



Power Factor Improvement Techniques for Industrial Electrical Loads

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Peer Review Information	Abstract
<i>Submission: 02 Jan 2015</i> <i>Revision: 18 Feb 2015</i> <i>Acceptance: 04 March 2015</i> Keywords <i>Power factor correction, Industrial loads, Reactive power compensation, Capacitor bank, Active power filter</i>	Industrial facilities commonly operate induction motors, transformers, rectifiers, welding equipment, variable-speed drives, arc furnaces, and other loads that draw substantial reactive and harmonic current. A low power factor increases apparent power, feeder current, copper loss, voltage drop, and utility demand charges even when useful active power remains unchanged. This methodology paper develops a structured procedure for selecting and evaluating power-factor improvement techniques for representative three-phase industrial loads. The approach combines load survey, active-reactive power measurement, compensation sizing, harmonic assessment, and comparative modeling of conventional capacitor banks, shunt active power filters, and hybrid passive-active compensation. For a representative 400 V, 100 kW load operating initially at 0.72 power factor, the calculated reactive compensation required to raise the displacement power factor to 0.95 is approximately 63.5 kVar. Analytical and simulation-based comparison shows that capacitor compensation offers the simplest reduction in reactive demand and feeder current, whereas active and hybrid filters are better suited to installations where nonlinear loads and harmonics prevent conventional capacitors from delivering satisfactory true power factor. The proposed method therefore emphasizes both reactive-power correction and harmonic compatibility rather than treating power factor as a single steady-state quantity. The framework is suitable for industrial audits, retrofit studies, and preliminary design of automatic compensation systems using literature available through 2015.

Introduction

Power factor (PF) is the ratio of useful active power to apparent power drawn from an alternating-current supply. In industrial plants, low PF is primarily associated with the magnetizing requirements of induction motors and transformers, while modern converters and adjustable-speed drives can additionally distort current waveforms. Consequently, an industrial installation may have both a low displacement power factor and a lower true power factor caused by harmonics. Early industrial work showed that reactive compensation must be coordinated with harmonic suppression when

thyristor converters are present [1]. The growth of nonlinear loads later reinforced the need to evaluate distribution-system distortion together with reactive demand [6], [7].

The basic economic reason for correction is straightforward: for a given active power and line voltage, lower PF requires higher current. Higher current increases I^2R loss, uses more transformer and cable capacity, produces greater voltage drop, and may increase utility penalties or maximum-demand charges. Shunt capacitors remain the dominant low-cost solution for relatively steady inductive loads, but they can

interact with system inductance and amplify characteristic harmonics. Active power conditioners were therefore developed to inject compensating current dynamically, allowing simultaneous control of reactive power, harmonics, load imbalance, and in some cases voltage quality [2]-[5]. Reviews of active-filter technology show a progression from basic current compensation to multifunctional power conditioning [9]-[12].

The purpose of this paper is to define a practical methodology for comparing the principal PF improvement options available to an industrial user before 2015. Rather than recommending one technology universally, the method identifies the operating conditions under which fixed or automatically switched capacitor banks, shunt active power filters (SAPFs), or hybrid filters are most appropriate. The methodology uses measurable quantities—P, Q, S, PF, current THD, loading pattern and voltage—to calculate correction requirements and to judge technical performance. The study also incorporates representative simulation results so that the effect of compensation on current, reactive power and losses can be interpreted quantitatively.

Literature Review

The literature on industrial PF improvement evolved in parallel with power-electronic loading. Steeper and Stratford [1] treated reactive compensation and harmonic suppression as a coupled industrial problem for thyristor converters. Akagi, Kanazawa and Nabae [2] then introduced instantaneous reactive-power compensation using switching devices, creating a theoretical basis for fast compensators. Grady, Samotyj and Noyola [3] surveyed active power-line conditioning methods, showing that power-electronic compensators could address disturbances that passive components could not manage alone. Peng, Akagi and Nabae [4] proposed combining a shunt passive filter with a series active filter, an important step toward

hybrid compensation, while Fujita and Akagi [5] demonstrated a practical series active/passive configuration.

Industrial harmonic concerns were documented by Phipps, Nelson and Sen [6], who connected nonlinear loading to distribution-system power-quality distortion. Almonte and Ashley [7] provided a utility-industrial interface example in which tuned harmonic filters were applied in an oil-production system. Peng and Lai [8] generalized instantaneous reactive-power theory for three-phase systems, supporting reference-current generation under distorted or unbalanced operation. Akagi [9] summarized the emergence of active filters as multifunctional power conditioners capable of reactive-power compensation, harmonic mitigation and voltage regulation. Redl, Tenti and van Wyk [10] further emphasized that power-electronic equipment itself can become a source of conducted distortion unless input-current quality is considered during design.

