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Power Factor Improvement Using Grid-Connected Solar Photovoltaic Systems: An Approximate Real-World Analytical Study of an 11-kV Industrial Feeder

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تحسين معامل القدرة باستخدام أنظمة الطاقة الشمسية الكهروضوئية المتصلة بالشبكة: دراسة تحليلية تقريبية واقعية لمغذي صناعي بجهد 11 كيلوفولت

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Abstract:
This study evaluates the potential of a grid-connected solar photovoltaic (PV) system equipped with a smart inverter to improve power factor in electrical distribution networks. An approximate real-world analytical case study was developed for a balanced 11-kV industrial feeder, 8 km in length, supplying a 1,000-kW and 800-kVAr inductive load with an initial lagging power factor of 0.781. Four operating conditions were examined: the uncompensated base case, conventional capacitor-bank compensation, smart-inverter reactive-only compensation, and daytime smart-PV operation at 800 kW active output. The calculations show that improving power factor to 0.95 using a capacitor bank requires approximately 471 kVAr and reduces feeder current from 67.2 A to 55.2 A. Achieving a power factor of 0.98 through reactive-only inverter support requires approximately 597 kVAr. During daytime operation, a 1.2-MVA inverter producing 800 kW retains an estimated reactive capability of 894 kVAr, exceeding the approximately 759 kVAr required to maintain a 0.98 power factor at the point of common coupling. Under the stated feeder assumptions, the reactive-only smart-inverter case reduces approximate copper losses by 36.5%, while combined local PV generation and reactive compensation produce a substantially larger reduction in grid current and feeder losses. The results indicate that smart PV inverters can provide flexible, continuous power-factor correction and voltage support, while avoiding some limitations of mechanically switched capacitor banks. However, the numerical results are engineering estimates based on disclosed assumptions rather than field measurements or validated simulation outputs. The study therefore provides a transparent preliminary design framework that can be refined using measured load profiles and MATLAB/Simulink validation.

Keywords: Power factor correction; Solar photovoltaic systems; Smart inverter; Reactive power compensation; Distribution networks.

الملخص
تهدف هذه الدراسة إلى تقييم إمكانية تحسين معامل القدرة في شبكات التوزيع الكهربائية باستخدام منظومة خلايا شمسية مرتبطة بالشبكة ومزودة بعاكس ذكي قادر على حقن القدرة غير الفعالة أو امتصاصها. اعتمدت الدراسة منهجًا تحليليًا تطبيقيًا تقريبيًا يمثل مغذيًا صناعيًا متوازنًا بجهد 11 كيلوفولت وطول 8 كم، يغذي حملًا فعليًا مقداره 1000 كيلوواط و800 كيلوفار، بمعامل قدرة ابتدائي قدره 0.781 متأخر. تمت مقارنة أربع حالات تشغيل: الحالة الأساسية، التعويض بواسطة بنك مكثفات،

تشغيل العاكس الذكي لتعويض القدرة غير الفعالة فقط، والتشغيل النهاري المتزامن للمنظومة الشمسية بقدرة 800 كيلوواط مع التحكم في القدرة غير الفعالة. أظهرت الحسابات التقريبية أن رفع معامل القدرة إلى 0.95 بواسطة المكثفات يحتاج إلى نحو 471 كيلوفار، ويخفض تيار المغذي من 67.2 إلى 55.2 أمبير، في حين يحتاج الوصول إلى معامل قدرة 0.98 باستخدام العاكس الذكي إلى نحو 597 كيلوفار عند عدم إنتاج القدرة الفعالة. وفي التشغيل النهاري، يستطيع عاكس بقدرة اسمية 1.2 ميغافولت أمبير، عند إنتاج 800 كيلوواط، توفير ما يصل إلى 894 كيلوفار، وهي قيمة أعلى من الاحتياج المقدر البالغ 759 كيلوفار للحفاظ على معامل قدرة 0.98 عند نقطة الربط. وتشير النتائج إلى أن العاكس الذكي يمكنه تقليل التيار والهبوط في الجهد والخسائر النحاسية بصورة ملحوظة، مع مرونة أعلى من بنوك المكثفات. إلا أن النتائج تمثل تحليلًا هندسيًا تقريبيًا وليست قياسات ميدانية أو مخرجات محاكاة معتمدة. وتوصي الدراسة بالتحقق اللاحق باستخدام MATLAB/Simulink وبيانات أحمال فعلية.

