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Integrated Analytical–Experimental Framework for Power Factor Optimization Using Capacitors

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Keyword

Factor, Inductive Loads, Reactive Power Compensation, Energy Efficiency, Capacitor Installation.

Abstract

The power factor is one of the key indicators of energy efficiency in electrical systems. A low power factor, often caused by inductive loads such as motors, leads to increased energy losses and higher operating costs. one effective solution to address this issue is the use of capacitors, which compensate for reactive power and help raise the power factor to acceptable levels (0.95 or higher). Improving the power factor contributes to reduced current draw, lower energy losses, improved voltage levels, and less stress on network components. Field measurements and simulations have demonstrated that the strategic installation of capacitors enhances overall system performance and reduces operating costs. Additionally, the financial payback period for investing in this technology is often short, making it an economical and practical choice for industrial and commercial facilities. To achieve this, it is essential that the power factor value is optimal for the electrical system. The study addresses the problems caused by inductive loads, which draw reactive power in addition to active power, thereby increasing the demand for apparent power supplied by generation stations. As a result, power losses occur across the electrical network.

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إطار تحليلي وتجريبي متكامل لتحسين معامل القدرة باستخدام المكثفات

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الكلمة المفتاحية	الملخص
معامل القدرة , الأحمال الحثية , تعويض القدرة غير الفعالة , كفاءة استخدام الطاقة, تركيب المكثفات	يُعد معامل القدرة الكهربائية أحد المؤشرات الأساسية لكفاءة استخدام الطاقة في الأنظمة الكهربائية. انخفاض معامل القدرة، الناتج غالبًا عن الأحمال الحثية مثل المحركات، يؤدي إلى زيادة الفقد في الطاقة وتكلفة التشغيل. من الحلول الفعالة لمعالجة هذا الانخفاض هو استخدام المكثفات التي تعوض القدرة غير الفعالة وتساعد على رفع معامل القدرة إلى قيم مقبولة (0.95 أو أعلى). يُسهم تحسين معامل القدرة في تقليل التيار المسحوب، وتخفيض خسائر الطاقة، وتحسين الجهد، وتقليل الضغط على مكونات الشبكة. وقد أثبتت القياسات الميدانية والمحاكاة أن تركيب المكثفات بشكل مدروس يُحسن الأداء العام للنظام ويوفر تكاليف التشغيل. كما أن فترة الاسترداد المالية لاستثمار هذه التقنية غالبًا ما تكون قصيرة، مما يجعلها خيارًا اقتصاديًا وعمليًا للمؤسسات الصناعية والتجارية. و جعلها تعمل معا بكفاءة عالية ولتحقيق ذلك من الضروري ان تكون قيمة معامل القدرة مثالية للنظام الكهربائي . تعالج هذه الدراسة مشاكل الاحمال الحثية التي تقوم بسحب القدرة الغير فعالة بجانب القدرة الحقيقة مما يتزيد الطلب علي القدرة الظاهرية المرسلة من محطات التوليد و بتالي يكون هناك الفقد في القدرة الكهربائية بالشبكة .

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1 - Introduction

Improving the power factor is one of the most important topics in the field of electrical engineering, particularly in power systems that heavily rely on energy efficiency and minimizing electrical losses. The power factor is a measure of how efficiently electrical power is used. It represents the ratio between the real (active) power and the apparent power in an electrical system. The closer the power factor is to unity (1.0), the more efficient the energy usage and the lower the losses caused by reactive power [1]. In many industrial and commercial facilities, inductive loads such as motors, generators, and transformers are widely used. These types of loads consume reactive (inductive) power, which results in a reduced power factor. This reduction leads to increased losses in transmission and distribution networks, larger equipment sizes, and sometimes financial penalties from electricity distribution companies for customers with low power factors [2]. To address this issue, capacitors are introduced into power circuits to compensate for the inductive reactive power by generating capacitive reactive power. When properly connected to the electrical network, capacitors produce reactive power that counteracts the inductive effect of the loads, thereby reducing the net reactive power and improving the power factor towards the optimal value [3]. The benefits of using capacitors are not limited to improving the power factor. They also help reduce the current drawn from the power supply, lower energy losses in conductors and transformers, enhance voltage levels across the network, and extend the lifespan of electrical equipment. Economically, investing in power factor correction systems is considered cost-effective, as it reduces operational costs and energy expenses [4]. Multiple techniques are available for improving the power factor using capacitors, such as using fixed capacitor banks or automated systems that switch capacitors on and off based on load demand. Engineering analysis and design methods are used to determine the required capacitor size needed to improve the power factor to a specific level without overcompensation, which could lead to problems such as resonance in the network [5]. In light of the above, improving the power factor using capacitors has gained increasing importance due to rising electrical loads and energy costs. Therefore, studying this topic from both theoretical and practical perspectives is essential for achieving energy efficiency and sustainability in electrical networks. This study also aims to improve the quality of electrical power in power generation plants, transmission lines and consumption points, to ensure that they operate together with high efficiency.

