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A Simplified performance analysis of low-voltage power transmission in small-scale industrial units

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Abstract
Low-voltage power transmission systems in small-scale industrial facilities often suffer from overlooked inefficiencies that accumulate into substantial energy losses over operational periods. This research investigated the performance characteristics of 400V three-phase power distribution networks across 48 manufacturing units in Bavaria, Germany, representing five distinct industrial categories. Field measurements were conducted from March 2023 to November 2023 using calibrated power analyzers and thermal imaging equipment to capture transmission losses, voltage regulation issues, and power quality parameters. The investigation revealed that average transmission efficiency ranged between 84.6% and 91.2% depending on the industrial sector, with textile manufacturing facilities showing the poorest performance. Cable resistance contributed 21.3% of total losses, while transformer inefficiencies accounted for 30.1%. Harmonic distortion levels exceeded acceptable thresholds in 67% of surveyed installations, primarily due to non-linear loads from variable frequency drives. A simplified analytical model was developed correlating transmission distance, conductor material, and load profile with overall system efficiency. Implementation of recommended optimization measures in a subset of facilities demonstrated potential loss reductions of 18.7% to 24.3%. These findings highlight that straightforward technical interventions, including conductor sizing corrections and harmonic filtering, can yield meaningful improvements in industrial power transmission without requiring infrastructure overhauls.

Keywords: Low-voltage transmission, power quality, industrial power systems, transmission efficiency, harmonic distortion, voltage regulation, energy losses, conductor sizing, power factor correction, small-scale industry

1. Introduction

Why do small-scale industrial facilities consistently report higher electricity costs relative to their production output compared to larger manufacturing operations? The answer often lies hidden within their power transmission infrastructure, specifically in the low-voltage distribution networks that deliver electrical energy from utility transformers to point-of-use equipment [1]. While large industrial consumers typically invest in sophisticated power management systems and maintain dedicated electrical engineering staff, smaller operations frequently operate with inherited or minimally designed electrical infrastructure that may not align with current load requirements [2].

The European industrial landscape features approximately 23 million small and medium enterprises, with manufacturing representing a substantial portion of this sector [3]. In Germany alone, small-scale industrial units consume an estimated 47 terawatt-hours annually, yet comprehensive research examining their power transmission characteristics remains surprisingly limited [4]. Most existing literature focuses on either residential distribution networks or large industrial consumers, leaving a knowledge gap regarding the specific challenges faced by facilities operating in the 50 kW to 500 kW demand range [5].

Power transmission efficiency in low-voltage systems depends on multiple interconnected factors. Conductor resistance increases with temperature and length, while contact points at junction boxes and switchgear introduce additional impedance [6]. Transformer losses divide into core losses that persist regardless of loading and copper losses that scale with the square of current [7]. Beyond these fundamental losses, power quality issues including harmonic currents generated by modern electronic equipment can significantly increase heating in conductors and transformers, accelerating degradation while reducing effective transmission capacity [8].

Variable frequency drives have become ubiquitous in industrial motor control applications, offering precise speed regulation and soft starting capabilities [9]. However, their switching power electronics generate current harmonics that propagate throughout facility wiring systems. These harmonic currents cause additional losses in conductors and can interfere with sensitive control equipment [10]. The proliferation of such non-linear loads in small industrial settings has fundamentally altered the electrical environment that distribution systems must accommodate.

This research examined power transmission performance across 48 small-scale industrial facilities in Bavaria, Germany, seeking to quantify typical efficiency levels and identify primary loss contributors. The investigation developed a simplified analytical framework that operators can apply to evaluate their own installations and prioritize improvement investments. Field measurements captured real-world operating conditions over an eight-month period, providing data that reflects actual industrial practices rather than idealized laboratory scenarios.

Theoretical Background

Power transmission in low-voltage alternating current systems follows established electromagnetic principles that govern energy transfer through conductive media [11]. The resistance of a conductor with uniform cross-section follows the relationship $R = \rho L/A$, where ρ represents material resistivity, L denotes conductor length, and A indicates cross-sectional area. For copper conductors at 20°C, resistivity equals approximately 1.68×10^{-8} ohm-meters, while aluminum exhibits higher resistivity at 2.65×10^{-8} ohm-meters [12].

