Materials Research Proceedings 64 (2026) 544-553 https://doi.org/10.21741/9781644904091-68

Power Factor Correction Analysis for Moroccan Industrial Facilities: Technical and Economic Evaluation

Chaimaa Labyad[1]

[1]School of Science and Engineering, Al Akhawayn University P.O Box 104, Hassan II Avenue, 53000Ifrane, Morocco

C.Labyad@aui.ma

Keywords: Power Factor Correction, Reactive Power Compensation, Industrial Energy Efficiency, ONEE Tariff, Morocco Electricity Sector, Economic Analysis, Simulink/ MATLAB Simulation

Abstract. Despite Morocco's ambitious National Energy Efficiency Strategy and growing industrial electrification, poor power factor remains a major contributor to system inefficiency and high electricity bills and in Moroccan industrial facilities, where small induction motors (0.5–2 hp) incur up to 20% reactive power surcharges under ONEE tariff structures, while simultaneously increasing transmission losses and placing unnecessary strain on the national grid infrastructure[1,6]. This study develops and validates an optimized shunt capacitive power factor correction system for a representative single-phase R-L load (R = 10 Ω, L = 50 mH, 1.526 kW) connected to Morocco's standard 230 V, 50 Hz low-voltage grid. Comprehensive phasor-domain circuit analysis in Simulink MATLAB, supported by resonance analysis and detailed phasor diagrams, identifies 140 μF as the global optimum. This single capacitor raises power factor from 0.537 to 0.999 (86 %improvement), reduces line current by 46.2% (from 12.35A to 6.64 A), and cuts reactive power by 97.1 % (from 2396 VAR to 70 VAR). Economic analysis using 2024-2025 ONEE tariffs shows 33-month payback with 1,933 MAD/year savings and 10-year NPV of 9,467 MAD. Therefore, this study demonstrates a technically feasible and economically attractive energy efficient intervention for Moroccan industrial facilities, that aligns fully with national energy policy objectives [1,9].

1. Introduction

The power factor, as the ratio of real power performing useful work to the apparent power drawn from the grid, serves as a main measure of efficiency in AC systems. The predominance of inductive loads such as induction motors, transformers, welders, and fluorescent lighting in industrial applications[5] results in current lagging voltage, shifting lowers power factor and raising reactive power demand, thereby increasing the current carrying requirement on the electrical system for the same real power leading to excessive I^2R losses, wasted heating of conductors, voltage drops along distribution feeders, and reduced capacity of transformers, switchgear, and cables. Thus, Poor power factor accelerates aging of facilities and restricts future industrial growth, as well as increasing operating costs of the industrial processes. This challenge is particularly relevant to the Moroccan context, where industry accounts for over 35% of national electricity consumption [6], and small and medium induction motors dominate inductive load. Empirical observations suggest that many industrial motors operate at power factors well below 0.60, leading to facilities to incur significant technical inefficiencies and related financial penalties [8]. Depending on specific applications under ONEE's medium-voltage tariff structure, industries could pay up to 20% surcharges for poor power factor, along with avoidable network losses and capacity constraints. These issues are increasingly relevant as Morocco, under its National Energy Strategy [1], targets major gains in energy efficiency and industrial competitiveness by 2030. Despite these developments, power factor correction adoption remains limited. Facility managers

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 license. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI. Published under license by Materials Research Forum LLC.

lack guidance on optimal capacitor sizing, face uncertainty about resonance risks, and have limited economic data reflecting current ONEE and ANRE tariffs. This study addresses these gaps by developing a complete technical and economic structure for power factor correction adapted to Moroccan industrial conditions. We model of a representative 1.526 kW motor load operating on Morocco's 230 V, 50 Hz grid, determining optimal parallel capacitance using phasor-domain analysis and resonance validation, and quantifying economic outcomes based on current ONEE/ANRE tariffs, providing clear performance metrics: annual savings, payback period, ROI, and NPV. This paper presents the literature review (Section 3) methodology (Section 4), results (Section 5), and conclusions (Section 6).