الكلمات المفتاحية: : معامل القدرة؛ الخلايا الشمسية؛ العاكس الذكي؛ تعويض القدرة غير الفعالة؛ شبكات التوزيع.

1. Introduction

The growth of distributed solar photovoltaic generation is changing the operational role of power-electronic inverters. Solar PV is no longer viewed only as an active-power source; modern inverters can also regulate reactive power, support feeder voltage, and provide grid services. The International Energy Agency has identified solar PV as a principal driver of global renewable capacity expansion, reinforcing the importance of integrating PV in a manner that supports, rather than weakens, distribution-network performance (International Energy Agency [IEA], 2024).

Power factor is a basic measure of how effectively apparent electrical power is converted into active power. Industrial feeders commonly supply induction motors, transformers, compressors, pumps, welding equipment, and air-conditioning systems. These loads require magnetizing reactive power and consequently draw a higher current than would be necessary for the same active-power demand at unity power factor. Higher current increases conductor losses, voltage drop, transformer loading, and the required ratings of cables and protective devices (Bollen, 2000; Grainger & Stevenson, 1994).

Conventional correction methods include fixed or automatically switched capacitor banks, synchronous condensers, static VAR compensators, and STATCOMs. Capacitor banks remain attractive because of their low cost, but their compensation is discrete, they may be unsuitable for rapidly varying demand, and they can interact with network harmonics. In contrast, a voltage-source inverter can vary its reactive output continuously within its apparent-power capability. IEEE Std 1547-2018 formalized several functions relevant to distributed-energy-resource inverters, including voltage and reactive-power control (IEEE, 2018).

An important practical complication is that local PV active-power production can reduce the active power imported from the grid while the facility's reactive demand remains largely unchanged. The measured power factor at the point of common coupling may therefore deteriorate unless the inverter also supplies reactive power. Recent work has emphasized both the technical and financial implications of this effect in networks with high PV penetration (Dullius et al., 2024).

This paper presents a complete but deliberately transparent approximate case study. It does not claim to report field measurements or a validated dynamic simulation. Instead, it uses standard three-phase power equations, an explicitly defined industrial feeder, and sensitivity analysis to estimate the technical performance of smart-inverter compensation. This form of preliminary engineering analysis is useful for feasibility screening, equipment sizing, and identifying the measurements required before detailed design.

1.1 Research Problem

Industrial distribution feeders with low lagging power factor experience avoidable current, losses, and voltage drop. Although a PV system reduces imported active energy, unity-power-factor operation of the PV inverter does not compensate the facility's reactive demand and may worsen the apparent power factor recorded at the point of common coupling. The research problem is therefore to determine whether the unused apparent-power capacity of a suitably rated PV inverter can provide sufficient reactive support to improve the point-of-coupling power factor under representative industrial operating conditions.

1.2 Objectives

- Quantify the reactive compensation required to raise the power factor of a representative industrial feeder.
- Compare conventional capacitor-bank correction with continuous smart-inverter compensation.
- Evaluate feeder current, approximate voltage drop, and copper-loss changes under each operating condition.
- Examine how PV active output affects the reactive capability of the inverter and the feasibility of maintaining a 0.98 power factor.
- Provide a reproducible preliminary framework for later MATLAB/Simulink and field-data validation.

2. Literature Review

Reactive-power compensation is a long-established method of reducing current and improving voltage regulation. Classical power-system texts show that shunt capacitors supply leading reactive power locally and reduce the reactive component imported through the feeder (Grainger & Stevenson, 1994; Kundur, 1994). FACTS technologies provide faster and more continuous support but at higher capital and control complexity (Hingorani & Gyugyi, 2000).

Distributed PV introduces a controllable converter at the customer or feeder level. Smart-inverter studies have shown that Volt-VAR and power-factor control can improve voltage profiles and increase PV hosting capacity. Ding et al. (2017) evaluated autonomous Volt-VAR operation for voltage-reduction energy savings and power quality. O'Connell and Keane (2017) developed Volt-VAR curves for PV inverters, while Lee et al. (2020) examined optimal parameters for the Volt-VAR function.

