OPTIMIZATION OF REACTIVE POWER MANAGEMENT IN INDUSTRIAL PHOTOVOLTAIC SYSTEMS USING SMART INVERTERS AND COMPENSATION UNITS: A REAL-WORLD CASE STUDY

Paulina Vukobratović[1]*,
[0009-0009-6573-3620]

Miloš Dobrojević[2]
[0000-0003-3798-312X]

[1]Elmag,
Subotica, Serbia

[2]University Singidunum,
Belgrade, Serbia

Correspondence:
Paulina Vukobratović

e-mail:
paulina.majnaric1@gmail.com

Abstract:

This paper investigates the optimization of reactive power management in an industrial facility supplied by a hybrid energy system consisting of a photovoltaic (PV) power plant and the distribution grid. The study focuses on minimizing excessive reactive energy consumption and improving the power factor through the application of advanced control strategies. An experimental analysis was conducted under real operating conditions using a 500 kW PV system. Measurements of active power, reactive power, and power factor were performed at 5-minute intervals across three distinct scenarios: 1) a conventional inverter without reactive power control, 2) a smart inverter with Volt-Var functionality, and 3) a combined solution integrating a conventional inverter with an automatic reactive power compensation system. The results show that the implementation of Volt-Var control reduces reactive energy consumption by approximately 41%, while the combined approach achieves a significant reduction of reactive energy exchange with the grid and maintains the power factor close to unity ($\cos\varphi \approx 0.99$). The findings demonstrate that hybrid control strategies significantly enhance both technical performance and economic efficiency by reducing utility penalties and improving overall operational conditions, with expected benefits in network efficiency and voltage stability. The main contribution of this work is a validated, measurement-based comparison of reactive power management approaches in a real industrial environment, providing practical guidelines for the optimal design and operation of PV-integrated systems.

Keywords:

Reactive Power Management, Photovoltaic Systems, Smart Inverters, Volt–Var Control, Power Factor Optimization.

INTRODUCTION

The global energy landscape is characterized by a continuous increase in electricity consumption, and an urgent need to reduce greenhouse gas emissions driven by climate change. In countries such as Serbia, where electricity generation still largely depends on coal, the energy sector faces significant environmental pollution and resource depletion [1], as well as issues related to grid stability and transmission losses. As a response, photovoltaic (PV) power plants have emerged as a viable solution, enabling clean and decentralized energy production while reducing the load on the overall power system [2].

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With the continuous reduction in technology costs and the availability of financial incentives, investments in renewable energy systems are becoming increasingly economically viable. At the same time, they contribute to improved energy independence. Furthermore, modern equipment, particularly advanced inverters, plays an important role in stabilizing local distribution networks and optimizing overall system performance. These developments have stimulated extensive research into both conventional and renewable energy sources, as well as improvements in energy efficiency and rational energy use [3].

In such systems, electricity is typically supplied by distribution companies, and consumers are billed based on their energy consumption. With the continuous increase in electricity prices, consumers are motivated to reduce their energy costs, while distribution operators aim to maintain a stable and reliable power supply.

2. REACTIVE POWER

One of the key challenges in this context is the management of reactive power. In alternating current systems, consumers require both active and reactive energy for proper operation. Active power represents the useful component of energy that performs work, while reactive power is necessary for the operation of inductive loads such as electric motors, transformers, and inductors, Figure 1. However, excessive reactive power leads to several negative effects, including increased current load on system components, higher voltage drops, and increased active power losses.

The efficiency of energy utilization is commonly expressed through the power factor (cosφ), defined as the ratio between active and apparent power. Ideally, the power factor should be close to unity, but in real industrial systems it is often significantly lower due to the presence of reactive loads.

When the power factor drops below a prescribed limit (typically cosφ = 0.95), distribution companies impose financial penalties for excessive reactive energy consumption. As a result, improving the power factor becomes both a technical and economic priority.

In systems that integrate multiple energy sources, such as photovoltaic generation combined with grid supply, the management of reactive power becomes more complex. In such hybrid systems, reactive power can be supplied either from the grid, generated by smart inverters, or compensated using dedicated compensation systems. Proper coordination of these elements is essential for ensuring stable operation, reducing energy losses, and minimizing operational costs.