2. Literature review

Power factor correction through capacitor banks represents the most economically viable method for industrial applications, as established in IEEE Standard 141-1993 [5], which provides comprehensive design criteria for industrial power distribution. Capacitor banks generate leading reactive power that cancels lagging reactive power from inductive loads, reducing line current, and improving system efficiency. These systems can be configured as fixed banks for constant loads or automatic switched banks for variable profiles. While synchronous condensers and active correction systems offer enhanced performance for high-power applications, capacitor banks remain in the industry standard for small-to-medium facilities due to lower capital and maintenance costs [13]. Economic viability has been extensively documented, with Saied (1989) establishing typical payback periods of 18-36 months depending on utility tariff structures [6]. Recent industrial implementations confirm these findings: 12% monthly cost reductions in cement manufacturing, while Rajendran (2021) found passive systems offer 18–24 month payback periods for SMEs [10]. Electrotek Concepts documented payback periods of 10-27 months for facilities with installed capacitor costs of $35-45/kVAR . However, existing economic models predominantly address developed nations with stable tariff structures. Limited research examines developing economies where utility penalty structures may be poorly documented, and equipment costs vary significantly. Morocco's National Energy Strategy targets 52% renewable energy by 2030 and 20% energy efficiency improvement, with specific industrial targets of 22% [1,7]. Industry accounts for 35% of national electricity consumption, with manufacturing, mining, and textiles dominating [6]. The establishment of ANRE in 2024 introduced transparent transmission (TURT at 0.0639 MAD/kWh) and system services (TSS at 0.0635 MAD/kWh) tariffs, enabling precise economic assessment of efficiency investments [2]. ONEE, the state utility, operates as a single buyer and maintains grid infrastructure [14]. Despite these policy drivers, UNIDO's 2021 program identified critical barriers: limited facility manager awareness, uncertainty regarding optimal capacitor sizing, harmonic resonance concerns, and insufficient access to current economic data reflecting actual ONEE/ANRE tariffs [11]. Regional MENA utilities commonly impose 15-30% penalties for poor power factor, creating strong economic incentives. Harmonic distortion from nonlinear loads (VFDs, rectifiers) represents a primary concern, as capacitor-inductance interaction can create resonance conditions amplifying harmonic components [12]. Facilities with nonlinear loads exceeding 15-20% require harmonic analysis prior to installation. Detuned harmonic filter banks provide effective mitigation. Over- compensation, where excessive capacitance causes leading power factor and voltage rise, necessitates proper sizing methodology accounting for parallel R-L-C circuit characteristics. Automatic controllers provide protection while optimizing correction across varying load profiles. Despite extensive global research, no comprehensive studies validate power factor correction using Morocco's specific grid parameters (230V, 50Hz), representative industrial loads, and current 2024-2025 ONEE/ANRE tariff structures. This study addresses these gaps by providing validated MATLAB modeling, comprehensive phasor and resonance

analysis determining optimal capacitance, and detailed economic evaluation using verified current tariffs.

3. Methodology

3.1 Circuit Model and Component Parameters:

This study analyses power factor correction for a typical industrial inductive load connected to Morocco's electrical grid. The load is modeled as a series R-L combination (R = 10Ω, L = 50mH) powered by Morocco's standard grid parameters: 230V RMS voltage and 50 Hz single-phase AC source. These values represent typical small industrial motors (0.5-2 hp) used in Moroccan facilities for pumps, fans, and conveyors—the primary source of reactive power consumption. At 50 Hz, the inductive reactance is:

$X_L = 2\pi fL = 15.71\Omega$, resulting in an $|Z_L| = 18.62\ \Omega$ yielding low power factor of $\cos\varphi \approx 0.537$ (lagging).

To improve the power factor of the load to near unity, we implemented a power factor correction that employs by using parallel capacitive compensation, where capacitor C connected in parallel directly across the load terminals. This configuration was chosen because it allows the compensating capacitor bank to be connected or disconnected without interrupting the operation of the load, fully complies with standard power factor correction practices in industrial installations, and crucially —applies correction at the point of consumption. As a result, the reactive component of the current is canceled locally, significantly reducing the total current flowing through the upstream supply lines, cables, transformers, and switchgear, thus decreasing losses and improving the overall efficiency of the electrical distribution system.