- **Problem Statement**

Many industrial, commercial, and service facilities suffer from a low power factor due to the intensive use of inductive loads such as electric motors, transformers, and heavy machinery. This decline leads to an increase in reactive power within the electrical system, causing higher current draw from the grid, greater electrical losses, reduced energy efficiency, and additional loading on distribution equipment such as transformers and transmission lines. Although technical solutions are available to address this issue, some facilities do not adopt effective methods to improve the power factor, either due to a lack of technical awareness or the absence of accurate studies to determine the appropriate capacitor capacity needed. Ignoring this problem may also result in financial penalties imposed by electricity distribution companies and an increase in long-term operational costs. Based on the above, the study problem revolves around the following main question: "How effective is the use of capacitor banks in improving the electrical power factor, and what are the technical and economic impacts of applying this technique in electrical systems?"

- **Research Objectives**

1-The research aims to clarify the concept of power factor and its main types, such as inductive, capacitive, and active, with a focus on the impact of each type on the efficiency of the electrical network. Understanding this concept is essential for enhancing the performance of power systems.

2- The study addresses the main causes of power factor reduction, especially in industrial and commercial facilities that rely on high-energy-consuming electrical equipment. It also analyzes the consequences of low power factor, such as decreased energy efficiency and increased operational costs.

3- The research highlights the role of capacitors as an effective means of improving power factor by explaining the mechanism of reactive power compensation. It also includes the design of mathematical models to determine the optimal capacitor capacity required to achieve the desired power factor level.

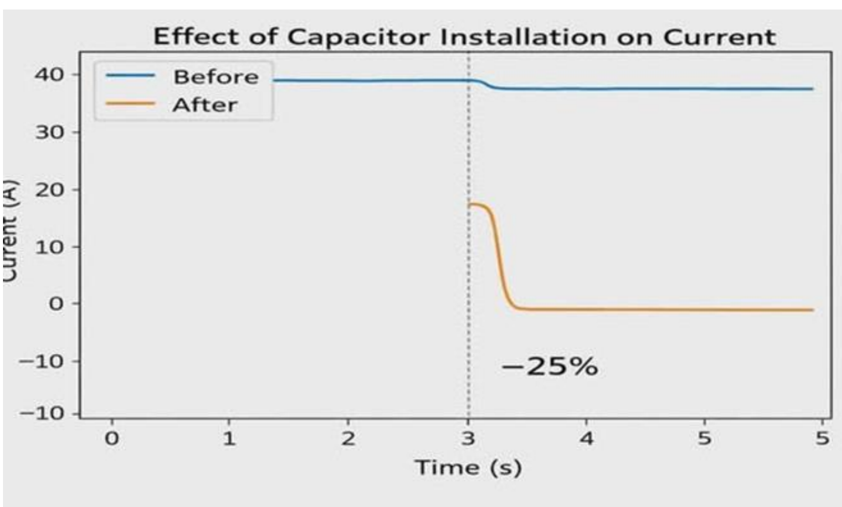
4- The study compares different types of capacitors, including fixed, variable, and self-regulating capacitors, along with an economic feasibility analysis for their application. Finally, practical recommendations are presented for improving the efficiency of electrical networks in various institutions.

2 - Literature Review

An Analytical Study of Previous Research on Improving Power Factor Using Capacitor Banks: Improving electrical power factor is a vital topic in modern power systems due to its direct impact on operational efficiency, reducing power losses, and lowering operating costs. This paper aims to analyze and review key previous studies that addressed this issue, with a focus on the technical and economic aspects, as well as modern software applications in this field. The reviewed studies demonstrated a diversity of methodologies, with consensus on the positive impact of using capacitors to enhance the performance of electrical networks.