Possible solutions for reactive power management include the installation of compensation systems when energy is drawn from the grid, as well as the utilization of reactive power capabilities of smart inverters in PV systems. In industrial applications where both energy production and consumption occur simultaneously, reactive power control becomes a critical factor in optimizing system reliability, efficiency, and equipment lifetime. For this reason, this study focuses on the experimental analysis of reactive and active energy consumption under different operating conditions, with the aim of identifying the most effective solution for reducing excessive reactive energy [4-7].

In order to achieve this objective, measurements were conducted under three distinct operating scenarios in a real industrial environment, enabling a comparative evaluation of different reactive power management approaches.

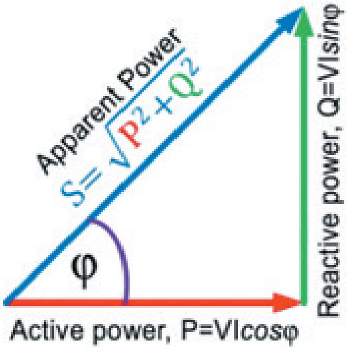

Figure 1. Active and reactive energy, and their interrelation

3. SYSTEM DESCRIPTION AND EXPERIMENTAL SETUP

The analyzed system represents a real industrial facility supplied by a hybrid energy configuration consisting of a photovoltaic (PV) power plant and the distribution grid. The PV system has an installed capacity of 500 kW and operates in a self-consumption mode, supplying part of the facility's energy demand while the remaining energy is drawn from the distribution network. The system is connected at the low-voltage level (0.4 kV), with transformation to the medium-voltage network (20 kV). The industrial process operates in two shifts, from 06:00 to 22:00.

The facility includes a range of electrical loads typical for industrial environments, such as production machinery, compressors, HVAC systems, lighting, and auxiliary equipment. These loads are predominantly inductive in nature, resulting in significant reactive power demand and reduced power factor.

To evaluate the impact of different reactive power management strategies, three distinct operating scenarios were defined:

- Scenario 1 - PV system operating with a conventional Huawei string inverter, model SUN2000-330KTL-H1 without reactive power control (Volt–Var function disabled) and without a reactive power compensation system. The inverter operates in passive mode, meaning that it does not contribute to reactive power regulation. Consequently, all reactive power demand is supplied by the grid, Figure 2.
- Scenario 2 - PV system operating with a smart inverter utilizing Volt–Var control, without an additional compensation system. The inverter actively participates in voltage and reactive power control through the Volt–Var characteristic Q(U), enabling dynamic generation or absorption of reactive power depending on network conditions [8], Figure 3.
- Scenario 3 - PV system operating with a conventional inverter in combination with an automatic reactive power compensation system. Reactive power is primarily managed by an automatic compensation system consisting of capacitor banks, contactors, and a power factor controller, while the inverter operates at a power factor close to unity, Figure 4.

3.1. MEASUREMENT SETUP

The measurement campaign was conducted using a three-phase network analyzer (PR 800, "Metrika"), installed at the point of common coupling within the main distribution board. The analyzer was connected via flexible current transformers placed on the conductors linking the PV system and the distribution grid, specifically on phases L1, L2, L3, and neutral (N). This configuration enabled direct monitoring of energy flows between the PV system, the grid, and the facility loads.

Measurements were performed with a temporal resolution of 5 minutes, recording the following parameters:

- active energy,
- reactive energy drawn from the grid,
- reactive energy supplied by the inverter,
- reactive energy supplied by the compensation system,
- power factor ($\cos\varphi$).

Each scenario was analyzed over a full working day under comparable operating conditions:

- Scenario 1: 08.12.2025, 06:00–22:00
- Scenario 2: 15.12.2025, 06:00–22:00
- Scenario 3: 16.12.2025, 06:00–22:00

3.2. DATA VALIDATION AND ACCURACY

The validity of the measured data was verified using fundamental electrical relationships. The apparent power S and power factor cosϕ were calculated based on measured active power P and reactive power Q, according to:

$$S = \sqrt{P^2 + Q^2}, \ \cos\varphi = \frac{P}{S}$$

The calculated values showed full agreement with the measured data across all observed intervals, confirming the correctness of the measurement setup and the accuracy of the acquired data.

Measurement reliability was further ensured by the use of a high-accuracy instrument and a consistent measurement configuration across all scenarios. The fixed installation point minimized external influences unrelated to the operational mode of the PV system. The chosen sampling interval provided sufficient temporal resolution to capture variations in load and generation.