3.2 Analytical Simulation and Technical Analysis:

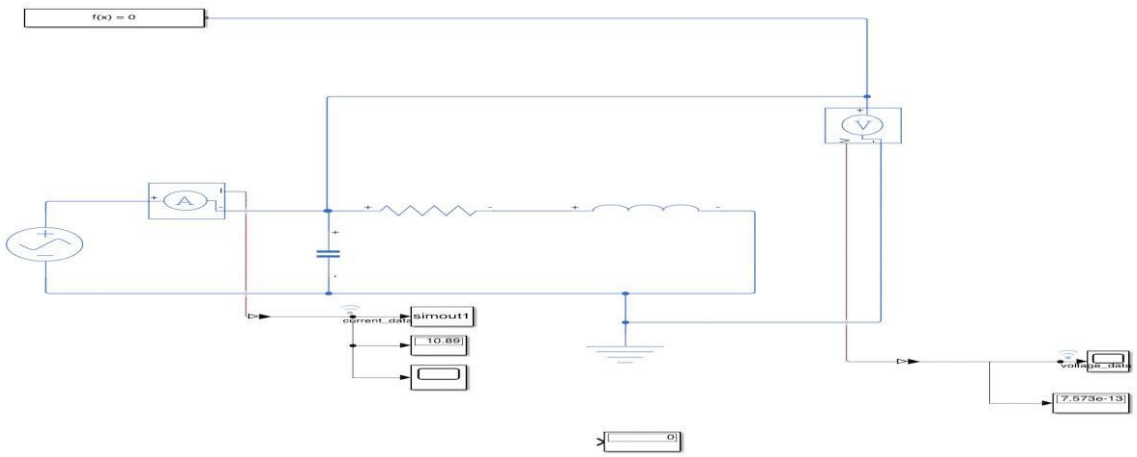


Figure 1. *MATLAB/Simulink Circuit Model for Power Factor Correction Analysis: Single-Phase R-L Load with Parallel Shunt Capacitor (230V, 50Hz, R = 10Ω, L = 50mH)*

Initial circuit modeling employed Simscape/Simulink visual circuit construction (Figure1), in addition to MATLAB analytical modeling based on phasor-domain circuit theory that directly applies fundamental circuit laws (Kirchhoff's current law, Ohm's law with complex impedance) without relying on numerical solver convergence. This analytical method computes for each capacitor value C in the test range [0, 50, 100, 125, 140, 150, 160, 175, 200, 225, 250, 300, 350, 400, 500] μF, the following phasor calculations were performed:

1. Inductive reactance (constant): $X_L = \omega L = 15.71\ \Omega$
2. Capacitive reactance: $X_C = 1/(\omega C)$, where: $\omega = 2\pi f = 314.16$ rad/s

Materials Research Proceedings 64 (2026) 544-553 https://doi.org/10.21741/9781644904091-68

3. R-L branch impedance (complex): $Z_{RL} = R + jX_L = 10 + j15.71\ \Omega$
4. R-L branch current (phasor): $I_{RL} = 230\angle 0° / (10 + j15.71)$
5. Capacitor current (phasor): $I_C = 230\angle 0° / (-jX_C)$
6. Total supply current (phasor sum): $I_{total} = I_{RL} + I_C$
7. Power factor: $PF = \cos(\text{angle}(I_{total}))$
8. Real, reactive, and apparent powers:

$$P = 230 \times |Itotal| \times PF$$

$$Q = 230 \times |I_{total}| \times \sin(\text{angle}(I_{total}))\ S = 230 \times |I_{total}|$$

Dense sampling in the 100-200 μF region (125, 140, 150, 160, 175 μF) accurately resolve the optimal correction point.

3.3 Multi-Method Validation of the Analytical Model:

To ensure accuracy and reliability of simulation results and gain deeper physical insight into the power factor correction mechanism, we adopted two independent validation methods: resonance analysis, phasor diagram construction that confirms numerical accuracy and highlights the differences between ideal resonant compensation and practical power factor correction at fixed grid frequency.

3.3.1 Resonance Analysis:

Resonance theory provides analytical estimation of capacitance needed for reactive power compensation. For parallel R-L-C circuits, simplified analysis (neglecting resistance) predicts unity power factor when $X_L = X_C$, yielding theoretical optimal capacitor: $C_{theory} = 1 / (\omega^2 L) = 202.6$ μF. However, with R = 10 Ω is comparable to $X_L = 15.71$ Ω, then the actual current minimum and therefore the true optimal capacitance for unity power factor at 50 Hz deviates slightly from 203 μF. Resonant frequency for the L-C combination is calculated as:

$f_r = 1 / (2\pi\sqrt{LC})$ and varies from approximately 225 Hz (at C = 10 μF) to 50.9 Hz (at C = 202.6 μF). This behavior was further confirmed by a full frequency-response analysis of of the total input impedance magnitude |Zin(f)| and phase angle ∠Zin(f) over the range 10–500 Hz independently verifies the above findings and demonstrates that the optimal power factor correction at 50 Hz is achieved well before the circuit reaches its natural resonance. Consequently, the proposed compensation scheme operates safely away from resonant conditions, eliminating any risk of dangerous overvoltage or overcurrent.