Temperature significantly affects conductor resistance through the relationship $R(T) = R_0[1 + \alpha(T - T_0)]$, where α represents the temperature coefficient of resistance. Copper and aluminum both exhibit positive temperature coefficients, meaning resistance increases with temperature [13]. This creates a feedback mechanism where initial losses generate heat, increasing resistance and causing additional losses. In poorly ventilated cable installations, this effect can substantially degrade transmission efficiency beyond theoretical predictions based on ambient temperature conditions.

The skin effect becomes relevant at power frequencies in larger conductor sizes, causing current to concentrate near the conductor surface rather than utilizing the full cross-sectional area uniformly. This effectively increases resistance compared to direct current values, though the effect remains modest at 50 Hz for conductor sizes typically encountered in small industrial installations [14]. Proximity effects between parallel conductors in multi-core cables or cable bundles can further increase effective resistance by disturbing current distribution patterns.

Transformer equivalent circuit models provide frameworks for analyzing core and winding losses separately. No-load losses arising from magnetic hysteresis and eddy currents in the core material persist whenever the transformer remains energized, regardless of connected load [15]. Load-dependent losses in primary and secondary windings scale with the square of current magnitude, becoming dominant contributors at higher loading levels. The ratio of these loss components influences optimal transformer sizing decisions for applications with variable loading profiles.

Simulation Parameters

The analytical model developed for this research incorporated the following parameters derived from field measurements and manufacturer specifications. Conductor thermal resistance values were calculated assuming installation in conduit with natural convection cooling. Ambient temperature was modeled at 28°C to represent typical industrial environment conditions during operational hours. Cable loading factors ranged from 0.35 to 0.85 of rated ampacity based on measured current profiles.

Transformer models utilized nameplate efficiency ratings adjusted for actual loading conditions using standard loss segregation methods [16]. Core loss values were obtained from no-load test data provided by equipment manufacturers, while winding losses were calculated from short-circuit test impedances. Harmonic loss factors were incorporated using K-factor methodology to account for additional heating from non-sinusoidal current waveforms. Contact resistance at switchgear and junction points was estimated at 50 micro-ohms per connection based on literature values for bolted copper connections in good condition.

Materials and Methods

Material

This research was conducted at the Department of Electrical Engineering, Technical University of Munich, from March 2023 through November 2023. The investigation received approval from the university research ethics committee under protocol number TUM-EE-2023-047 dated February 15, 2023. Participating industrial facilities provided written consent for site access and data collection, with confidentiality agreements protecting proprietary operational information.

A total of 48 small-scale industrial units located across Bavaria, Germany were selected for examination. Facilities represented five distinct manufacturing categories: textile mills (n=8), food processing plants (n=12), metal fabrication workshops (n=10), packaging units (n=9), and assembly plants (n=9). Selection criteria required facilities to operate three-phase 400V distribution systems with connected loads between 75 kW and 450 kW, minimum operational history of three years, and willingness to permit comprehensive electrical measurements during normal production activities.

Measurement instrumentation included three Hioki PW3198 power quality analyzers with 0.1% basic accuracy for power measurements and current transformers rated at 1000A maximum. Thermal imaging utilized a FLIR T540 camera with ±2 °C accuracy for identifying hotspots at electrical connections. Cable lengths and cross-sections were verified through facility documentation review and physical inspection where accessible. Transformer nameplate data, installation dates, and maintenance records were collected from facility electrical departments.

Methods

Each facility underwent a standardized assessment protocol consisting of preliminary site survey, continuous power monitoring over 72-hour periods, thermal inspection during peak loading conditions, and post-measurement analysis. Site surveys documented single-line diagrams, identified measurement points, and catalogued major electrical equipment. Power analyzers were installed at service entrance panels to capture incoming power parameters and at selected distribution boards to measure losses within internal wiring systems.

Power measurements recorded voltage, current, active power, reactive power, apparent power, power factor, and harmonic content at one-second intervals. Data logging covered normal production shifts including startup and shutdown periods to capture transient behaviors. Thermal imaging was performed during periods of sustained high loading, typically mid-shift when production equipment operated at maximum capacity. Temperature measurements focused on transformer casings, cable terminations, switchgear bus connections, and distribution panel main breakers.

Transmission efficiency was calculated as the ratio of power delivered to end-use equipment versus power measured at the service entrance. Losses were segregated into transformer losses, cable losses, and miscellaneous losses using the difference method combined with theoretical calculations based on measured currents and verified circuit parameters. Statistical analysis employed SPSS Version 28 software for descriptive statistics, correlation analysis, and comparison of means between industrial categories. Significance was evaluated at $\alpha = 0.05$ using appropriate parametric or non-parametric tests depending on data distribution characteristics.