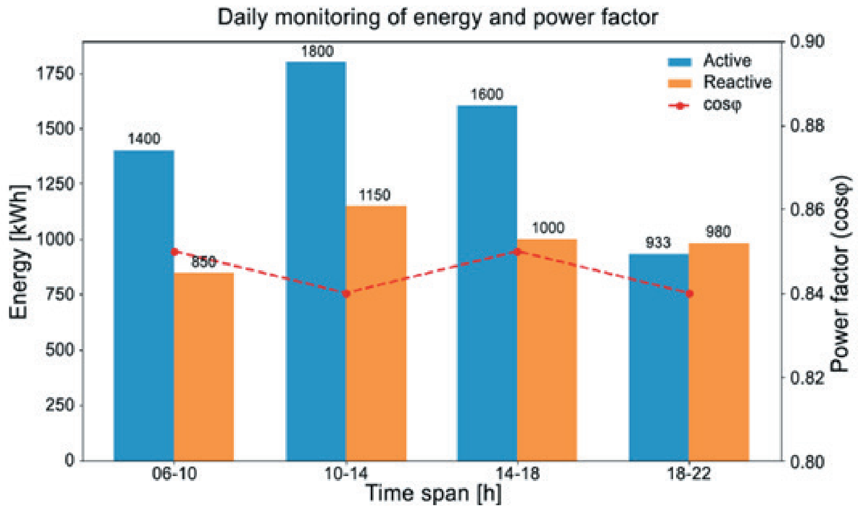

Figure 2. Scenario 1, active vs. reactive energy

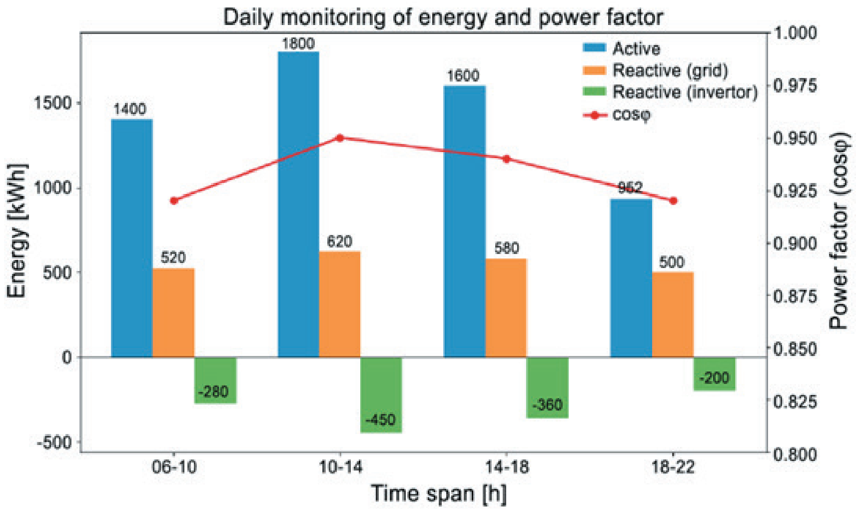

Figure 3. Scenario 2, invertor-absorbed reactive energy

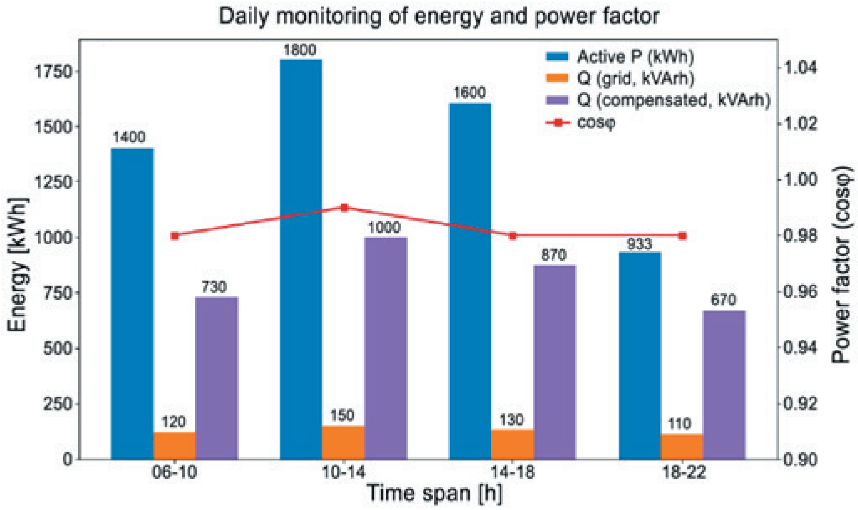

Figure 4. Scenario 3, compesation of reactive energy

3.3. LIMITATIONS OF THE STUDY

Certain limitations should be noted when interpreting the results. The measurements were conducted during December, which implies reduced solar irradiance and shorter daylight periods, potentially affecting PV system performance. Additionally, although measurements were taken during comparable working days, minor variations in industrial load profiles may introduce deviations in active power consumption.

The analysis is limited to the low-voltage level within the facility, meaning that effects on the medium-voltage network and transformer-level dynamics are not directly measured. Furthermore, the compensation system was dimensioned based on the conditions observed in Scenario 1 (225 kVAr), and the study does not consider extreme future load expansions that could require system reconfiguration.

Despite these limitations, the methodology provides a reliable basis for comparative evaluation of reactive power management strategies under real operating conditions.

4. RESULTS AND DISCUSSION

The experimental results provide a comparative evaluation of reactive power behavior and power factor performance across the three analyzed scenarios under real operating conditions, Figure 5.

In Scenario 1, where the inverter operates without reactive power control and no compensation system is installed, the system exhibits the least favorable performance. The power factor remains at a relatively low level (approximately cosφ ≈ 0.84–0.85), while reactive energy consumption reaches its maximum values, particularly during peak production hours (10:00–14:00). In this period, reactive energy demand exceeds 1000 kVArh, indicating