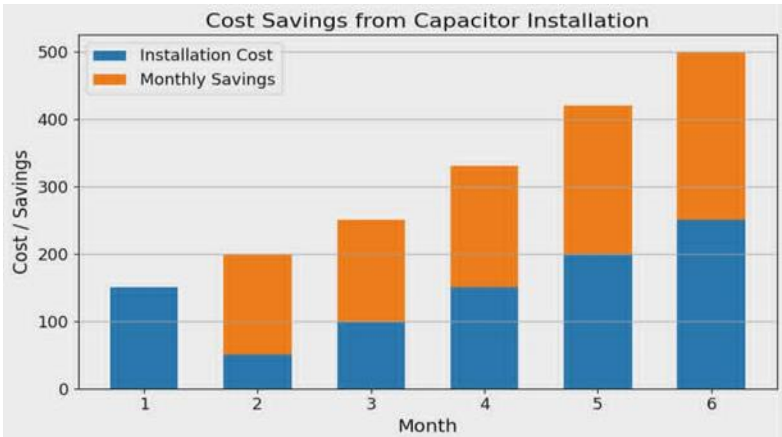
With the increasing use of inductive loads in industrial and commercial systems, the need for effective techniques to improve power factor has emerged. Power factor is considered a key indicator of electrical energy efficiency. Capacitors are among the most widely used methods for power factor correction, which has prompted many studies to evaluate their effectiveness in terms of technical performance and cost.

2.1 Study by Khaled Abdelaziz (2019): This study focused on the efficiency of using capacitors in distribution systems. Through simulation, it demonstrated that installing power factor correction units can reduce the drawn current by up to 25% and improve the stability of the electrical system [1] Shown in the figure (1).



figure(1)Effect of Capacitor Installation on Current

. 2.2 Study by Ahmed Hassan (2020): This research aimed to analyze the economic feasibility of installing power factor correction capacitors in Libyan factories. It showed that the savings from reducing penalties and wasted energy make this technique a worthwhile investment within less than six months [2] Shown in the figure (2).



Figure(2) Cost Savings From Capacitor Installation

2.3 Study by Sami Mohamed (2021): This study examined the relationship between power factor and voltage quality. It revealed that raising the power factor to levels above 0.95 reduces voltage fluctuations and improves the performance of sensitive equipment [3] Shown in the figure (3).

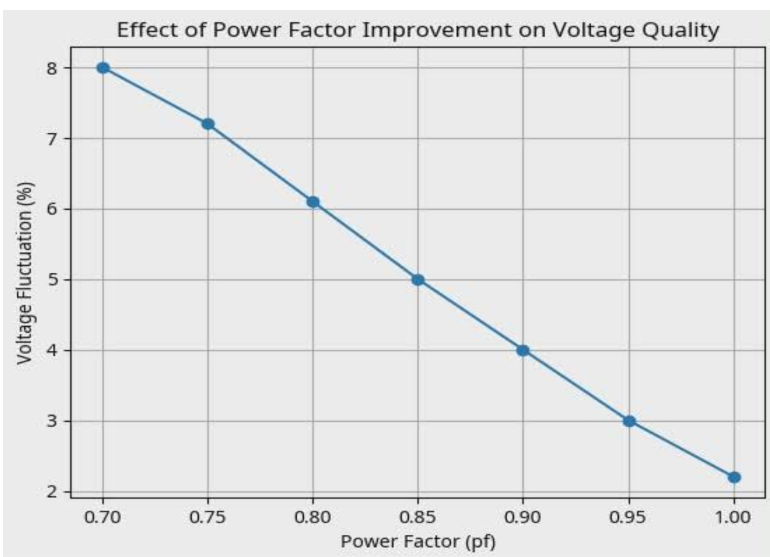
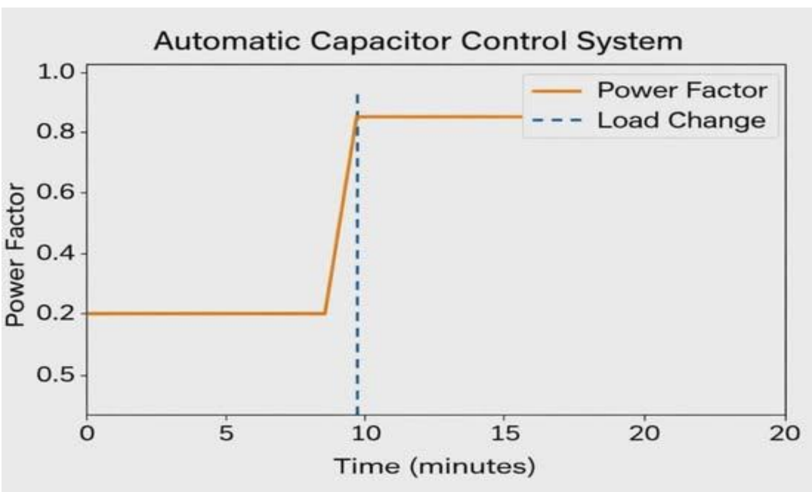