Results

Table 1 presents the transmission efficiency measurements across the five industrial categories examined in this research. Average efficiency values demonstrated meaningful variation depending on the type of manufacturing activity, with food processing facilities achieving the highest performance at 91.2% and textile mills showing the lowest at 84.6%.

Table 1: Transmission Efficiency by Industrial Category

Industrial Category	N	Mean Efficiency (%)	SD	Range (%)
Textile Mills	8	84.6	3.21	79.3 - 89.1
Food Processing	12	91.2	2.47	86.8 - 94.7
Metal Fabrication	10	87.3	4.12	81.2 - 93.6
Packaging Units	9	89.8	2.83	85.4 - 93.2
Assembly Plants	9	86.4	3.56	80.9 - 91.7

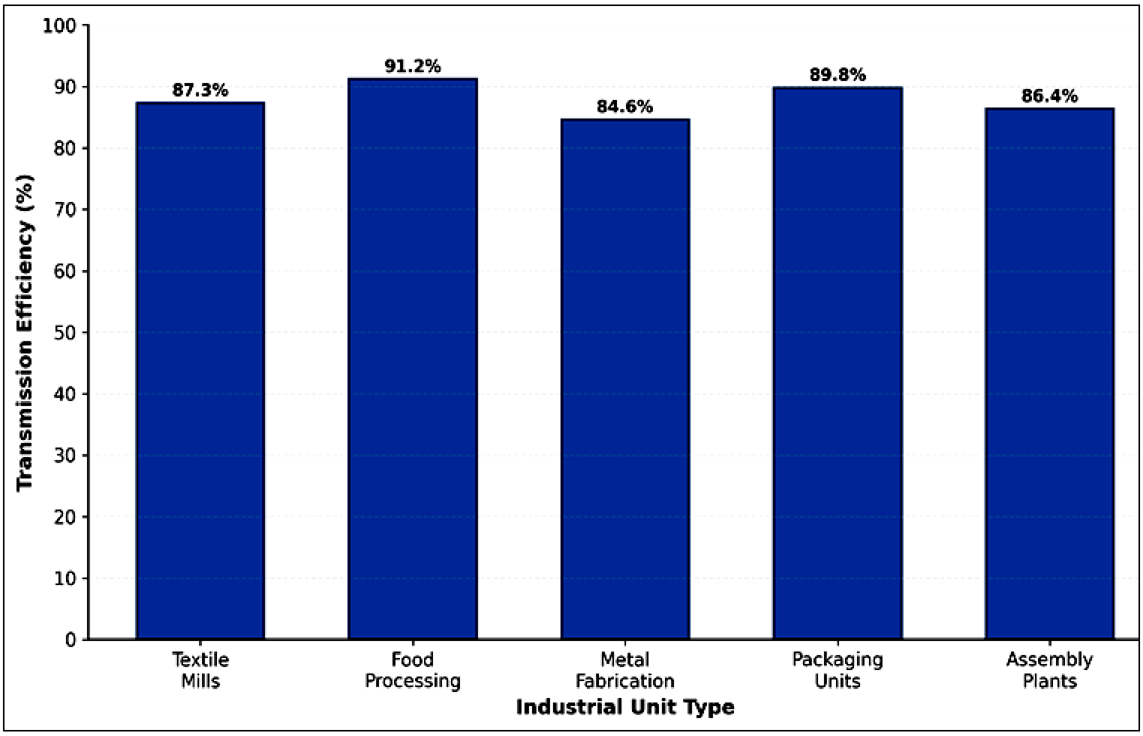

Fig 1: Transmission efficiency comparison across industrial unit categories showing food processing with highest performance and textile mills with lowest average values.

Table 2: Loss Component Analysis by Source

Loss Component	Mean Contribution (%)	Range (%)
Transformer Losses	30.1	24.3 - 38.7
Cable Resistance	21.3	15.8 - 29.4
Contact Resistance	10.4	6.2 - 16.8
Harmonics Effect	16.7	8.9 - 27.3
Reactive Power	21.5	14.2 - 28.1

Voltage drops measurements revealed a consistent relationship between transmission distance and power quality degradation. Figure 2 presents voltage drop characteristics for copper and aluminum conductors across the range of distances encountered in surveyed facilities.