NREL simulation and field-oriented reports found that advanced inverter functions can alter feeder voltage and reactive-power flow and that their settings must be coordinated with existing voltage-regulation equipment (Ding et al., 2016; Giraldez et al., 2018). More recent evaluations continue to treat smart inverters as practical distribution-management resources rather than passive interfaces.

Research has also highlighted limitations. Inverter reactive capability decreases as active output approaches the inverter's apparent-power rating. Therefore, reactive support at high irradiance may require inverter oversizing, active-power curtailment, storage, or coordinated operation with capacitor banks. Ismeil et al. (2023) compared improved inverter-control techniques for increasing PV hosting capacity, while Chathurangi et al. (2022) reviewed voltage-rise-constrained hosting-capacity assessment.

A further issue is billing power factor. Dullius et al. (2024) showed that PV penetration can influence low-power-factor penalties because active imports fall while reactive demand may remain. This strengthens the case for explicitly controlling inverter reactive power at industrial prosumer sites.

The literature supports smart-inverter compensation, but site-level feasibility depends strongly on load power, reactive demand, inverter size, PV output, feeder impedance, and the utility's power-factor definition. The present study contributes a transparent approximate analysis in which these quantities are shown directly rather than hidden within a simulation model.

Table 1. Critical comparison of relevant studies

Study	Year	Approach	Main contribution	Limitation
Ding et al.	2017	Autonomous Volt-VAR	Voltage and power-quality support	Feeder-specific settings required
O'Connell & Keane	2017	Volt-VAR curves	Reactive control for distribution voltage	Focus primarily on voltage
Lee et al.	2020	Volt-VAR parameter optimization	Improved smart-inverter settings	Model-dependent results
Chathurangi et al.	2022	PV hosting-capacity review	Identified voltage-rise constraints	Not a site-level PF design
Ismeil et al.	2023	Inverter control with storage	Higher hosting capacity	Added storage and control complexity
Dullius et al.	2024	PF penalties with PV	PV can worsen measured PCC PF	Tariff and jurisdiction dependent
Present study	2026	Approximate industrial-feeder analysis	Transparent PF and inverter sizing	Requires field/simulation validation

3. Theoretical Framework

3.1 Power Triangle and Power Factor

For a balanced three-phase system, active power P, reactive power Q, and apparent power S are related by:

$$S = \sqrt{P^2 + Q^2} \quad (1)$$

$$PF = P / S = \cos(\phi) \quad (2)$$

For a given active load, the reactive power associated with a selected power factor is:

$$Q = P \tan(\cos^{-1}(PF)) \quad (3)$$

3.2 Required Compensation

The compensation required to change the initial angle phi1 to the target angle phi2 is:

$$Q_c = P[\tan(\phi_1) - \tan(\phi_2)] \quad (4)$$

3.3 Three-Phase Current

$$I = S / (\sqrt{3}\, V_{LL}) \quad (5)$$

Reducing reactive power reduces S and consequently feeder current when active power and voltage remain constant.

3.4 Inverter Reactive Capability

$$Q_{inv,max} = \sqrt{S_{inv}^2 - P_{PV}^2} \quad (6)$$

Equation (6) defines the circular apparent-power limit. Reactive capability is greatest at low active output and decreases as PV output approaches the inverter rating.

3.5 Approximate Feeder Loss and Voltage Drop

$$P_{loss} = 3 I^2 R \quad (7)$$

$$\Delta V_{LL} \approx \sqrt{3}\, I (R \cos(\phi) + X \sin(\phi)) \quad (8)$$

These expressions are suitable for preliminary balanced-feeder estimation. A detailed load-flow model is required when loads are distributed, phases are unbalanced, conductor temperature varies, or voltage-dependent loads are important.

4. Materials and Methods

The study uses a deterministic analytical case rather than measured field data. All parameters are disclosed so that the calculations can be reproduced or replaced with site data. The selected values represent a medium-sized industrial facility rather than a specific named installation.

