automation to energy systems, including photovoltaic systems. PID controllers adjust the system output by comparing errors between desired setpoint and the actual measured value.

For PV systems, instead of the traditional PID structure, we commonly use Proportional-Integral (PI) form, which is more practical, simpler and offers better performance since Derivative part, while can predict future errors, it's also known to amplify noise in highly sensitive signals such as in our case. Due to inverter switching, load transients, or environmental changes, current and voltage signals may fluctuate rapidly and amplifying such noises with Derivative part can lead to control instability or oscillations.

The PI controller, by contrast, offers a robust and reliable balance between precision and simplicity. It consists of two main parts, the proportional term *Kp*, which reacts to the current error, and the integral term *Ki*, which accumulates past errors. In PV systems that operate with relatively predictable and slowly varying dynamics the PI controller is sufficient to correct deviations without inducing instability.

$$u(t) = K_p * e(t) + K_i \int_0^t e(\tau) d\tau$$

u(t) - the output control signal which is given to the inverter in our case

e(t) – computed error, difference between setpoint and actual value

Kp – proportional gain, and Ki – integral gain

To use PI regulator in digital controllers, such as in our case, we need to do discrete time interpolation and use trapezoidal approximation for the integral term:

$$u[k] = u[k-1] + K_p(e[k] - e[k-1]) + K_i T_s e[k]$$

Which can be simplified to: $u[k] = K_p e[k] + K_i T_s \sum_{i=0}^{k} e[i]$

Ts – Sampling time (in our case is 500ms)

k – discrete time steps.

3.2. Electrical system wiring schematics: CT sensors in PV systems are usually placed in the node where total energy consumption measurement is possible. For large and industrial applications, usually the best point to perform this measurement is the output of the transformer, and for smaller applications such as houses, the recommended point is right after electricity meter. For total energy consumption measurement, three CT sensors are required (as shown in figure 1). A general wiring diagram is provided below:

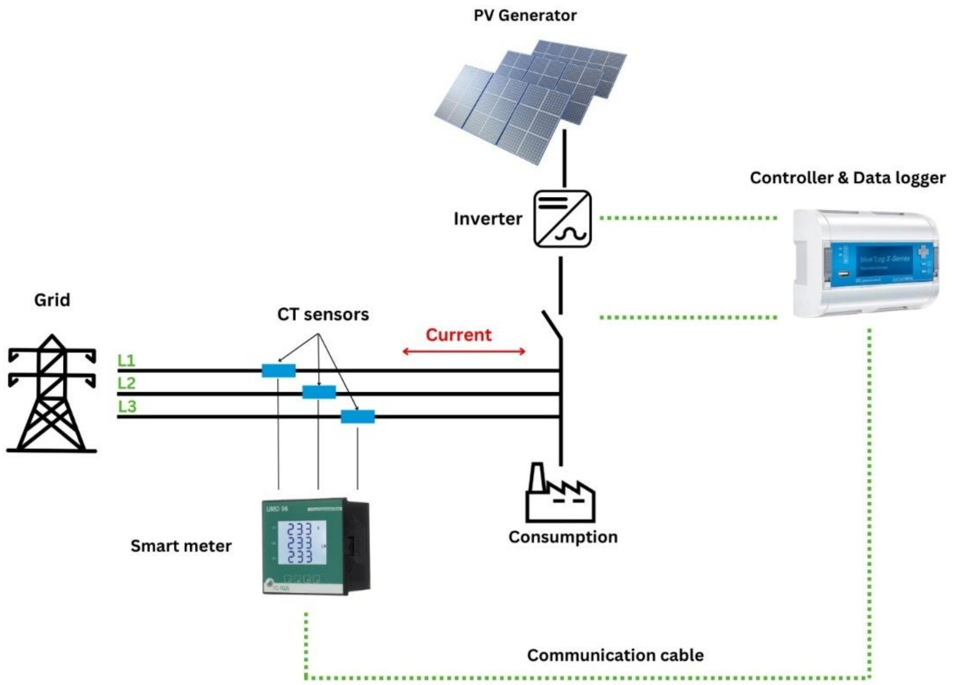

Figure 3. Electrical system wiring schematics.