3.3.2 Phasor Diagram Analysis:

Phasor diagrams validate the correction mechanism through voltage-current phase relationships, impedance triangles, and power triangles. Current phasor diagrams show capacitor current (IC, leading 90°) canceling motor current lagging component, reducing total line current and aligning it with voltage.

3.4 Economic Analysis:

3.4.1 Electricity Tariff Structure:

Our Economic analysis included Moroccan specific electricity tariff components for medium-voltage industrial customers [2,3]. The total electricity cost has three elements established by regulatory authorities [2]: base energy (0.95 MAD/kWh), transmission network usage (TURT, 0.0639 MAD/kWh), and system services (TSS, 0.0635 MAD/kWh), totaling 1.0774 MAD/kWh [2,3]. Power factor penalties follow industry-standard progressive structure with 20% surcharge for PF < 0.60.

3.4.2 Power Factor Penalty Structure:

Moroccan utilities apply surcharges to customers operating with poor power factor to recover costs associated with reactive power provision and system capacity requirements. While ONEE's (Office National de l'Électricité et de l'Eau Potable) specific penalty tariff is not publicly disclosed in recent documentation, this analysis employs industry-standard progressive penalty structure based on IEEE Standard 1409-2012 for utility reactive power charges [IEEE, 2012],comparable MENA region utility practices (Egypt, Jordan, UAE)[8] and the economic principles of capacity allocation and loss recovery.The applied penalty structure (Table 2) uses conservative rates to avoid overestimating economic benefits. Baseline power factor of 0.537 incurs 20% surcharge (billing multiplier 1.20×), while corrected power factor of 0.999 eliminates all penalties (multiplier 1.00×). This conservative approach ensures that actual implementation may yield equal or superior economic performance. Facilities should confirm contractual penalty rates with ONEE for precise economic projections.

3.4.3 Investment and Operating Cost Components:

Investment costs include capacitor component (30 MAD/µF mid-range industrial- grade) and 30% installation labor. For 140 µF: component cost 4,200 MAD, installation 1,260 MAD, total 5,460 MAD. Operating schedule assumes two-shift operation (16 h/day, 26 days/month = 4,992 hours/year).

Transmission line resistance estimated at R_{line} = 0.5Ω for typical medium-sized facility. Financial metrics include payback period, ROI, and NPV (5% discount rate).

4. Results & Discussions

4.1 Power Factor Correction Technical Performance:

4.1.1 Optimal Capacitor Value and Performance Metrics:

A parametric sweep was conducted over 15 capacitance values ranging from 0 to 500 µF to determine the optimal shunt capacitor for the 1.526 kW inductive load. The results, shown in Figure 2, clearly identify **C = 140 µF** as the global optimum, achieving a power factor of 0.999, a 46.2 % reduction in line current, and a 97.1 % reduction in reactive power, phase angle near-zero (-2.6°), and reactive power reduced 97.1% (from 2396 VAR to 70 VAR). The practical optimal range of 125-160 µF maintains power factor above 0.95, avoiding utility penalties while providing robust corrections.

