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Optimization of Series and Shunt Capacitor Compensation for Power Factor Improvement in Electrical Power Systems

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Abstract: Background: Power factor improvement stands as a vital requirement because low power factor generates multiple challenges which include rising power loss during transmission and unstable voltage levels and decreased system operational capacity. The solution to these problems arrives through capacitor compensation which uses shunt capacitors as the main solution for actual operational systems. Methods: This study conducted a quantitative data gathering first-hand information from 185 electrical experts completed a standardized survey. The study selected participants demonstrated specific expertise through its purposive sampling technique. Descriptive statistics together with Pearson correlation analysis to study power factor improvement relates to shunt capacitors and series capacitors and load levels and harmonic distortion and voltage levels and power loss reduction. Results: Shunt capacitors serve as the primary solution which users select at 68.1% frequency while hybrid systems follow at 57.8% and users select series capacitors at 51.9%. The primary advantage exists in power factor enhancement which accounts for 40.0% of the benefits followed by efficiency improvement at 28.1%. The correlation analysis demonstrates that shunt capacitor usage produces the most substantial positive correlation with power factor improvement at $r = 0.72$ and series capacitors create a substantial effect at $r = 0.65$. Power loss reduction ($r = 0.60$) and voltage level ($r = 0.54$) demonstrate moderate positive relationships. The system performance shows negative effects from harmonic distortion because of the correlation coefficient which reached -0.51. Conclusion: The study establishes that shunt capacitor compensation serves as the main power factor enhancement method which delivers the most effective results.

Keywords: Shunt Capacitor, Series Capacitor, Electrical Power System, Power Factor Improvement, Correlation Analysis.

1. Introduction

The core of modern industrial development and socio-economic growth depends on electrical power systems which face growing operational challenges because of increasing energy needs and complicated electrical load patterns [1]. Power factor stands as the most essential performance metric which shows well a system uses its electrical power [2]. The power system experiences major problems because of low power factor values which create high current flow and transmission losses and unstable voltage levels and reduced system capacity [3]. Technical systems function at lower performance levels because of these problems which generate major financial losses for utilities and their customers [4]. Reactive power in industrial and distribution systems leads to about 20-30% higher energy losses which makes power factor correction essential for achieving sustainable and affordable operations [5], [6].

Power factor improvement and system efficiency optimization become possible through capacitor compensation which provides an affordable and dependable solution [7]. The system achieves better voltage control and reduced transmission losses through its capacitor system which delivers localized reactive power support to reduce the reactive power demand from transmission lines [8]. Shunt capacitors serve as popular distribution network components because they offer basic operation at minimal installation expenses [9]. Transmission systems employ series capacitors to maintain stable voltage levels while they boost their ability to move electrical power [10]. The system operates through flexible AC transmission system (FACTS) devices which combine with hybrid compensation methods to deliver dynamic control solutions [11]. Conventional capacitor-based solutions remain the most common power factor correction method which accounts for almost 60 to 70 percent of all power systems implementation [12].

The capacitor compensation methods show good results but their performance depends on multiple system elements which include load changes and harmonic interference and voltage stability and network arrangement [13]. The study conducts a data-based evaluation of power system experts provide real-world knowledge about the efficiency of series and shunt capacitor compensation systems. We combine hands-on experience with statistical analysis to study how operational variables impact power factor performance through their investigation. The research team conducts an investigation to prove their compensation techniques will work with various system types which include industrial facilities and power networks for transmission and distribution. The research applies a systematic correlation-based analytical method to advance reactive power management systems while generating important data which improves power system operational efficiency and reliability and sustainability performance.

2. Methodology

2.1 Study Design and Data Acquisition

A numerical approach for its analytical framework which measures well capacitor compensation methods enhance electrical power system power factor performance. Distributed a structured questionnaire survey to 185 participants worked in various professional fields including electrical engineering and technical work and industrial expertise and research activities in 2023 January to June. Purposive sampling to select participants had both theoretical understanding and hands-on experience with power system operation. The dataset contains three different system types which include industrial systems and transmission systems and distribution systems to show various operational situations [14]. The research method combines theoretical knowledge with practical experience from fieldwork to create a single analytical system which produces more dependable results that work across various situations [15].