Table 2. Case-study assumptions

Parameter	Assumed value	Interpretation
Nominal line-to-line voltage	11 kV	Common industrial distribution level
Feeder length	8 km	Representative radial feeder
Total phase resistance	2.0 ohm/phase	Approx. 0.25 ohm/km
Total phase reactance	2.4 ohm/phase	Approx. 0.30 ohm/km
Active load	1,000 kW	Industrial peak operating point
Reactive load	800 kVAr	Inductive motors and transformers
Initial power factor	0.781 lagging	Calculated from P and Q
Capacitor target	0.95	Common contractual target
Smart-inverter target	0.98	High-quality operating target
PV inverter rating	1.2 MVA	20% above 1-MW PV nominal size
Daytime PV output	800 kW	Representative high-output condition

4.1 Evaluated Scenarios

Scenario 1. Base case: 1,000 kW and 800 kVAr imported from the grid with no compensation.

Scenario 2. Conventional capacitor bank: reactive power is reduced to the amount corresponding to PF = 0.95.

Scenario 3. Smart inverter, reactive-only mode: the inverter supplies the reactive compensation needed for PF = 0.98 while active PV output is zero or curtailed.

Scenario 4. Daytime smart-PV mode: local PV supplies 800 kW and the inverter supplies enough reactive power to maintain PF = 0.98 at the point of common coupling.

4.2 Scope and Validity

The calculations assume a balanced, sinusoidal, steady-state system. Harmonics, inverter switching losses, voltage-dependent load behavior, protection coordination, short-circuit strength, and dynamic controller response are outside the present scope. The study is therefore a feasibility-level engineering analysis. Its findings should not be interpreted as guaranteed field performance.

5. Results

Table 3. Approximate technical results

Scenario	Grid active power (kW)	Grid reactive power (kVAr)	Power factor	Line current (A)	Voltage drop (%)	Feeder copper loss (kW)
Base case	1000.0	800.0	0.781	67.2	3.240	27.1
Capacitor bank (PF=0.95)	1000.0	328.7	0.950	55.2	2.305	18.3
Smart inverter - reactive only (PF=0.98)	1000.0	203.1	0.980	53.6	2.056	17.2
Smart PV inverter - daytime (800 kW PV, PF=0.98)	200.0	40.6	0.980	10.7	0.411	0.688

5.1 Base Case

The uncompensated load has an apparent power of 1280.6 kVA and a power factor of 0.781. At 11 kV, the estimated line current is 67.2 A. With the assumed feeder impedance, the approximate voltage drop is 3.24% and the three-phase copper loss is 27.1 kW. These values provide the reference against which the compensation methods are compared.

5.2 Capacitor-Bank Compensation

To increase the power factor to 0.95, the grid reactive power must be reduced to 328.7 kVAr. The required capacitor-bank rating is therefore approximately 471.3 kVAr. The estimated current decreases to 55.2 A, a reduction of 17.8%. Approximate feeder copper loss decreases from 27.1 kW to 18.3 kW, corresponding to a reduction of 32.4%.

5.3 Smart-Inverter Reactive-Only Compensation

Maintaining PF = 0.98 for the original 1,000-kW load requires grid reactive power of only 203.1 kVAr. The inverter must therefore inject approximately 596.9 kVAr. The current falls to 53.6 A and estimated copper loss to 17.2 kW. Relative to the base case, this is a current reduction of 20.3% and a loss reduction of 36.5%.

5.4 Daytime Smart-PV Operation

At a PV active output of 800 kW, the facility imports only 200 kW of active power. To maintain a 0.98 power factor at the point of common coupling, grid reactive power should be limited to 40.6 kVAr, requiring inverter injection of approximately 759.4 kVAr. A 1.2-MVA inverter operating at 800 kW has an estimated reactive capability of 894.4 kVAr; therefore, the target is feasible with a margin of about 135.0 kVAr under the idealized steady-state assumptions.

The resulting grid current is approximately 10.7 A. The very large reduction compared with the base case is caused by both local active-power generation and reactive compensation. It should not be attributed solely to power-factor correction.