In this diagram, is shown a plant which can be a factory or anything similar which consumes electricity, grid which supplies constant source of electricity, PV generators which supply a source of electricity when there is enough solar irradiance, CT sensors, smart meter as well as Bluelog XC controller and data logger.

CT sensors here serve as reference elements, they measure the amount of energy being consumed and send this information to the controller, which then determines how much solar energy needs to be produced to match the consumption. If the consumption is not fully covered, the system needs to draw additional energy from the grid. Otherwise, if the consumption is lower than the potential production of the photovoltaic system, the controller instructs the inverters on how much energy to clip to meet energy regulatory rules and requirements.

*3.3***.** Real-time monitoring and data logging: Because of the use of CT sensors, by using devices such as Bluelog, we can measure and send data straight to the cloud in real time. When we have data on the cloud, we can also store these data (log them) for later analysis.

Firstly, base values for *Kp* and *Ki* were set, then the system was tested on a real environment and working conditions, because of the data logging capabilities, we were able to analyze the performance of the system and tune *Kp* and *Ki* parameters respectively to achieve a better performance. After a few iterations of changes and parameter tuning, we were able to achieve optimal system performance which we can back by actual data.

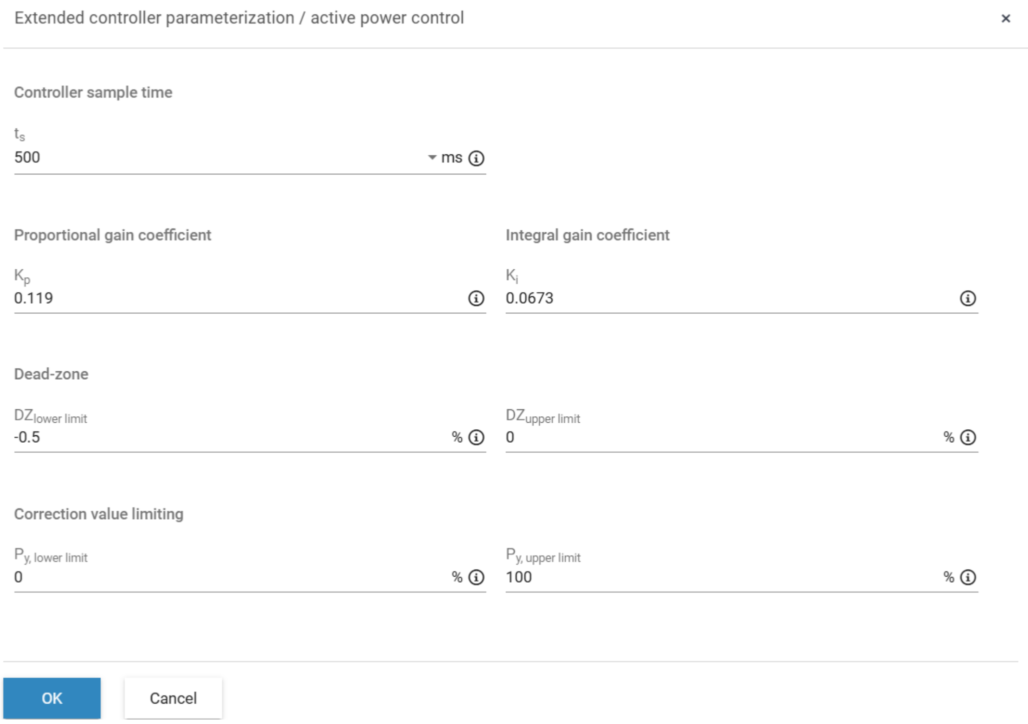

Figure 4. Optimal PI values shown in controller parametrization page.

ts = 500 ms – Sampling time of the controller which updates its calculations every 500 ms.
Kp = 0.119 – Proportional gain.
Ki = 0.0673 – Integral gain to ensures gradual correction of accumulated errors.
Dead zone – The range where small errors do not trigger corrective actions.
Py upper limit – Restricts the controller's output within safe bounds: from 0% to 100% in this system.