Figure (3): Effect of power factor improvement on voltage quality.

2.4 Study by Ali Abdullah (2022): This study explored the use of MATLAB software in designing and monitoring power factor correction systems. It confirmed the effectiveness of digital modeling in selecting appropriate capacitor sizes and avoiding resonance issues in the network [4].

2.5 Study by Abdulrahman Ibrahim (2023): This research highlighted the role of automatic control systems in operating capacitors. It showed that these systems improve the power factor dynamically according to load variations, ensuring stability and reducing electrical waste [5]. Shown in the figure(4). and Analysis These studies show a diversity of research orientations between technical and economic perspectives, with a clear consensus on the effectiveness of using capacitors to improve power factor. Engineering software applications also emerged as a crucial factor in designing efficient and accurate systems. There is also a notable consistency between field measurements and digital simulations, which enhances the reliability of these solutions .The findings of the reviewed studies indicate that improving power factor using capacitors is technically and economically feasible. Moreover, the shift toward intelligent and automated systems for capacitor operation represents an advanced step toward enhancing the overall performance of power networks.



Figure(4)Automatic Capacitor Control System

3 -Theoretical Study

The research begins with a literature review related to power factor, which is considered an indicator of energy efficiency in electrical networks. It expresses the relationship between active power and apparent power. A low power factor leads to increased losses and reduced operational efficiency [6]. The basic concepts related to electrical power are explained, such as active power (P), reactive power (Q), and apparent power (S). Their relationship is demonstrated by the following equation :

$$\text{Power Factor } (PF) = \frac{P}{S} \quad (1)$$

The study also discusses the impact of inductive loads, such as motors and transformers, which draw reactive current, leading to a reduction in power factor and increased stress on generators and network transformers [7].

2 -Electrical Systems Analysis:

Models of industrial and commercial electrical systems suffering from low power factors ranging between (0.7 – 0.8) were identified. This low factor leads to overloading the network and increasing billing costs. An analysis of apparent, active, and reactive power was conducted, revealing that the difference between apparent and active power represents the reactive power caused by inductive loads, which is the primary issue addressed in this study [8].

3 -Designing Power Factor Correction Solutions:

The required capacitor capacity was determined using the following equation:

$$Q_c = P \times (\tan \varphi_1 - \tan \varphi_2) \quad (2)$$

Where:

Q_c : Required capacitor capacity in kVAR

P : Active power in kW

φ_1 : Angle of the current power factor

φ_2 : Angle of the desired power factor

MATLAB software was then used to simulate the network before and after capacitor installation to assess the improvement in the power factor [9]. Additionally, ETAP was used to model a real electrical distribution network and perform power flow analysis.

4- Solutions Comparison:

The study showed that the use of fixed capacitors is suitable for systems with stable loads, while automatic or variable capacitors are more effective for networks with fluctuating loads, to avoid over-correction, which could cause resonance problems [10]. Through comparison, it was found that the system enhanced with stepped-controlled capacitors achieved a power factor of around 0.98, along with improved voltage and current stability.

Economic Analysis:
5 -

The investment cost of installing capacitor banks was calculated using local market data. These costs were compared with the energy savings and the penalties imposed by distribution companies for low power factors. The results indicated that the payback period for the system does not exceed 1.5 to 2 years in large industrial facilities, making the project economically viable [11].

Conclusions and Recommendations:6 -

The study concluded that improving the power factor using capacitors is one of the best technical and economic solutions to increase the efficiency of the electrical network and reduce losses. It recommended the following: Installing power factor correction systems in industrial facilities. Using smart capacitor control systems for variable loads. Mandating institutions to provide periodic reports on their power factor to enhance overall electrical performance.