2.2 Variable Framework and Functional Model

The study defines power factor improvement as the dependent variable (Y), representing overall system efficiency enhancement. Six independent variables were selected based on their technical significance in power system performance: shunt capacitor compensation (X_1), series capacitor compensation (X_2), electrical load level (X_3), harmonic distortion level (X_4), system voltage level (X_5), and power loss reduction index (X_6) [16], [17]. These variables collectively capture both operational and performance-related aspects of electrical systems [18]. The relationship among variables is expressed through a linear functional model:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_6 X_6 + \varepsilon$$

The system parameters reveal their positive and negative effects on power factor performance through this formula which shows how each parameter affects system performance [19]. The system operates with coefficients which determine strongly variables connect to each other and which direction their relationship will follow. Contains unexplained variability which stems from the error term during its operation [20].

2.3 Statistical and Analytical Approach

The research team used descriptive statistical methods to summarize their data which included respondent characteristics and electrical system information and capacitor compensation details [21]. The Pearson correlation analysis served to establish connections between power factor improvement and their corresponding influencing elements [22], [23]. Correlation coefficient is mathematically expressed as:

$$r = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \sum(y_i - \bar{y})^2}}$$

where; r represents the correlation coefficient, and x¯, y¯ denote the mean values of variables. The equation provides a method to assess the degree of linear connection between two variables by showing their strength and direction of association [24]. The obtained results underwent evaluation through established threshold values which help interpret the data. The analytical framework allows scientists to analyze system behavior through its robust analytical structure which enables them to understand power factor improvement through different compensation methods and operational parameters [25].

3. Results

3.1 Respondent Professional Profile Distribution Analysis

The respondent profile shows a diverse distribution of professionals involved in electrical power systems, with a total of 185 participants as presented in **Figure 1.**

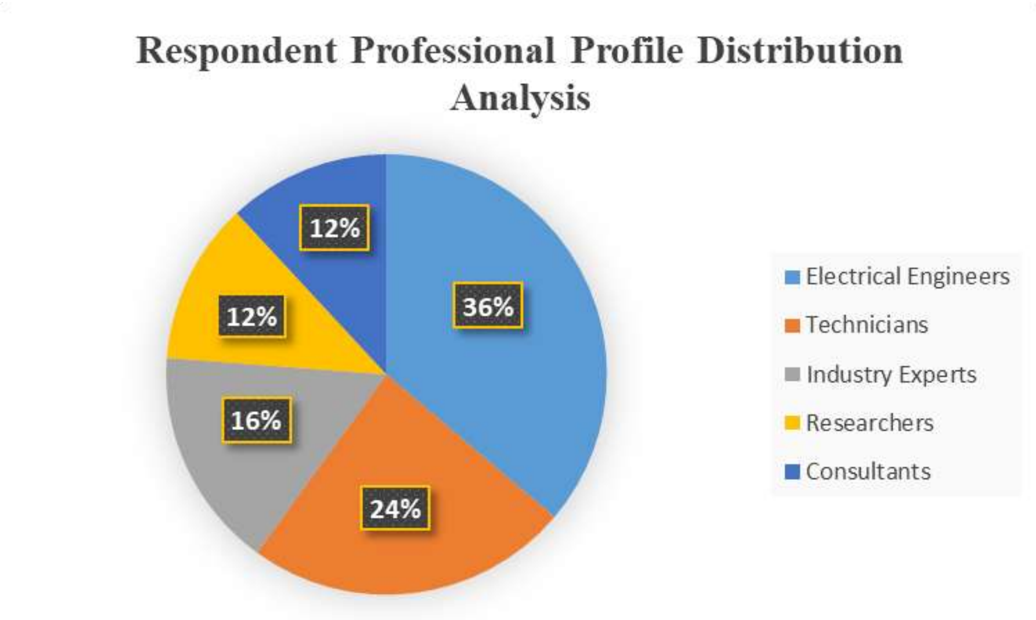

Figure 1. Respondent Professional Profile Distribution Analysis.

The dataset consists mainly of electrical engineers because they make up 36.2% of the sample which shows the data contains strong technical knowledge from actual field work. The power system applications show technicians making up 23.8% of the total which reveals their operational and maintenance perspective. The system performance and optimization practices receive strategic and managerial insights from industry experts who make up 16.2% of the group. We consist of 11.9% researchers and 11.9% consultants who provide academic and advisory perspectives to the analysis. The research team obtained equal amounts of theoretical and practical data which makes their results more reliable and applicable in real-world situations.

3.2 Distribution of Electrical System in Study

The system characteristics of the respondents show a diverse representation of electrical power infrastructures as shown in **Table 1**.

Table 1. Distribution of Electrical System in Study.