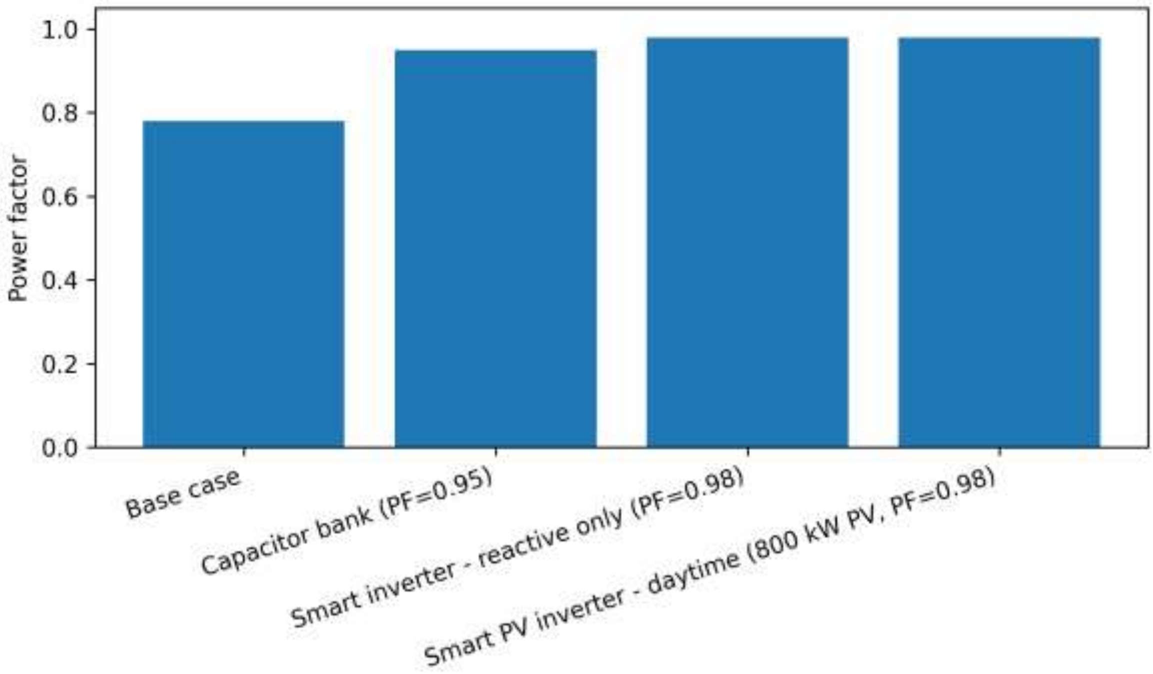

Figure 1. Approximate power factor under the evaluated scenarios.