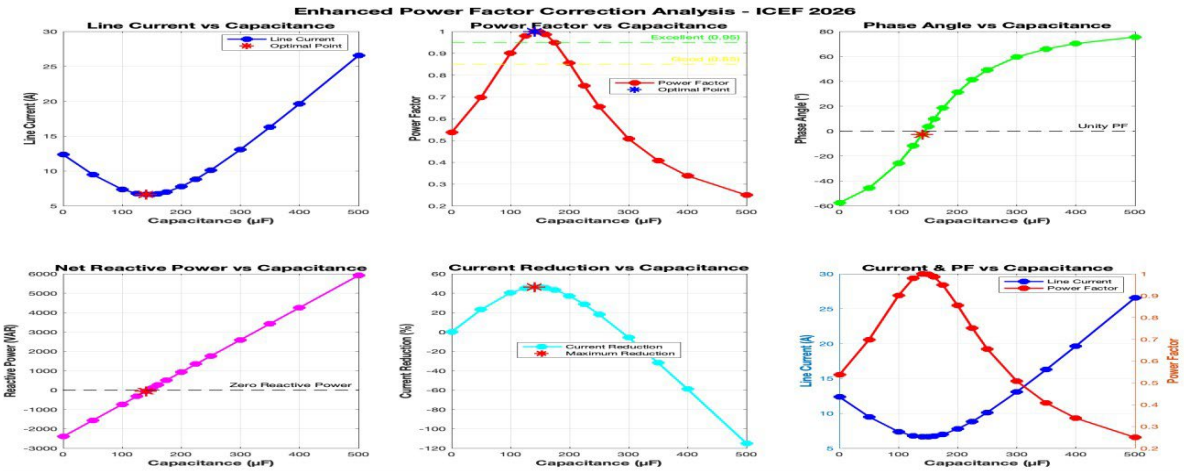


Figure 2. *Effect of shunt capacitance (0–500 µF) on power factor correction performance: (a) line current, (b) power factor, (c) phase angle, (d) reactive power, (e) current reduction %, and (f) combined current & PF. Optimal performance at 140 µF : PF = 0.999, 46.2 % current reduction, 97.1 % reactive power compensation.*

Table1: Comparison of key electrical parameters before and after power factor correction

Parameter	Baseline (No Cap)	Corrected (140 µF)
Line Current	12.35 A	6.64 A
Power Factor	0.537 (POOR)	0.999 (EXC)
Phase Angle	−57.52°	−2.62°
Real Power	1526 W	1526 W
Reactive Power	−2396 VAR	−70 VAR
Apparent Power	2841 VA	1527 VA

Comparison of key electrical parameters before and after power factor correction using the optimal 140 µF shunt capacitor bank.

4.1.2 Resonance Analysis and Theoretical Validation:

Resonance analysis (Figure 3) validates simulation results through frequency-domain evaluation and comparison with theoretical predictions. Figure 3 in Appendix present frequency-domain resonance analysis and theoretical validation of shunt power factor correction (R = 10 Ω parallel load, 230 V, 50 Hz): (a) impedance magnitude, (b) impedance phase angle, (c) zoomed impedance magnitude near 50 Hz, and (d) inductive vs capacitive reactance crossover. Frequency-domain analysis (Figure 3) confirms 140 µF yields optimal impedance at 50 Hz, avoiding resonance while achieving zero phase crossing at operating frequency. The 30.9% deviation from theoretical 202.6 µF (simplified series-resonance formula) reflects parallel R-L-C topology effects with non-negligible resistance (R = 10Ω comparable to X_L = 15.71Ω), demonstrating the importance of full-circuit analysis for practical power factor correction systems.