System Type	Frequency	Percentage (%)
Industrial System	72	38.9
Distribution System	65	35.1
Transmission System	48	25.9
Renewable-Integrated System	25	13.5
Mixed Power System	18	9.7

Industrial systems represent the majority of responses with 38.9 percent because most users operate in environments that require power factor optimization due to their high power consumption. The distribution systems make up 35.1 percent of the total because they perform essential functions which distribute power through medium and low voltage networks while managing voltage control and power efficiency. The transmission systems which operate at 25.9 percent demonstrate their crucial function because they need to distribute power across extensive distances while handling reactive power loads. The research includes renewable-integrated systems which make up 13.5% and mixed power systems at 9.7% to show modern hybrid energy systems which combine traditional and renewable power sources. The study needs different types of electrical networks because this approach will gather data about their operational performance at various levels.

3.3 Preferred Capacitor Compensation Methods

The research data indicates that shunt capacitors serve as the primary power factor correction solution according to 68.1% of the survey participants who chose this option as shown in **Table 2.**

Table 2. Preferred Capacitor Compensation Methods.

Compensation Method	Frequency (n)	Percentage (%)
Shunt Capacitor	126	68.1
Hybrid	107	57.8
Series Capacitor	96	51.9
FACTS Devices	44	23.8
Synchronous Condenser	33	17.8

The distribution systems operate through these systems because they provide basic functionality at affordable prices which works well for most distribution networks. The hybrid method stands as the second most popular choice because 57.8% of survey participants use it which shows people now want to merge different approaches for improved operational results. The research shows that 51.9% of users select series capacitors which mainly serve to enhance voltage stability and decrease power loss in transmission networks. The research shows that 23.8% of respondents use FACTS devices and other advanced solutions because these systems require higher investment and complex operation. Synchronous condensers are the least used at 17.8%. The research shows that traditional capacitor methods continue to lead the market but modern electrical power systems now use hybrid systems and advanced technologies for improved system performance and stability maintenance.

3.4 Benefits of Capacitor Compensation Systems

The findings demonstrate that capacitor compensation delivers its main advantage through power factor enhancement because 40.0% of respondents selected this option according to **Figure 2.**

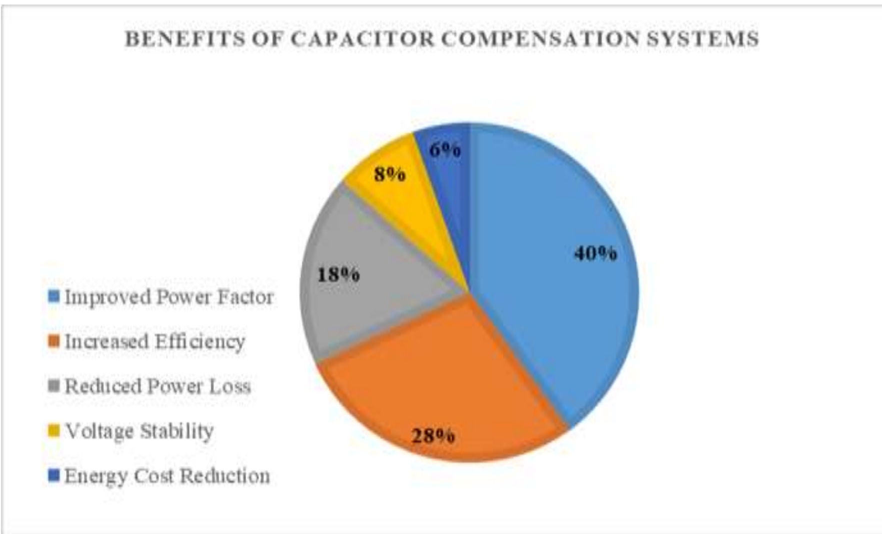

Figure 2. Benefits of Capacitor Compensation Systems.

The data shows that systems achieve their main advantages through improved management of reactive power. The data shows that 28.1% of respondents believe compensation leads to better energy usage which results in higher operational efficiency. The system experiences an 18.4% decrease in power loss which indicates that technical losses within the system have been effectively reduced. The system achieves 8.1% stability in voltage which produces better system reliability along with fewer voltage fluctuations. Energy cost reduction is the least reported benefit at 5.4%, although it still provides economic advantages. The research demonstrates that capacitor compensation generates its main value by improving technical system performance through power factor enhancement and efficiency optimization while producing additional economic advantages.

3.5 Correlation Analysis

The correlation analysis shows the relationship between power factor improvement and different electrical system variables in **Table 3.**

Table 3. Pearson Correlation Matrix (r values).