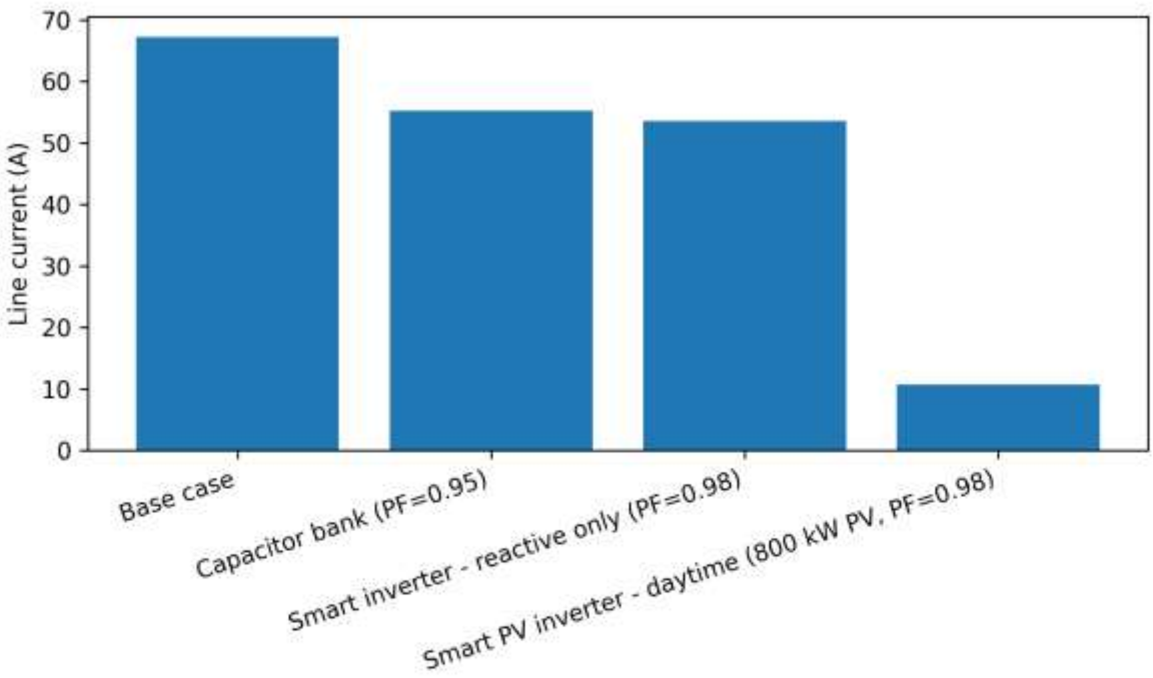

Figure 2. Approximate grid current under the evaluated scenarios.

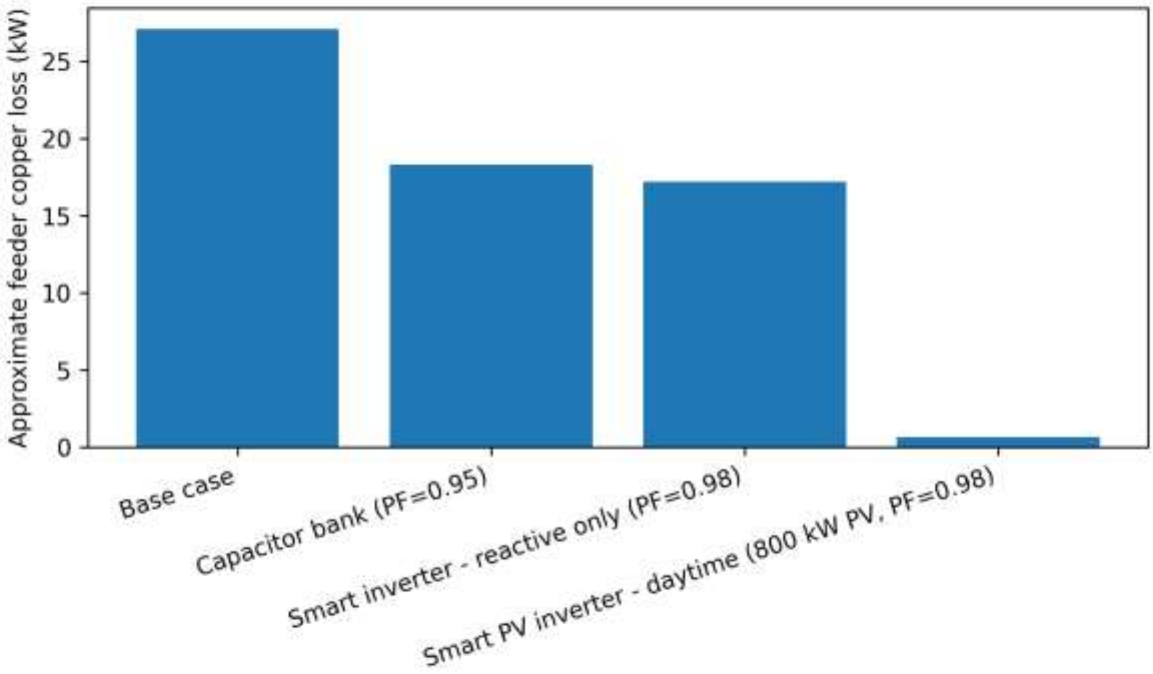

Figure 3. Approximate feeder copper losses under the evaluated scenarios.

5.5 Sensitivity to PV Active Output

Table 4. Sensitivity of reactive capability to PV active output

PV active output (kW)	Inverter Q capability (kVAr)	Q required for PF 0.98 (kVAr)	Q injected (kVAr)	Grid Q (kVAr)	Resulting PF	Target feasible
0	1200.0	596.9	596.9	203.1	0.980	True
200	1183.2	637.6	637.6	162.4	0.980	True
400	1131.4	678.2	678.2	121.8	0.980	True
600	1039.2	718.8	718.8	81.2	0.980	True
800	894.4	759.4	759.4	40.6	0.980	True
1000	663.3	800.0	663.3	136.7	-	False

The sensitivity results show that the 1.2-MVA inverter can theoretically maintain a 0.98 point-of-coupling power factor for PV outputs between 0 and 800 kW. At 1,000 kW active output, the available reactive capability falls below the 800-kVAr load demand, and active grid import approaches zero; under this condition, conventional power factor becomes an unstable or uninformative performance measure. A utility may instead specify reactive-power limits, displacement factor, or a Q(P) characteristic.