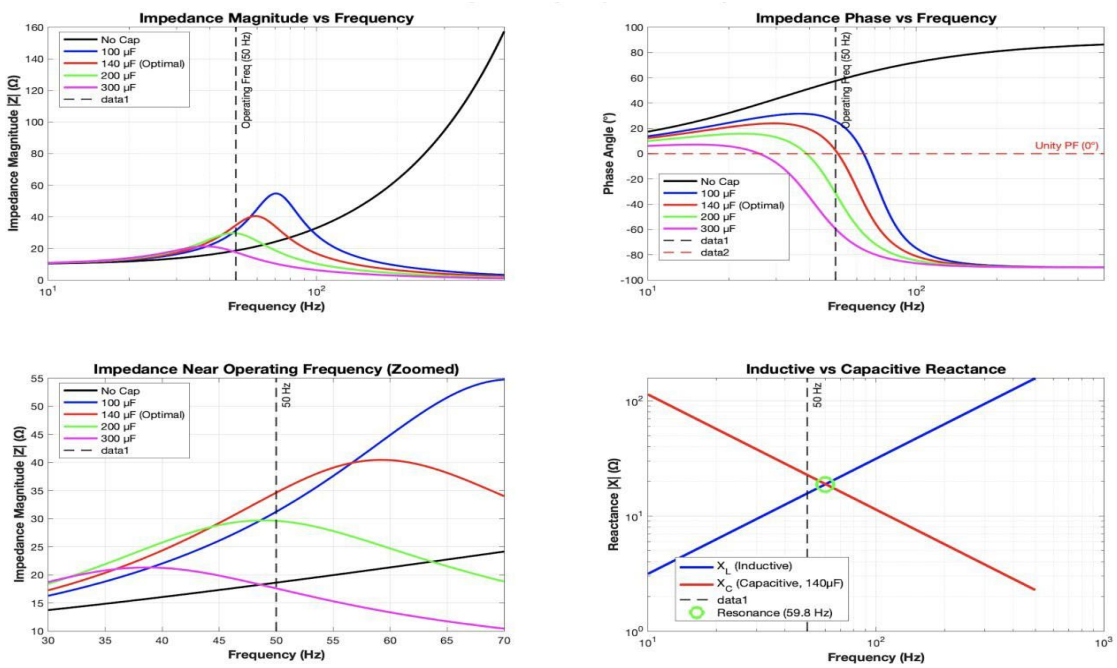


Figure 3. *Frequency-domain resonance analysis and theoretical validation of shunt power factor correction (R = 10 Ω parallel load, 230 V, 50 Hz): (a) impedance magnitude, (b) impedance phase angle, (c) zoomed impedance magnitude near 50 Hz, and (d) inductive vs capacitive reactance crossover.*

Materials Research Proceedings 64 (2026) 544-553 https://doi.org/10.21741/9781644904091-68

4.1.3 Phasor Relationships and Correction Mechanism:

Phasor diagram analysis provides visual representation of power factor correction mechanism through voltage-current phase relationships, impedance triangles, and power triangles. Figure 4 visualizes the correction mechanism: the 140 µF capacitor injects leading current (+90°) that cancels the motor's lagging reactive component, reducing total line current from 12.35A to 6.64A and aligning it with voltage (residual lag only 2.6°). The corrected power triangle shows reactive power reduced to 70 VAR (97%), apparent power to 1527 VA, achieving PF = 0.999.

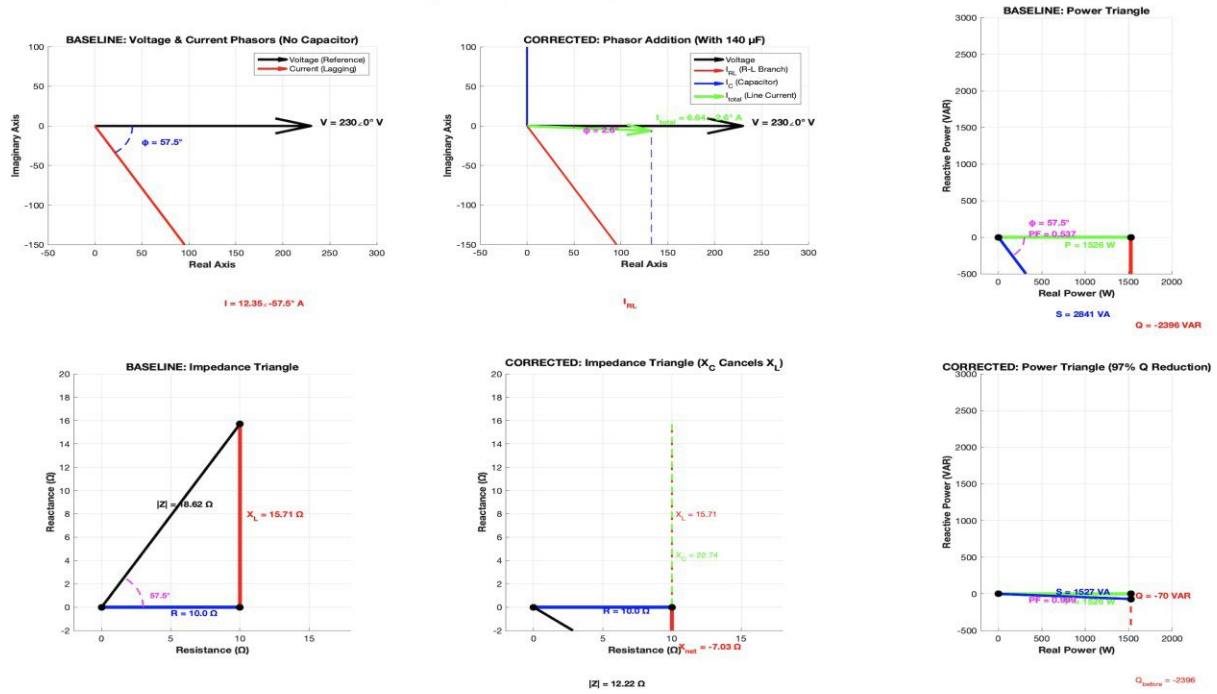


Figure 4. *Phasor and triangle analysis of power factor correction mechanism (230 V, 50 Hz, R = 10 Ω parallel load)*

4.2 Economic Analysis and Financial Performance:

Economic analysis using ONEE 2024-2025 tariffs (1.0774 MAD/kWh) and 20% penalty for PF<0.60 demonstrates strong viability. For two-shift operation (7,618 kWh/year), uncorrected operation (PF = 0.537) costs 9,848 MAD/year (8,207 MAD base + 1,641 MAD penalty). The 140 µF system (5,460 MAD investment) eliminates the penalty and reduces I^2R losses from 381 to 110 kWh/year (291 MAD/year savings), yielding total savings of 1,933 MAD/year (19.6% reduction). This delivers 33.9-month payback, 77% 5-year ROI, and 9,467 MAD 10-year NPV (5% discount). Sensitivity analysis confirms attractive payback across one- to three-shift scenarios and capacitor price variations.