Variable	PF (Y)	X_1	X_2	X_3	X_4	X_5	X_6
PF (Y)	1.00	0.72	0.65	0.48	-0.51	0.54	0.60
X_1	0.72	1.00	0.58	0.41	-0.39	0.46	0.52
X_2	0.65	0.58	1.00	0.37	-0.42	0.44	0.49
X_3	0.48	0.41	0.37	1.00	-0.33	0.29	0.35
X_4	-0.51	-0.39	-0.42	-0.33	1.00	-0.36	-0.41
X_5	0.54	0.46	0.44	0.29	-0.36	1.00	0.50

X_6	0.60	0.52	0.49	0.35	-0.41	0.50	1.00

PF (Y) = Power Factor Improvement; X_1 = Shunt Capacitor Compensation
X_2 = Series Capacitor Compensation; X_3 = Electrical Load Level
X_4 = Harmonic Distortion Level; X_5 = System Voltage Level
X_6 = Power Loss Reduction Index

The data demonstrates that power factor (Y) strongly correlates with shunt capacitor usage (X_1 = 0.72), showing that power factor improves when shunt capacitors receive more application. The system optimization process shows positive results through the application of Series capacitors (X_2 = 0.65) which demonstrate their ability to enhance the system. Load level (X_3 = 0.48) has a moderate positive correlation, suggesting that higher load conditions moderately influence compensation needs. The system performance and power quality experience negative impacts from harmonic distortion (X_4 = -0.51) which demonstrates an adverse relationship. The data shows unidirectional connections between system voltage (X_5 = 0.54) and power loss reduction index (X_6 = 0.60) with power factor improvement.

4. Discussion

The research findings that capacitor compensation delivers essential operational value to power distribution networks which operate in electrical systems. The research results from 185 industry professionals show that shunt and series capacitor technologies deliver essential benefits which enhance power factor and system efficiency and maintain voltage stability during normal operating conditions [26]. Shunt capacitors receive the most extensive application for compensation purposes because they represent 68.1% of all used methods which makes them valuable for distribution systems. The devices have become popular because people find them easy to set up while they provide effective load-level power factor improvement at a low price. The hybrid approach (57.8%) also shows strong acceptance, reflecting a shift toward more balanced and optimized compensation strategies. Engineers now use shunt and series methods together to achieve better system results through their combined approach. Series capacitors operate in more than half of transmission systems to enhance voltage control performance and decrease the reactance which affects power lines [27].

The analysis of benefits shows that capacitor compensation brings about major technical progress to the system. The system shows its best performance through power factor improvement at 74.1% which proves that capacitor systems effectively reduce reactive power demand. The system now operates with better efficiency because its electrical infrastructure experiences reduced load [28]. The operational value of compensation systems becomes clear through their ability to improve efficiency by 67.6% and decrease power losses by 63.8%. The upgraded system delivers its best value to organizations which need to lower their power consumption while maintaining their financial budget [29]. The research shows that capacitor compensation functions as a voltage stabilizer to maintain proper voltage levels when electrical loads shift [30]. The system needs this feature because its industrial devices need to operate on steady power supply. The energy cost reduction (51.9%) exists at a lower level than technical improvements yet it creates a valuable financial advantage for organizations which consume power at scale.

Correlation analysis provides deeper insight into system behavior. The power factor improvement through shunt capacitor operation shows a strong positive correlation with r = 0.72 which proves its primary influence on system optimization. The research shows that series capacitors (r = 0.65) produce excellent results when used to improve system performance through transmission network applications. The power loss reduction index (r = 0.60) further supports the economic and technical value of capacitor compensation in reducing energy losses. The research reveals that harmonic distortion (r = -0.51) creates a strong negative effect which shows that bad power quality results in lower compensation system performance thus requiring proper attention. The research demonstrates that capacitor compensation provides an effective solution to enhance the performance of electrical power systems. The practical applications of shunt and series capacitors remain essential while hybrid methods have started to gain popularity as a method for achieving optimized system design [31], [32]. The research shows that successful power factor improvement requires both capacitor installation and proper maintenance of power quality and system equilibrium.

5. Conclusion

The research findings demonstrate that capacitor compensation serves as an efficient solution to enhance power factor performance in electrical power systems. Shunt capacitors operate as the primary method that transmission systems use for voltage stabilization, but series capacitors help maintain voltage stability in their operations. The research findings demonstrate that the system achieved better efficiency levels, together with improved power factor and decreased power loss. The system runs into two main problems because its harmonic distortion levels and its installation expenses create ongoing difficulties. The analysis shows that all compensation methods link directly to better system performance.

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