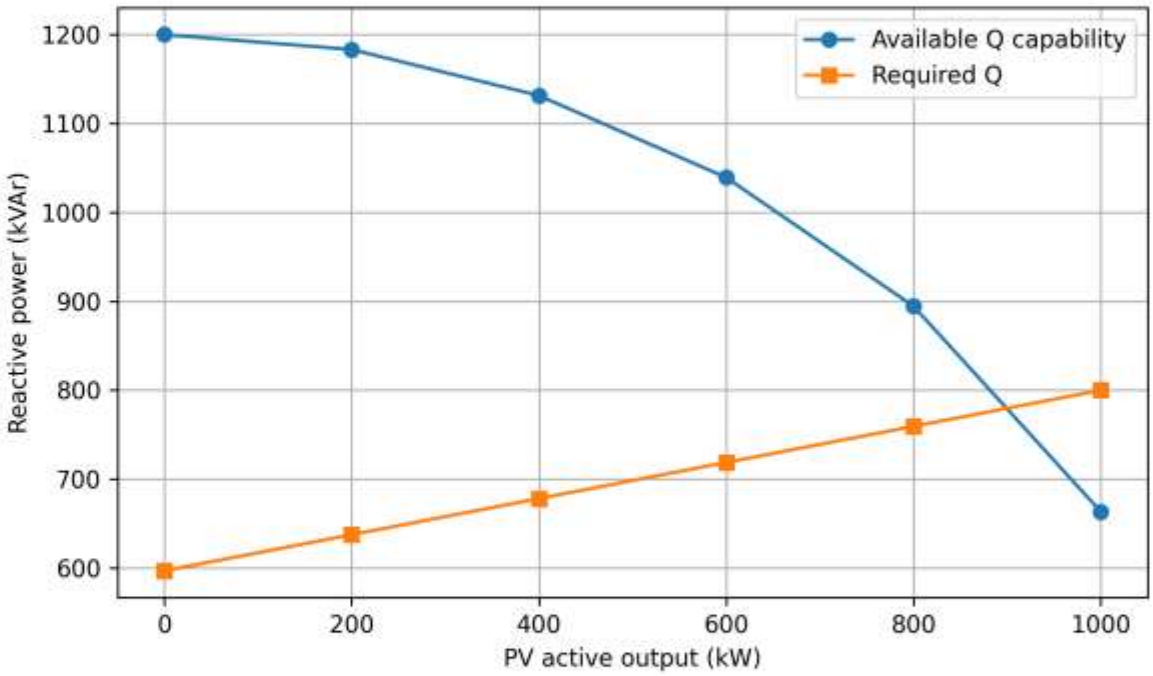

Figure 4. Available inverter reactive capability and reactive power required for PF = 0.98.

6. Discussion

The calculations confirm the fundamental technical benefit of local reactive compensation: lower apparent power and lower feeder current. A fixed capacitor bank provides a substantial improvement at comparatively low cost, but the amount of compensation is fixed or stepwise. If the industrial load changes significantly, the bank may undercompensate or overcompensate. Smart inverters can vary reactive output continuously and can therefore follow changing operating conditions.

The analysis also demonstrates why inverter rating is central to the design. A 1-MVA inverter producing 1 MW has no spare apparent-power capacity in an idealized circular capability model. Reactive support then requires active-power curtailment or an oversized inverter. In the case study, the 1.2-MVA rating creates sufficient headroom at 800 kW PV output. This finding is consistent with smart-inverter research showing that reactive support and hosting-capacity improvement depend on the inverter's P-Q operating limits (Ismeil et al., 2023).

Power factor at the point of common coupling should be interpreted carefully when local PV generation is high. If active import becomes small while reactive import remains, the calculated PF may appear poor even though the facility's physical load has not changed. The daytime controller must therefore increase reactive support as active import falls. This issue has direct billing implications where tariffs penalize low power factor (Dullius et al., 2024).