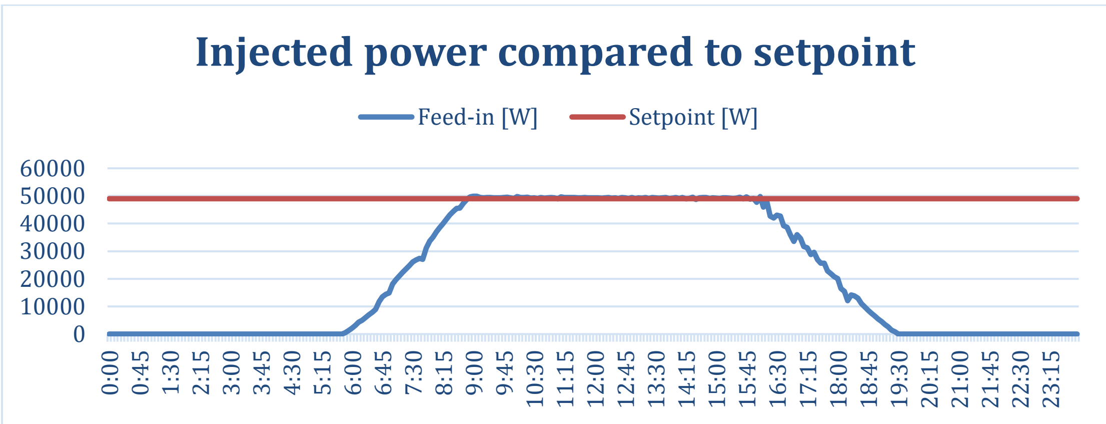

Figure 5. Analysis of the system performance compared to setpoint.

When analyzing the system performance from logged data we can clearly conclude that the system performance is optimal and it's never exceeding (overshooting or undershooting) by more than ±1.5%.

4. Data analysis

Data analysis is essential for evaluating efficiency of PV systems, comparing how much generated energy is self-consumed versus how much is fed into the grid. It also identifies consumption trends and optimization opportunities for improving energy balance and reducing grid dependency. Below is attached a picture of the analyzed system during the entire day.