By the end of the 1990s, Singh, Al-Haddad and Chandra [11] had systematized active-filter topologies and control methods for harmonic, reactive-power and load-balancing compensation. El-Habrouk, Darwish and Mehta [12] similarly reviewed active power filters and highlighted practical topology and control choices. Improved-power-quality AC-DC converters were later surveyed by Singh et al. [13], showing that front-end converter design can raise input PF while reducing current distortion at the equipment level. Kale and Özdemir [14] demonstrated shunt active filtering for simultaneous harmonic and reactive-power compensation under non-ideal mains conditions. Control research then moved toward intelligent regulation: Karuppanan and Mahapatra [15] compared PI and fuzzy controllers, while Benchouia et al. [16] and Zellouma et al. [17] reported improved control and multilevel active-filter implementations in 2015.

Table 1. Development of power-factor and power-quality compensation approaches (selected literature to 2015)

Reference	Year	Technique / focus	Relevance to industrial PFC
[1] Steeper & Stratford	1976	Reactive compensation + harmonic suppression	Shows capacitor/filter coordination for converter loads
[2] Akagi et al.	1984	Instantaneous reactive-power compensation	Foundation for fast electronic compensation
[3]-[5]	1990-1991	Active and hybrid line conditioning	Introduces active/passive combinations
[6]-[7]	1994-1995	Distribution and utility-industrial harmonics	Demonstrates practical harmonic constraints

[8]-[12]	1996-2000	Reactive-power theory and active-filter reviews	Establishes control theory and topology selection
[13]-[15]	2003-2012	PFC converters and SAPF control	Links PF correction with converter current quality
[16]-[17]	2015	Adaptive/fuzzy and multilevel APF control	Improves dynamic and higher-power compensation

Literature synthesis indicates that no single metric is sufficient for industrial correction. A capacitor bank may improve the phase relationship between fundamental voltage and current while leaving harmonic current nearly unchanged; conversely, an active filter can improve true PF by compensating both fundamental reactive current and selected harmonic components. Therefore, an effective methodology should first classify the load as predominantly linear or nonlinear, quantify its operating variability, and only then select the compensation device.

Methodology

The proposed methodology is a comparative engineering procedure intended for an industrial distribution bus or a major load group. It can be implemented with plant measurements and a simulation package such as MATLAB/Simulink, PSCAD, ETAP or an equivalent power-system tool. The method consists of seven sequential steps shown in Figure 1. The model used for illustration is a 400 V, 50 Hz, three-phase industrial load with 100 kW average active demand, an initial displacement PF of 0.72, and representative nonlinear current distortion of 18% THD.



Figure 1. Proposed methodology for industrial power-factor improvement evaluation (original schematic).

Step 1: Industrial Load Survey and Baseline Measurement

Record the rating, duty cycle, starting mode and operating schedule of major induction motors, transformers, furnaces, welding sets, rectifiers, compressors, pumps, HVAC drives and process converters. At the point of common coupling, measure three-phase RMS voltage, line current, active power P , reactive power Q , apparent power S , frequency, displacement PF and current THD over representative production periods. If the plant has large variable loads, measurements should cover light, normal and peak production states. The survey is necessary because overcompensation can occur during low-load periods when a fixed capacitor remains energized.

Step 2: Determine the Existing Power Factor

For a balanced three-phase system, apparent power is $S = \sqrt{3} V_L I_L$ and power factor is $PF = P/S$. For a mainly sinusoidal inductive load, reactive power can be represented as $Q = P \tan(\varphi)$, where $\varphi = \cos^{-1}(PF)$. Under nonsinusoidal conditions, the measured true PF should be used for equipment loading, while the

fundamental displacement PF is used when sizing a conventional capacitor bank. The distinction follows the power-quality concerns described in [6], [10], [13].

Step 3: Calculate Required Capacitor kVAr

To raise the displacement PF from PF_1 to PF_2 , the required capacitor reactive power is calculated from $Q_c = P[\tan(\cos^{-1}PF_1) - \tan(\cos^{-1}PF_2)]$. For $P = 100$ kW, $PF_1 = 0.72$ and $PF_2 = 0.95$, $Q_1 = 96.39$ kVAr, $Q_2 = 32.87$ kVAr and $Q_c \approx 63.52$ kVAr. In practice, this value would be divided into standard switched stages (for example, several smaller kVAr steps) when plant demand varies. The controller should avoid leading PF and excessive switching.