The calculated voltage-drop and loss values are illustrative because a real 8-km feeder normally contains distributed loads, conductor sections, transformers, and branch circuits. Nevertheless, the direction and approximate scale of improvement follow the established I-squared-R relationship. A field-ready study should replace the lumped impedance with measured conductor data and perform three-phase load flow.

Smart-inverter compensation should not automatically be considered a complete replacement for capacitor banks. A hybrid design may be more economical: capacitors can provide the steady base reactive requirement, while the inverter supplies fast variable compensation and voltage support. This reduces inverter oversizing and preserves reactive capability during high PV production.

From an operational perspective, protection, harmonics, thermal limits, utility interconnection rules, and controller coordination must be considered. IEEE Std 1547-2018 provides a framework for DER interconnection and interoperability, but the exact settings must comply with the applicable national grid code and utility requirements (IEEE, 2018).

6.1 Indicative Economic and Environmental Interpretation

If the facility operates near the analyzed load for 4,000 h/year, the reduction in feeder copper loss between the base case and reactive-only smart-inverter case would be approximately 39,588 kWh/year. At an illustrative energy value of USD 0.12/kWh, this corresponds to about USD 4,751/year. Using an illustrative grid-emission factor of 0.45 kg CO_2/kWh, avoided losses would correspond to approximately 17.8 t CO_2/year. These figures exclude inverter losses, capital cost, maintenance, financing, and tariff-specific reactive-power penalties; they are sensitivity indicators rather than a bankable economic assessment.

7. Limitations

- The study uses an assumed industrial feeder and does not use measured site data.
- The feeder is represented by a lumped balanced impedance; distributed and unbalanced load flow is not modeled.
- The inverter is represented by its steady-state P-Q capability and not by a detailed dynamic controller.
- Harmonics, switching losses, temperature effects, protection constraints, and grid-strength limits are excluded.
- The indicative economic analysis uses assumed operating hours, energy value, and emission factor.
- The calculated results should be validated using MATLAB/Simulink, MATPOWER, ETAP, or DIgSILENT and, where possible, field measurements.

8. Conclusion

This paper developed an approximate real-world analytical assessment of power-factor correction using a grid-connected PV system with a smart inverter. For the representative 11-kV industrial feeder, the initial 1,000-kW and 800-kVAr load produced a lagging power factor of 0.781 and an estimated line current of 67.2 A. A conventional capacitor bank of approximately 471 kVAr raised the power factor to 0.95. Smart-inverter injection of approximately 597 kVAr raised it to 0.98 during reactive-only operation and reduced the estimated feeder copper loss by 36.5%. During daytime operation at 800 kW PV output, a 1.2-MVA inverter retained approximately 894 kVAr of reactive capability, which was sufficient to provide the estimated 759 kVAr required to maintain a 0.98 power factor at the point of common coupling. The analysis demonstrates that smart PV inverters can provide flexible power-factor correction and voltage support, particularly when inverter apparent-power headroom is deliberately included in system design. However, the results are preliminary engineering estimates, not field or validated simulation results. The principal recommendation is to use the presented framework as the basis for a second-stage MATLAB/Simulink study with measured hourly active and reactive load profiles.

9. Recommendations

• Measure active power, reactive power, voltage, current, harmonics, and power factor at the point of common coupling for at least four representative weeks.

- Size the inverter using the required simultaneous active and reactive operating point rather than PV active capacity alone.
- Compare pure inverter compensation with a hybrid capacitor-plus-inverter configuration.
- Implement a Volt-VAR or Q(P) controller with limits that comply with the applicable interconnection code.
- Validate the steady-state estimates using MATLAB/Simulink or a three-phase distribution load-flow package.
- Perform a tariff-specific economic assessment including demand charges, reactive penalties, inverter losses, and equipment life.
- Conduct harmonic-resonance and protection-coordination studies before field implementation.

Declarations

Funding: No external funding was assumed for this analytical study.

Conflict of Interest: The author(s) declare no conflict of interest.

Data Availability: All numerical assumptions and calculated results used in this study are presented in the manuscript and accompanying CSV files.

Ethical Statement: The study does not involve human participants, animals, or personal data.

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