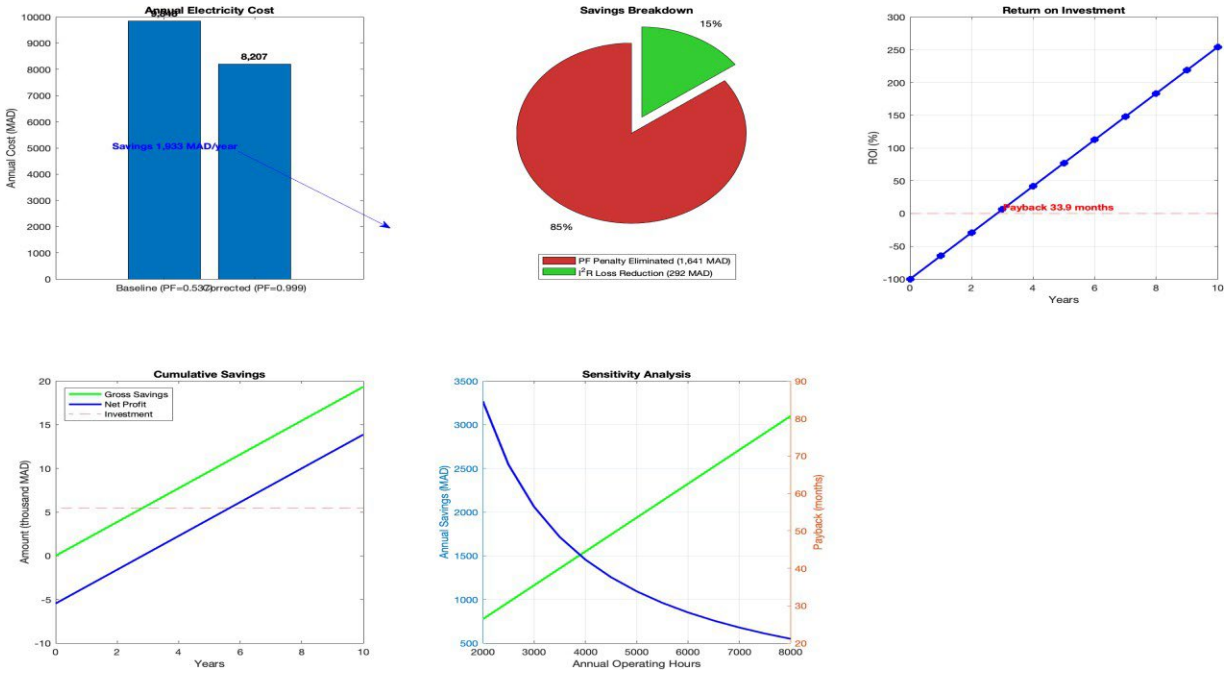


Figure 5. *Economic performance of the 140 µF shunt power factor correction system under ONEE 2024– 2025 medium-voltage tariffs (a) Annual electricity cost comparison (b) Savings breakdown and return- on-investment metrics: total annual saving.*

5. Study Limitations and Assumptions

The present analysis embraces a number of limitations and underlying assumptions that have to be recognized in order to appropriately interpret the technical and economic results. This analysis assumes industry-standard progressive penalty structure (20% surcharge for PF < 0.60) as ONEE-specific rates are not publicly disclosed. If actual penalties differ, economic gains derive primarily from I^2R loss reductions (~630 MAD annually), extending payback to ~104 months while maintaining positive ROI. The single- phase analysis is valid for three-phase applications with balanced phase-by-phase correction, though requiring 2.5-3×greater investment with proportional savings, preserving comparable payback and profitability ratios. The steady-state load model assumes constant R-L values. Facilities with significant load variability requires automatic switched capacitor banks for optimal correction. The analysis assumes ideal sinusoidal waveforms at 50 Hz. Facilities with nonlinear loads (VFDs, rectifiers, inverters) exceeding 20% of total load require harmonic analysis, as shunt capacitors may interact with system impedance creating resonance conditions. Detuned harmonic filter capacitors may be needed instead of simple capacitor banks. Results are specific to the 1.526 kW load modeled (R = 10Ω, L = 50mH). Other loads require specific analysis for optimal results.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