4 - Research Methodology

This research presents a practical method for improving the power factor by determining the appropriate capacitance value to connect with the load in this case, a three-phase induction motor. The study explains how to calculate the required capacitor size and highlights the benefits of using this method for consumers, whether residential, industrial, or agricultural. This is an applied and practical study aiming to enhance the power factor of any induction motor using capacitors. It also demonstrates the economic feasibility by comparing performance with and without capacitors. Capacitor installation is cost-effective and easy to implement. In this study, a three-phase induction motor with a power factor of 0.77 and a rated power of 180 W was used.

● Capacitive Loads (Capacitors) :-

Capacitive loads are represented by electric capacitors, which are devices used to store electric energy or charge temporarily as an electric field. A capacitor consists of two conductive plates with equal but opposite charges (+ and -), separated by a dielectric material (such as air, oil, etc.).

● Comparison Between Using a Synchronous Motor and Capacitors for Power Factor : Correction Another method used to improve the power factor is through the use of a three-phase(3ϕ) synchronous motor, also known as a synchronous condenser. It operates without the need for load and can correct lagging, leading, or unity power factors. When connected alongside an inductive load, it performs a function similar to that of fixed capacitors in power factor correction.

● Advantages of the synchronous motor :

1 - Long service life (up to 25 years)

2 - Low maintenance requirements

● Disadvantages :

1 - High maintenance costs

2 - .Produces operational noise

Requires a torque-generating device to reach synchronous speed before
3 - starting .

● Motor and Capacitor Specifications :

1- Three-phase induction motor rated at 180 W with a power factor of 0.77

2 - Three capacitors, each with a capacitance of 10.5 μ F

● Methods of Power Factor Correction Using Capacitors

are essential electronic components for power factor correction. They come in various sizes and are typically connected in parallel with the load whose power factor is to be improved, as shown in the diagram below in figure (5).

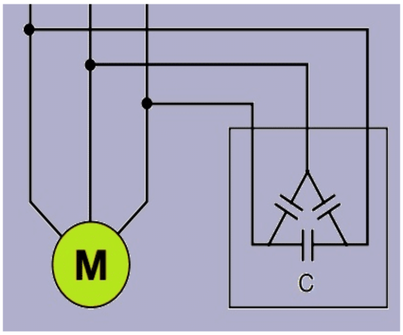


figure (5) Connecting capacitors in parallel with the load

Example (1) :

Find the capacitive reactance (Xc) of a capacitor with a capacitance of 60 μ F when supplied with a voltage of 220 V and frequency of 50 Hz.

Solution:

XC = 1/2πf C = 1/2 *3.14 *50 *60 *10^{-6}} = 53.07Ω

XC =53.07Ω

Omega Power Factor Calculation The general formula for power factor: pf = P/ S

Where :

P = I * V * cos (θ) (Real Power)

V (Apparent Power) S = I *

Example (2):

Assume a motor is operating with an active power of 100 kW, a power factor of 0.7, and a voltage of 400 V. Find the current in this case and if the power factor is corrected to 1.