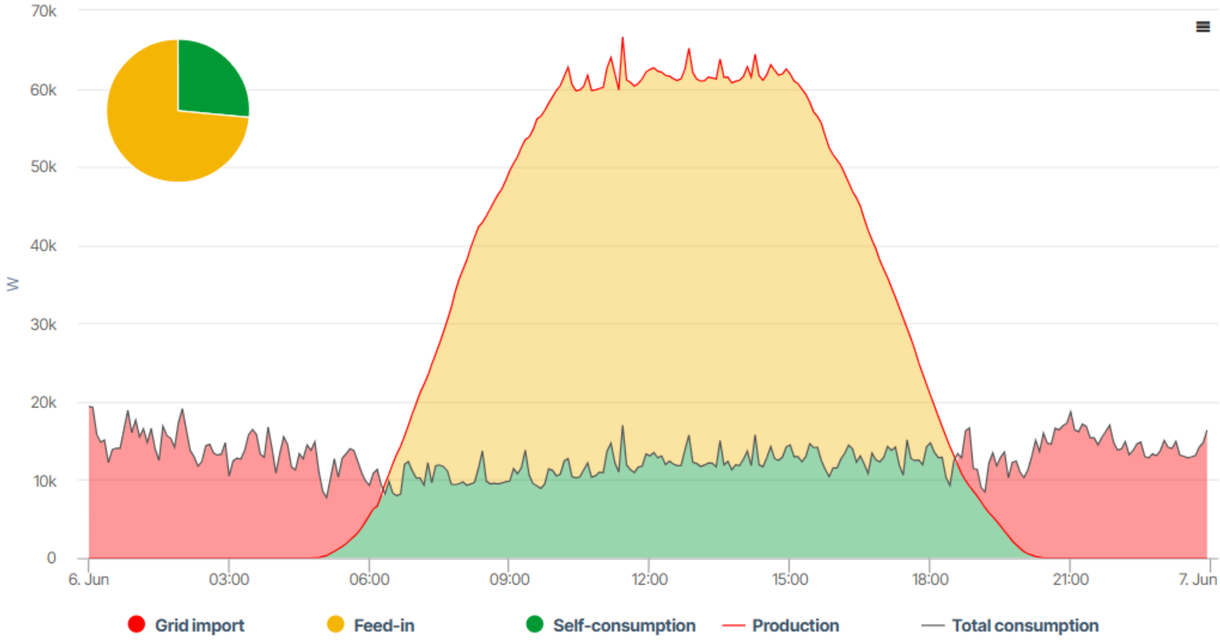

Figure 6. Daily energy flow of the system.

We can zoom-in and analyze each point in the graph in greater detail. For example:

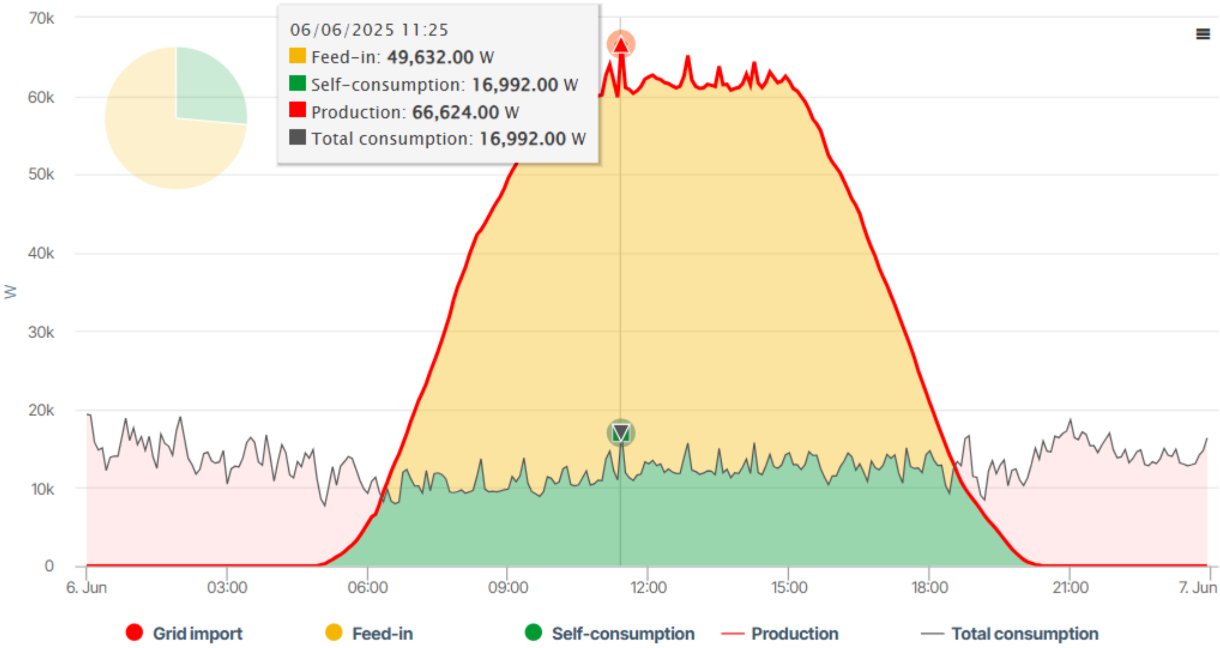

Figure 7. Detailed graph analysis at a certain time.

At first glance, it might look like the spike is overshooting our setpoint, but in actuality, it's within limits. The reason behind this spike is a rapid increase on demand current (by 5kW) in a short time frame, and PI controller has responded to it within 500ms.