a strong dependence on grid-supplied reactive power. Such operating conditions result in increased current loading, higher system losses, and financial penalties due to excessive reactive energy consumption. The absence of any local reactive power support confirms that conventional inverter operation does not contribute to voltage regulation or power factor correction.

In Scenario 2, the activation of the Volt–Var control function significantly improves system performance. The inverter dynamically generates or absorbs reactive power in response to voltage variations, leading to a noticeable reduction in reactive energy drawn from the grid. The results indicate a reduction of approximately 41% in reactive energy consumption compared to Scenario 1, while the power factor improves to values in the range of cosφ ≈ 0.90–0.95. Despite this improvement, the system does not fully eliminate excessive reactive energy, and occasional operation near the penalty threshold (cosφ = 0.95) is observed. This behavior highlights the inherent limitation of inverter-based reactive power control, particularly under varying load conditions and in the absence of dedicated compensation equipment.

In Scenario 3, the integration of an automatic reactive power compensation system yields the most favorable results. The compensation system, rated at 225 kVAr, operates in real time to maintain the power factor close to unity. The measured results show a drastic reduction in reactive energy drawn from the grid, with peak values reduced to approximately 150 kVArh during maximum load conditions.

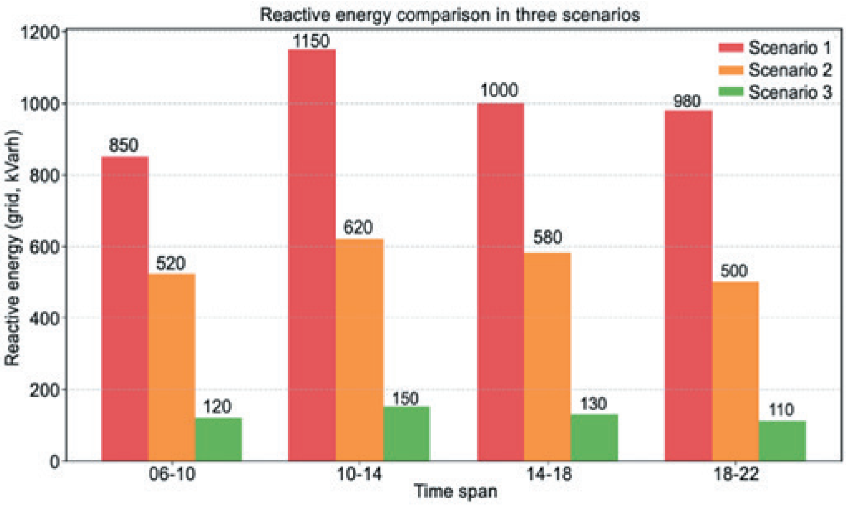

Figure 5. Reactive energy comparison in three given scenarios

The power factor consistently remains in the range of cosφ ≈ 0.98–1.00, effectively eliminating the risk of financial penalties. This configuration ensures stable voltage conditions, reduced current loading, and improved overall system efficiency.