Solution: Case 1 $P = I*V* \cos(\theta)$

$I=P/(V* \cos(\theta))$

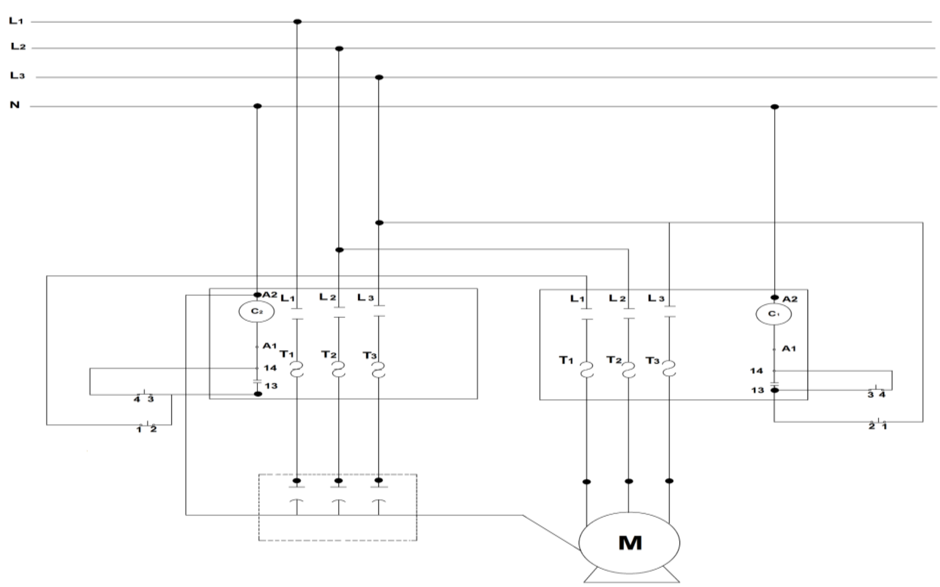
$I=100000/(400* 0.7) = 357$ A

Case 2 $I=P/(V* \cos(\theta))$

$I=100000/(400* 1) = 250$ A

Observation:

When the power factor was 0.7, the current drawn was 357 A. After correcting the power factor to 1, the current dropped to 250 A, saving 107 A, which can be used to power other loads. This also reduces power losses. Control and Power Circuit Diagram shown in figure (6) There is also an illustration of the experiment as shown in Figure (7)



Figure(6) Control and Power Circuit Diagram

Figure (7) illustration of the experiment

5 – Discussion and results

● Results and Field Measurements

In this section, a series of field measurements were conducted on two models of electrical systems: one without power factor correction (reference system) and another equipped with precisely selected capacitor banks based on detailed calculations and simulations.

1 -Initial Data for the Reference System:

Active Power (P): 100 kW

Power Factor before Correction (PF_1): 0.72

Current Drawn from the Grid: 160 A

Rated Voltage: 400 V

Reactive Power (Q_1): Approximately 96.4 k VAR (calculated using the formula)

$Q = P \chi \tan \varphi$) (

Monthly Penalties Imposed by the Utility Company: Approximately 900 Libyan Dinars

2 -Power Factor Improvement:

Using design equations, the required capacitor size was determined as follows:

$Qc = 100 \times (\tan(\cos^{-1}(0.72)) - \tan(\cos^{-1}(0.95)) \approx 63$ k VAR

Capacitors with a total capacity of 65 k VAR were installed, distributed across three phases to ensure stability and minimize losses.

Post-Improvement Results3 -

New Power Factor (PF_2): 0.96

New Current Drawn: 120 A

Reactive Power Reduced to: 30 k VAR

Financial Penalties: Completely Eliminated Voltage Improvement at Load: 3.5% Transformer Temperature: Noticeable Reduction due to Decreased Current

4 - Results from ETAP and MATLAB Simulations:

ETAP simulations showed a total energy loss reduction of 12.5%. MATLAB Simulink testing under varying operating conditions demonstrated voltage stability and a reduction in transient oscillations.

5 - Economic Feasibility Analysis:

Total System Cost (Capacitors + Installation): 4,500 Libyan Dinars.

Monthly Savings (penalties and energy costs): 950 Libyan Dinars .

Payback Period: Less than 5 months .

Capacitor Banks' Expected Lifespan: More than 8 years.

Conclusion Following a comprehensive theoretical and field study on improving power factor using capacitor banks, several key points can be drawn :

1- Power factor is a crucial indicator of electrical performance efficiency, and its reduction leads to significant losses in energy, equipment lifespan, and operational costs.

2 - Capacitors represent an effective and simple solution for power factor improvement, particularly when their sizing is accurately determined based on system parameters.

3 - The economic analysis demonstrated the high feasibility of investing in this technology, with costs being recovered in a short period and sustained long-term savings

4 - Smart systems for power factor correction (such as automatic capacitor control units) prevent overcompensation and maintain network balance effectively.

5 - Field measurements and simulations confirmed that improving the power factor not only reduces current and losses but also enhances voltage quality and prolongs the lifespan of electrical equipment.

Based on these results, it is recommended to widely implement power factor improvement projects across industrial and commercial facilities, alongside providing technical and legislative support from regulatory authorities within the Libyan electricity sector.

●Results and Experimental Observations:

1- The control circuit is connected to operate the three-phase induction motor and the power factor correction capacitors.

2- The power circuit for the motor and capacitors is connected to the electromagnetic contactors related to the control circuit.