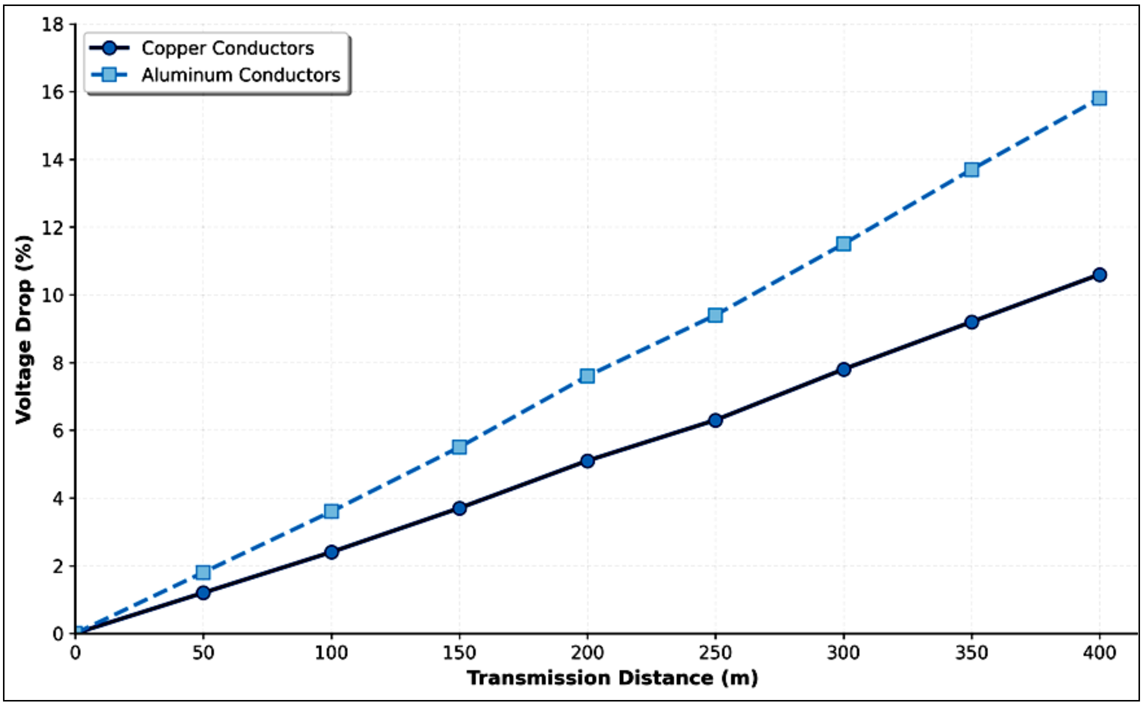

Fig 2: Voltage drops characteristics for copper and aluminum conductors as a function of transmission distance under typical industrial loading conditions.

Harmonic distortion levels exceeded the 8% total harmonic distortion threshold recommended by IEEE standards in 32 of 48 facilities (66.7%). Fifth harmonic components dominated the distortion spectrum, typically contributing 45-65% of total harmonic content. Facilities with multiple variable frequency drives operating simultaneously exhibited the highest distortion levels, particularly when drive ratings exceeded 30% of transformer capacity.