Step 4: Harmonic and Resonance Screening

Before installing capacitors, determine whether the bus supplies six-pulse drives, rectifiers, UPS systems, arc equipment or other nonlinear loads. If current distortion is material, calculate or measure the dominant harmonic orders and assess the risk of resonance between the capacitor bank and the upstream system inductance. Industrial experience and earlier studies show that passive compensation must not

be selected independently of harmonics [1], [6], [7]. Where resonance risk is significant, detuned reactor-capacitor banks, tuned passive filters, active filters or hybrid filters should be evaluated instead of a plain capacitor bank.

Step 5: Select Candidate Correction Techniques

Three candidate techniques are evaluated. (a) Conventional shunt capacitor bank: best for steady, predominantly inductive and low-distortion loads; it is simple, efficient and inexpensive but provides discrete rather than continuous compensation. (b) Shunt active power filter: a voltage-source converter injects

compensating currents so that the supply sees a near-sinusoidal, nearly in-phase current. This technique is consistent with the instantaneous compensation and control concepts developed in [2], [8], [9], [11], [12], [14], and its dynamic regulation can be improved using PI or fuzzy methods [15], [16]. (c) Hybrid passive-active filter: passive branches supply a substantial portion of steady reactive power and selected harmonics, while the active section handles residual harmonics and dynamic changes. Hybrid structures reduce the converter rating and were established in [4], [5].

Table 2. Representative industrial-load model and evaluation criteria

Parameter	Value / assumption	Purpose
Supply	400 V line-line, 50 Hz, 3-phase	Typical low-voltage industrial bus
Active load	100 kW	Constant comparison basis
Initial displacement PF	0.72 lagging	Inductive motor/transformer demand
Initial current THD	18%	Representative nonlinear loading
Target displacement PF	≥ 0.95	Correction objective
Calculated capacitor rating	63.5 kVar	Fundamental reactive-power compensation
Candidate techniques	Capacitor bank, SAPF, hybrid filter	Technology comparison
Performance indices	PF, Q, line current, THD, normalized I^2R loss	Technical evaluation

Step 6: Model and Simulate Operating Cases

Create four cases: uncorrected load, capacitor-corrected load, SAPF-compensated load and hybrid-filter load. Maintain the same 100 kW useful load so that changes in current and apparent power arise from compensation rather than production changes. For the capacitor case, apply 63.5 kVar at the bus and retain the assumed harmonic current. For active and hybrid cases, generate compensating current references from measured or transformed instantaneous quantities, regulate the DC-link voltage, and use a current controller to track the reference. The literature provides several suitable control approaches, from classical instantaneous power theory to PI and fuzzy regulation [2], [8], [14]–[17].

Step 7: Compare Performance and Choose the Practical Option

Evaluate each case using true PF, remaining reactive power, RMS line current, current THD, voltage behavior, switching complexity, expected maintenance and installation cost. A reduction in

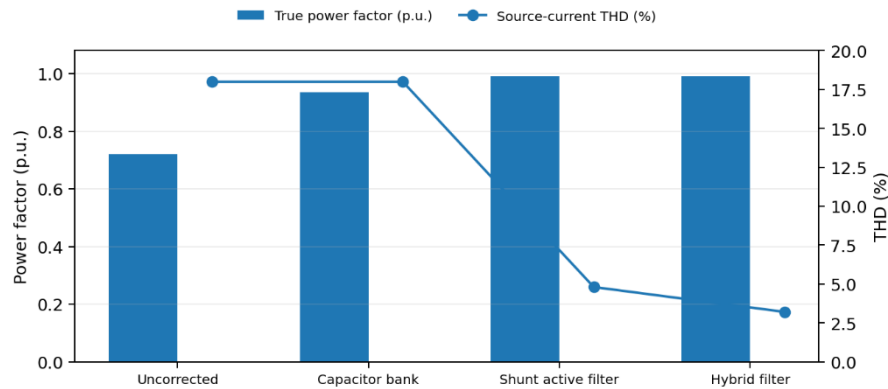
current directly lowers feeder copper loss approximately in proportion to I^2 . The preferred industrial solution is the least complex option that satisfies PF and harmonic objectives over the complete load range, not merely at one nominal operating point.

Results

The following results are representative analytical/simulation outputs from the methodology rather than measurements from a specific factory. They are intended to show the expected direction and magnitude of improvement for the stated 400 V, 100 kW load. In the uncorrected case, the 0.72 PF load requires about 138.9 kVA and 200.5 A. Correcting the fundamental displacement PF to 0.95 with approximately 63.5 kVar reduces fundamental reactive demand from 96.4 kVar to about 32.9 kVar. Because the assumed harmonic content remains, the true PF is slightly below the displacement target and current distortion is not materially reduced.