A direct comparison of the three scenarios clearly demonstrates the progressive improvement in system performance:

- Reactive energy drawn from the grid is reduced from approximately 3780 kVArh/day in Scenario 1 to 2220 kVArh/day in Scenario 2, and further to 510 kVArh/day in Scenario 3.
- The power factor improves from 0.845 (Scenario 1) to 0.93 (Scenario 2), reaching 0.985 in Scenario 3.
- Financial penalties are present in Scenario 1, potentially present in Scenario 2, and completely eliminated in Scenario 3.

These results confirm that while smart inverter functionalities provide a meaningful improvement, they are not sufficient as a standalone solution in industrial environments with high reactive power demand. The combined approach, integrating inverter-based control with dedicated compensation systems, provides the most robust and technically optimal solution for reactive power management.

5. TECHNO-ECONOMIC ANALYSIS

The techno-economic evaluation is based on the energy consumption profile of the analyzed industrial facility and the measured performance of the three scenarios.

The facility operates approximately 16 hours per day over 250 working days annually, resulting in an estimated annual energy consumption of approximately 1,375,200 kWh after applying a simultaneity factor. The average monthly consumption is approximately 114,600 kWh, corresponding to an average load of 344 kW.

In Scenario 1, the low power factor (cosφ ≈ 0.85) leads to substantial financial penalties due to excessive reactive energy consumption. In addition to direct costs, the increased reactive power flow contributes to higher system losses and additional stress on electrical equipment.

Scenario 2 reduces reactive energy consumption and improves the power factor, resulting in partial mitigation of penalty costs. However, due to the variability of operating conditions and the absence of precise control over the power factor, the risk of penalties remains. Therefore, this scenario can be considered a cost-effective intermediate solution with limited performance.

Scenario 3 provides the most favorable economic outcome. The installation of a 225 kVAr reactive power compensation system ensures that the power factor remains above the required threshold (cosφ ≥ 0.95), thereby eliminating penalty charges entirely. Furthermore, the improved power factor reduces current loading, which in turn decreases system losses and contributes to extended equipment lifetime.

The required compensation capacity was determined based on measured conditions from Scenario 1. For an initial power factor of cosφ ≈ 0.85 and a target value of cosφ ≈ 0.99, the required reactive power compensation was calculated as approximately 164 kVAr. After accounting for voltage conditions and system expansion margins, the final installed capacity was selected as 225 kVAr.

Although Scenario 3 involves higher initial investment costs compared to the other configurations, the reduction in operational costs, elimination of penalties, and improved system efficiency result in a favorable return on investment. The combined use of smart inverter functionalities and compensation systems thus represents an economically justified solution for industrial applications.

6. CONCLUSION

This paper presented a comparative analysis of reactive power management strategies in an industrial facility supplied by a hybrid photovoltaic and grid-based energy system. The study was based on real-world measurements conducted under three operational scenarios, enabling a direct evaluation of system performance in terms of reactive energy consumption and power factor.

The results demonstrate that conventional inverter operation without reactive power control leads to high reactive energy demand, low power factor, and significant financial penalties. The implementation of smart inverter control through Volt–Var functionality improves system performance by reducing reactive energy consumption and increasing the power factor; however, it does not fully eliminate excessive reactive power.

The most effective solution is achieved through the integration of an automatic reactive power compensation system in combination with inverter-based control. This approach ensures near-unity power factor, minimizes reactive energy exchange with the grid, and eliminates penalty costs. In addition to economic benefits, such operation improves overall system conditions and supports more efficient utilization of electrical infrastructure.

The main contribution of this work lies in a validated, measurement-based comparison of reactive power management approaches in a real industrial environment. The results provide practical guidance for the design and optimization of hybrid energy systems, emphasizing the importance of combining inverter-based control with dedicated compensation systems.

Future work may include long-term measurements under varying seasonal conditions, as well as the integration of advanced monitoring and control platforms (e.g., SCADA and IoT systems) to further enhance system performance and enable predictive energy management. [9-11]

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