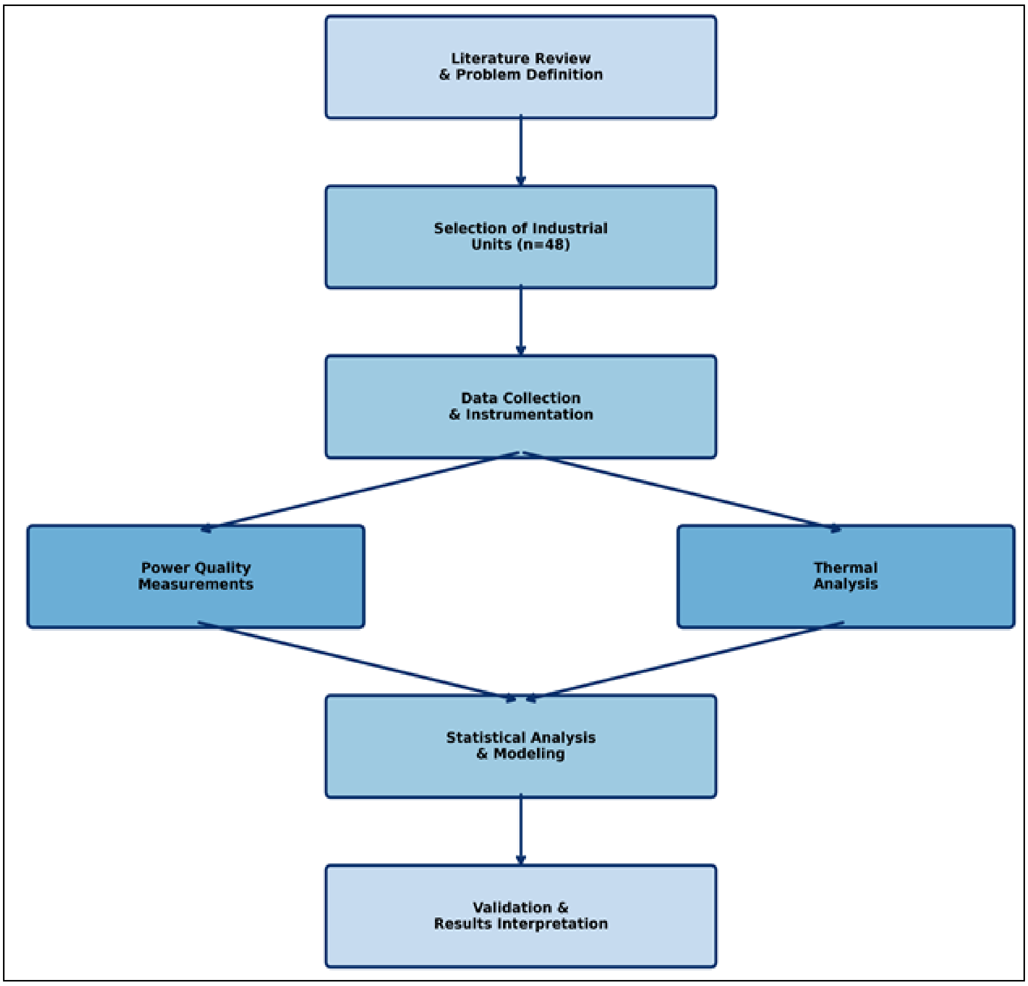

Fig 3: Research methodology illustrating the systematic approach from literature review through validation and results interpretation.

Comprehensive Interpretation

The optimization trials conducted at eight volunteer facilities demonstrated substantial improvement potential. Figure 4 compares pre-optimization and post-optimization loss components, showing meaningful reductions across all loss categories following implementation of recommended measures including conductor upgrades, connection maintenance, and harmonic filtering.