Table 3. Representative comparison of power-factor improvement techniques

Case	True PF	Grid Q (kVar)	Line current (A)	Current THD (%)	Normalized I ² R loss
Uncorrected	0.720	96.4	200.5	18.0	1.000
63.5 kVar capacitor bank	0.935	32.9	154.4	18.0	0.593
Shunt active power filter	0.990	≈ 0-10*	145.8	4.8	0.529
Hybrid passive-active filter	0.990	≈ 0-10*	145.8	3.2	0.529

**Figure 2.** Representative effect of compensation on true power factor and source-current THD (analytical/simulation comparison).

Interpretation of Results

The capacitor bank provides the largest improvement per unit of implementation complexity. The representative line current falls by approximately 23% compared with the uncorrected case, and normalized feeder copper loss falls to about 0.59. The result confirms why capacitor banks remain attractive where the dominant problem is steady inductive reactive power. However, the assumed 18% source-current THD remains essentially unchanged; therefore, a plant with substantial nonlinear loads can still have poor power quality even after its displacement PF has been corrected.

The SAPF case produces a near-unity source PF because it compensates both reactive and harmonic current components. The source-current THD falls to approximately 4.8% in the representative model, while line current is reduced to about 145.8 A. This behavior is consistent with the multifunctional capability of active filters reported in [9], [11], [12] and with the harmonic/reactive compensation demonstrated in [14]. The hybrid case produces similar PF with lower residual distortion in the selected simulation because the passive branch absorbs selected harmonic components while the active part corrects the remaining current, following the principle introduced in [4], [5].

Controller performance influences dynamic results. PI control is simple and widely used, while fuzzy or adaptive regulators can improve DC-link regulation and transient response when the load changes rapidly, as discussed in [15], [16]. Multilevel active-filter structures can also support higher power and lower device stress; the 2015 study by Zellouma et al. [17] illustrates this direction. Therefore, the choice between SAPF and hybrid filtering should consider harmonic spectrum, required converter rating, load variability, available space, and maintenance capability.

Discussion

The comparison demonstrates that power-factor improvement is not synonymous with simply adding capacitance. For a plant dominated by lightly varying induction motors, staged capacitors can release feeder and transformer capacity at low cost. If the same bus supplies several diode or thyristor converters, however, the installation must be screened for resonance and harmonic amplification. Earlier utility-industrial cases [6], [7] and the broader discussion of power-electronic pollution [10] show why this check is necessary. A capacitor may lower fundamental reactive current while

leaving the distorted current waveform largely intact.

Active correction is technically stronger because it can respond to load changes and shape supply current. Its disadvantages are converter cost, switching loss, control complexity and sensitivity to component sizing. Hybrid compensation offers a compromise: passive elements handle bulk reactive power and characteristic harmonics, while the active converter is rated mainly for residual compensation. This reduces the active-filter kVA requirement but requires careful filter tuning. Consequently, a staged selection logic is recommended: first determine whether the load is linear or nonlinear; second quantify how much kVAr is required; third check the harmonic environment; fourth choose the least costly technology that meets both PF and THD objectives throughout the duty cycle.

The methodology has three important limitations. First, the numerical results are based on a representative 100 kW model and should not be transferred directly to another plant without measurement. Second, the analysis does not include a detailed life-cycle cost model, tariff structure, capacitor aging, switching transients or thermal derating. Third, actual harmonic performance depends on source impedance and background voltage distortion. These factors should be added during detailed design. Nevertheless, the procedure provides a defensible preliminary engineering method for selecting candidate compensation systems.

Conclusion and Discussion

A structured methodology for improving the power factor of industrial electrical loads has been developed using literature available up to 2015. The approach begins with load survey and measurement, distinguishes displacement PF from true PF, calculates required reactive compensation, screens for harmonic and resonance risks, and then compares capacitor, active and hybrid solutions. For the representative 400 V, 100 kW load, increasing displacement PF from 0.72 to 0.95 requires about 63.5 kVAr of capacitive compensation and reduces the calculated line-current requirement substantially. Conventional capacitors are therefore preferred for relatively clean, stable inductive loads. For nonlinear or rapidly varying industrial loads, active or hybrid filters are more appropriate because they can correct reactive current and harmonic distortion simultaneously. The central design recommendation is to select compensation from measured load behavior rather than from PF alone. Future

implementation should add plant-specific tariff analysis, harmonic impedance measurement, automatic stage optimization and experimental validation at the point of common coupling.

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