I declare that the use of ChatGPT (OpenAI) in the preparation of this paper was conducted in accordance with applicable academic integrity guidelines and institutional policies. AI assistance was limited to supporting tasks such as language refinement, formatting, or idea organization, and all substantive content, analysis, and conclusions represent my own original work and understanding. I have reviewed and verified the accuracy of all information included, take full responsibility for the final submission, and have properly cited all sources in compliance with scholarly standards.

References

[1] Kingdom of Morocco - Ministry of Energy, Mines and Environment (MEMEE), "Stratégie Énergétique Nationale - Vers un modèle énergétique robuste, durable et compétitif," 2021. [Online].

Available: https://www.mem.gov.ma/Pages/strategie.aspx

[2] ANRE (National Regulatory Authority for Electricity), "Décision n° 01/24 portant approbation des tarifs d'utilisation des réseaux de transport et des services système," Bulletin Officiel du Royaume du Maroc, no. 7210, 2024. [Online]. Available: https://www.anre.ma

[3] ONEE (National Office of Electricity and Drinking Water), "Tarifs de Vente d'Électricité - Clientèle Professionnelle," 2023. [Online]. Available: https://www.onee.ma

[4] IEEE, "IEEE Recommended Practice for Electric Power Distribution for Industrial Plants (IEEE Red Book)," IEEE Standard 141-1993, 1993. [Online]. Available: https://standards.ieee.org/ieee/141/1046/

[5] International Energy Agency (IEA), "Morocco Energy Statistics," 2023. [Online]. Available: https://www.iea.org/countries/morocco

[6] M. M. Saied, "Power Factor Correction: Economic Feasibility and Technical Limitations," Electric Machines and Power Systems, vol. 16, no. 5, pp. 311-329, 1989. https://doi.org/10.1080/07313568908909393

[7] U.S. Department of Commerce, International Trade Administration, "Morocco - Energy Sector," Country Commercial Guide, 2024. [Online]. Available: https://www.trade.gov/country-commercial- guides/morocco-energy

[8] World Bank Group, "Morocco - Energy Efficiency Scale-Up Program," Project Document P173202, 2021. [Online]. Available: http://documents.worldbank.org/curated/en/099125103082236906

[9] M. Ahrens and Z. Konstantinovic, "Harmonic Filters and Power Factor Compensation for Cement Plants," IEEE Cement Industry Technical Conference, vol. 10, no. 1, pp. 77-103, 2005. https://doi.org/10.1109/CITCON.2005.1536514

[10] S. Rajendran, "Techno-Economic Viability of Power Factor Correction in Industrial Facilities," Energy Reports, vol. 7, pp. 2245-2254, Nov. 2021. https://doi.org/10.1016/j.egyr.2021.04.029

[11] UNIDO (United Nations Industrial Development Organization), "Morocco Industrial Energy Efficiency," 2021. [Online]. Available: https://www.unido.org/morocco

[12] IEEE, "IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems," IEEE Standard 519-2014, 2014. https://doi.org/10.1109/IEEESTD.2014.6826459

[13] B. Singh, S. Singh, A. Chandra, and K. Al-Haddad, "Comprehensive Study of Single-Phase AC-DC Power Factor Corrected Converters with High-Frequency Isolation," IEEE Transactions on Industrial Informatics, vol. 7, no. 4, pp. 540-556, Nov. 2011. https://doi.org/10.1109/TII.2011.2166798

[14] ONEE (Office National de l'Électricité et de l'Eau Potable), "Rapport Annuel," Casablanca, Morocco, 2023. [Online]. Available: https://www.onee.ma

[15] African Development Bank, "Morocco - Renewable Energy Development and Energy Efficiency Project," Tunis, Tunisia, 2022. [Online]. Available: https://www.afdb.org

[16] IEEE, "IEEE Recommended Practice for Establishing Liquid-Filled and Dry-Type Power and Distribution Transformer Capability When Supplying Nonsinusoidal Load Currents," IEEE Standard C57.110-2018, 2018. https://doi.org/10.1109/IEEESTD.2018.8457274