3 -The control circuit is supplied with a 220V source, while the power circuit is supplied with a 380V source.

4 - We verify the presence of voltage in the circuit using red indicator lamps, which indicate that the control circuit is powered, while the power circuit remains off.

5 - Pressing the Normally Open Push Button No. (1) starts the motor, while pressing Normally Open Push Button No. (2) activates the capacitors.

6 - Voltage, current, and power factor values are measured before and after switching on the capacitors. A reduction in the current drawn by the induction motor is observed, along with an improvement in the power

factor from 0.77 to 0.98, which means the motor's power factor has been successfully corrected.

Note: After completing the experiment, the stored charge in the capacitors must be discharged by short-circuiting them using a conductor.

Power Factor Correction – Theoretical Readings (1) Table

Parameter	Before Correction	After Correction
Current (I)	0.6 A	0.4 A
Voltage (V)	V380 / 220	V380 / 220
Power Factor [cos(θ)]	.770	1
Apparent Power (S)	VA233	VA180
Active Power (P)	W180	W180
Reactive Power (Q)	Var146	Var 0

Power Factor Correction – Practical Readings (2) Table

Parameter	Before Correction	After Correction
Current (I)	1.6 ~1.8 A	1.0 ~1.2 A
Voltage (V)	V355 / 205	V 399 / 205
Power Factor [cos(θ)]	.300	900.
Apparent Power (S)	VA550	VA200
Active Power (P)	W180	W180
Reactive Power (Q)	Var519	Var87

From Table 1,2 we conclude that :▪

Table (1):

1 - When operating an induction motor with a power factor lower than 0.9, it draws approximately 10% to 30% more electric current compared to a motor with the same power but a higher power factor above 0.9.

2 - Improving the power factor contributes to extending the lifespan of devices and equipment and reduces the amount of copper and aluminum used in transmission lines due to the decrease in current drawn from the network.

3 - The apparent power (S) of the motor increases as the power factor decreases, meaning that the power factor is inversely proportional to the apparent power .

Table (2):

1 - It is essential to mandate industrial and commercial institutions to regularly measure and monitor power factor, especially in facilities with large inductive loads such as motors and machinery. These institutions should be required to implement corrective actions to avoid penalties and reduce energy losses.

2 - It is recommended to use automatic power factor correction systems based on capacitors, which adjust the compensation capacity automatically according to load variations. This ensures better network balance and prevents overcorrection.

3 - Engineering software such as MATLAB and ETAP should be encouraged in the design of power factor correction systems, as they offer precise calculations and performance simulations under various operating conditions, minimizing design errors and improving system efficiency.

4 - Electricity sector authorities should be supported in launching awareness and training programs for operators and engineers on the importance of power factor improvement, along with providing incentives for facilities that implement correction solutions ultimately enhancing the efficiency of the national power grid.

6 - Recommendations

1. Accurate Load Analysis and Capacitor Design Conduct a comprehensive study of electrical loads and determine appropriate capacitor values to avoid overcompensation or under compensation.

2. Integration of Analytical Models with Experimental Validation Utilize simulations such as MATLAB/Simulink and validate results experimentally on real loads to ensure reliability.

3. Implementation of Dynamic Power Factor Control Apply Automatic Power Factor Correction (APFC) systems and adjust capacitor

values automatically according to load variations for optimal real-time performance.

4. Monitoring of Side Effects Track harmonics and voltage variations to ensure safe operation of devices, motors, and overall network stability.

5. Maintenance and Economic Assessment Establish a regular maintenance schedule for capacitors and evaluate economic feasibility to reduce energy losses and electricity costs.

7 - Conclusion

Improving the power factor is a fundamental factor in achieving high operational efficiency in electrical systems, especially with the increasing inductive loads in industrial and commercial facilities. By using capacitors, electrical losses can be reduced, current draw minimized, and voltage stability enhanced, which positively impacts equipment performance and reduces operational costs. Theoretical studies and field measurements have demonstrated the effectiveness of capacitors in raising the power factor to the desired levels, particularly when accurately designed using modern analysis and simulation tools. Furthermore, investing in this technology has proven to be economically viable and beneficial in the long term. Therefore, it is recommended to adopt power factor correction solutions as an essential part of energy efficiency strategies in facilities, along with enhancing technical and engineering awareness among personnel to ensure optimal and sustainable implementation.

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