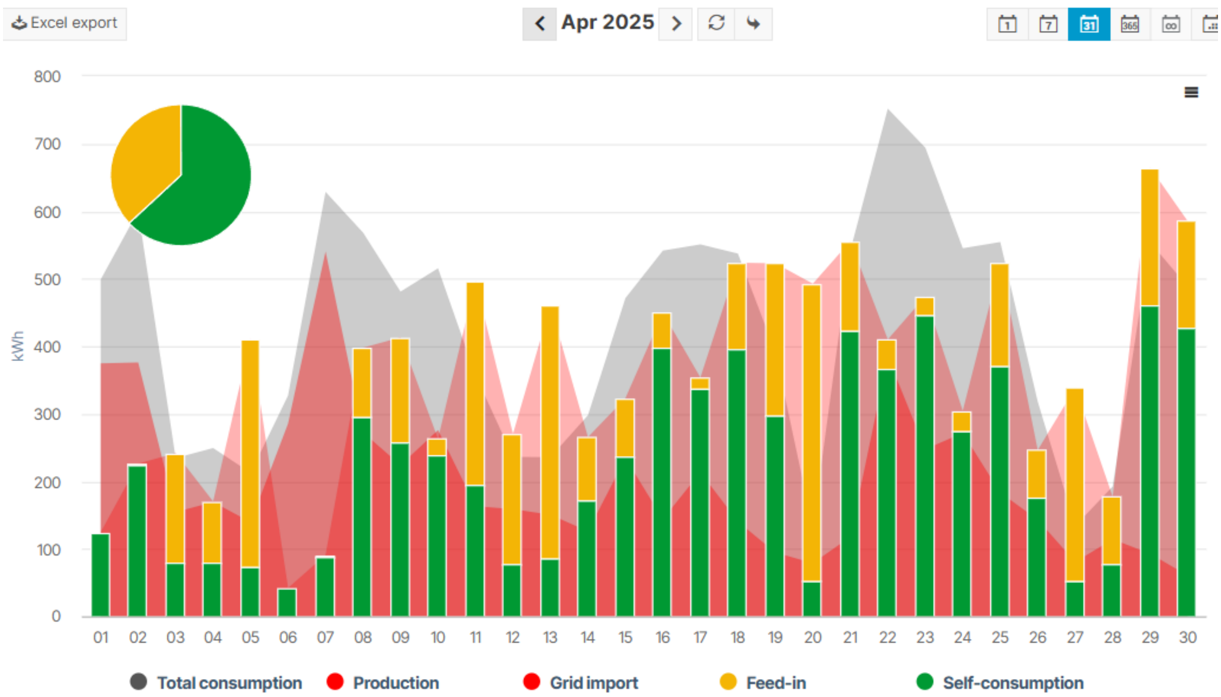

Figure 8. Monthly energy flow of the system.

Detailed view of production, grid import, feed-in and self-consumption of the analyzed system for a period of one month. Every Sunday (6, 13, 20, 27) can be easily tracked by low self-consumption and high grid feed-in except for April 6th, when we can tell that there was low energy production due bad weather.

Figure 9. Energy flow in each of the phases respectively and total power (red).

On the above picture, we can tell the analyze flow in each of the phases respectively and total power shown in red. Every time the graph goes over zero, we are feeding power into the grid, and every time we are below zero, we are importing power from the grid.

5. Conclusions

The study investigated the integration of CT sensors for real-time monitoring and PI control within PV systems, to achieve optimal operational performance. CT sensors proved highly reliable for precise and real-time monitoring of essential system parameters, including total energy consumption, self-consumption, and grid feed-in. This accurate and timely data acquisition was critical for implementing effective active power control, ensuring compliance with regulatory constraints on energy feed-in.

The PI controller was effective in maintaining the desired setpoint, balancing the generation and consumption demands of the PV system. Analysis revealed that despite overshoots, the system stayed within ±1.5% of the targeted setpoint, indicating robust performance under typical operational conditions. Nevertheless, specific transient scenarios—such as rapid fluctuations in solar irradiance—did challenge the PI controller, leading to minor setpoint deviations.

While the PI controller showed great performance, its limitations during rapid irradiance fluctuations suggest potential benefits from exploring more advanced control methodologies, such as Model Predictive Control. Also, reducing the sampling time from the current 500 ms to a shorter interval may enhance responsiveness to dynamic system changes.

Overall, integrating CT sensors and accurately tuned PI controller contributed to have an optimized PV system performance.

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