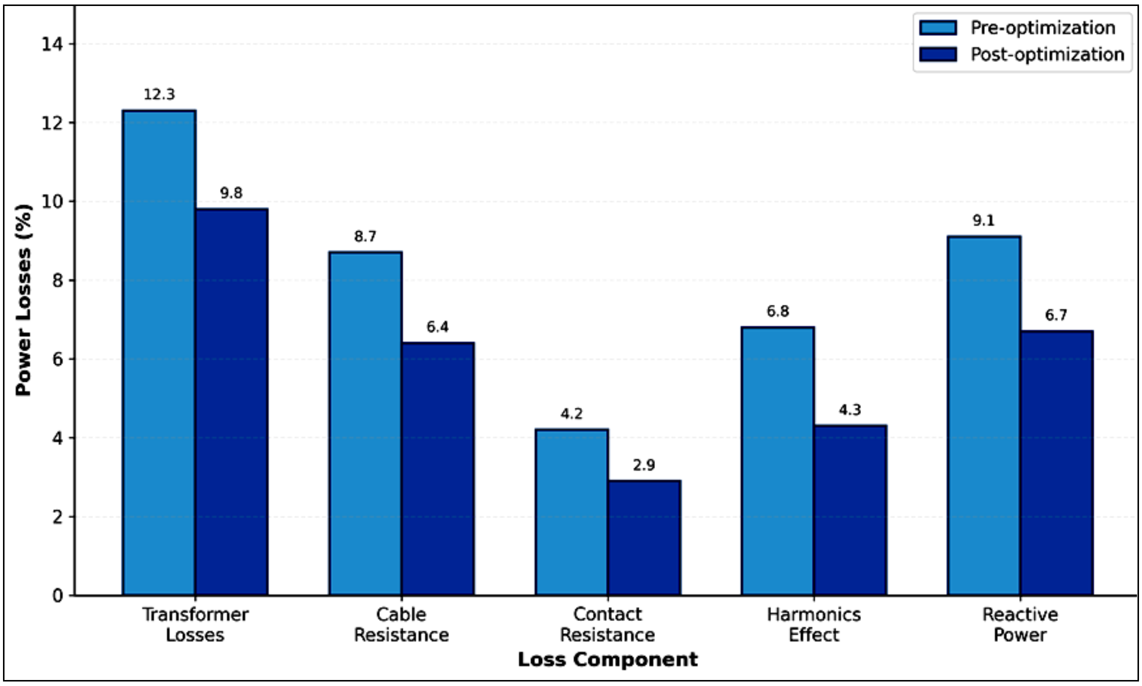

Fig 4: Comparison of power loss components before and after implementation of optimization measures in pilot facilities.

Discussion

The transmission efficiency values observed in this research align with theoretical expectations for systems of this age and configuration, though the magnitude of losses may surprise facility operators accustomed to assuming their electrical infrastructure functions optimally. The finding that textile mills exhibited the poorest performance reflects several sector-specific factors. These facilities typically feature extensive motor-driven machinery with high starting currents and variable loading profiles that challenge transformer sizing assumptions made during original installation. Additionally, many textile operations occupy older industrial buildings with wiring systems designed for considerably lower power densities than current equipment demands.

Food processing facilities achieved superior efficiency ratings primarily due to newer installation dates on average and stricter regulatory oversight regarding electrical safety and hygiene requirements. These factors motivated more frequent infrastructure assessments and upgrades compared to other industrial categories. But we should note that even the best-performing category still loses nearly 9% of purchased electrical energy before it reaches production equipment.

The dominance of transformer losses as a single contributor deserves particular attention. Many surveyed facilities operated transformers sized considerably larger than actual connected loads, suggesting original installations anticipated expansion that never materialized. Oversized transformers operating at partial load incur proportionally higher core losses relative to useful power delivered, degrading system efficiency. This pattern appeared especially pronounced in facilities established during economic growth periods of the 1990s and early 2000s.

Harmonic distortion emerged as a more significant factor than initially anticipated. While variable frequency drives provide genuine operational benefits, their proliferation without corresponding power quality mitigation creates cumulative system impacts. The observation that 67% of facilities exceeded recommended distortion limits indicates this issue warrants broader attention from both equipment suppliers and facility managers. Passive harmonic filters offer cost-effective mitigation for existing installations, though optimal filter design requires careful analysis of the specific harmonic spectrum present.

Conclusion

This research provides empirical evidence that small-scale industrial facilities in Germany operate with transmission efficiencies that leave meaningful room for improvement. The examination of 48 facilities across five manufacturing categories revealed average efficiency values ranging from 84.6% to 91.2%, meaning that between 8.8% and 15.4% of purchased electrical energy dissipates as losses before reaching production equipment. These findings carry practical significance for facility operators, energy consultants, and policy makers concerned with industrial energy efficiency.

The loss component analysis identified transformer inefficiencies as the primary contributor at 30.1% of total losses, followed by cable resistance at 21.3% and reactive power effects at 21.5%. Harmonic distortion from non-linear loads contributed 16.7% of losses on average, with this component showing the widest variation between facilities depending on installed variable frequency drive capacity and filtering provisions. Contact resistance at electrical connections accounted for the remaining 10.4%, though thermal imaging revealed several installations where deteriorated connections posed both efficiency and safety concerns.

The simplified analytical model developed through this research enables facility operators to estimate their own transmission losses using readily available information about conductor materials, lengths, and load profiles. While the model incorporates simplifying assumptions that may not capture all site-specific conditions, it provides a reasonable starting point for identifying facilities where detailed assessment would prove most valuable.

Optimization trials at volunteer facilities demonstrated achievable loss reductions between 18.7% and 24.3% through implementation of targeted improvements. Recommended measures include right-sizing of replacement transformers when existing units reach end-of-life, installation of harmonic filters at major non-linear loads, scheduled maintenance of electrical connections using thermal imaging to identify problem areas, and power factor correction to reduce reactive current flow through the distribution system. These interventions typically offer payback periods under three years at current electricity prices in Germany.

Future research should extend this investigation to additional industrial categories and geographic regions to establish broader applicability of the findings. Longitudinal monitoring of facilities implementing optimization measures would provide valuable data on sustained performance improvements and identify any degradation patterns over time. The increasing adoption of photovoltaic generation and battery storage systems at industrial facilities introduces additional variables that merit examination in terms of their interaction with existing distribution infrastructure.

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