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POWER FACTOR OPTIMISATION IN AN 11 KV INDUSTRIAL POWER SYSTEM USING HIGH-VOLTAGE CAPACITOR BANK

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Abstract: Power factor improvement is essential for efficient operation of industrial electrical systems, particularly in cement plants with large inductive loads. This paper presents a case study of automatic power factor Optimisation in an 11-kV industrial power system using high-voltage capacitor banks with series reactors and PLC-based control. The system consists of two 11 kV capacitor banks connected to the incoming 11 kV bus and controlled through a PLC integrated with the plant Distributed Control System (DCS). Electrical parameters were monitored using a Siemens SENTRON PAC3200 multifunction meter, and capacitor switching was performed automatically according to reactive power demand and predefined control limits. Actual plant operating data were analyzed before and after implementation. The incoming power factor improved from approximately 0.92–0.95 lagging to 0.99–1.00, with an observed value of approximately 0.9993 after compensation. The system reduced reactive power demand, feeder current, transformer loading, and associated electrical losses while improving power factor stability and voltage regulation. The improved power factor also enabled the plant to obtain the maximum 7% power factor incentive under applicable MPERC tariff provisions. The results demonstrate that PLC-controlled high-voltage capacitor banks provide a reliable and economically beneficial solution for reactive power compensation in medium-voltage industrial systems.

Keywords— Power Factor, Reactive Power Compensation, High-Voltage Capacitor Bank, 11 kV Power System, PLC Control, Distributed Control System, Series Reactor, Energy Efficiency.

INTRODUCTION

1.1 General

The performance of an industrial electrical system depends not only on the amount of electrical energy consumed but also on the efficiency with which electrical power is delivered to connected equipment. Power factor is an important parameter used to assess effective utilization of electrical power. A low power factor increases current for a given active power demand, resulting in higher losses, increased transformer and feeder loading, voltage variations and reduced utilization of electrical infrastructure. Cement plants contain large numbers of inductive loads such as induction motors, transformers, fans and compressors. These loads require reactive power and therefore influence the overall power factor. Maintaining a high-power factor is consequently important for efficient and economical plant operation.

1.2 Fundamentals of Power Factor

Power factor represents the relationship between active power and apparent power in an AC electrical system. It is expressed as PF = kW/kVA, and for a sinusoidal system PF = cos φ, where φ is the phase angle between voltage and current. Active power performs useful work, while reactive power is required by inductive equipment for establishing magnetic fields. As reactive power demand increases, the power factor decreases and the current required to transmit the same active power increases. The relationship among active power, reactive power and apparent power is $\mathbf{S^2 = P^2 + Q^2}$.

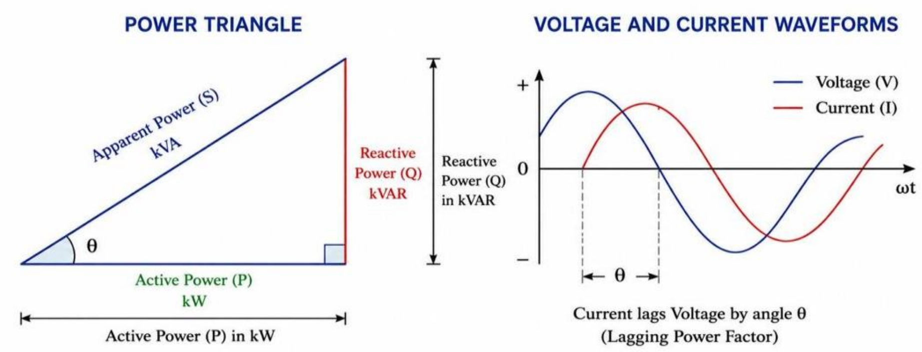

Fig. 1 Power factor triangle diagram and voltage, current waveforms

1.3 Power Factor Improvement Using Capacitor Banks

Power factor improvement is achieved by supplying leading reactive power to compensate for the lagging reactive power of inductive loads. In the present study, 11 kV high-voltage capacitor banks with series reactors are connected to the incoming 11 kV bus through dedicated vacuum circuit breakers and are automatically controlled by a PLC integrated with the plant DCS. Real-time electrical parameters obtained from the Siemens SENTRON PAC3200 multifunction meter are used to determine the required compensation and switching operation. The capacitor banks supply reactive power locally, thereby reducing the reactive power drawn from the utility, expressed as $\mathbf{Q_{(utility)} = Q_{(load)} - Q_{(capacitor)}}$. This reduces apparent power and current flow, improving the utilisation of transformers and feeders and reducing associated electrical losses. Automatic switching enables the compensation to respond to changing plant load conditions while avoiding unnecessary compensation. The use of series reactors further supports reliable operation of the HT capacitor-bank system, while PLC-DCS integration provides automatic and responsive control. In addition to the technical benefits, maintaining the required power factor provides an economic advantage through the applicable **MPERC power-factor incentive**. Thus, the proposed system provides an effective approach for automatic reactive power compensation and improved electrical-system performance under actual industrial operating conditions.

2. NEED OF THE STUDY

The electrical system of a cement manufacturing plant is characterized by a large number of inductive loads, including high-capacity motors, crushers, kiln drives, fans, compressors and other process equipment. These loads demand considerable reactive power and consequently influence the power factor of the 11-kV incoming supply. Before implementation of the centralized HT capacitor-bank system, the plant operated with a **lagging power factor of approximately 0.90–0.95**, resulting in increased reactive power flow through the incoming electrical system.

The existing compensation arrangement was therefore insufficient to consistently maintain the desired power factor under varying plant operating conditions. This created the need for a **centralized, automatic and responsive reactive power compensation system at the 11-kV level**. To address this requirement, two 11 kV HT capacitor banks equipped with series reactors were installed and integrated with a **PLC-based control system and the plant DCS** for automatic switching according to the prevailing reactive power requirement. The effectiveness of the proposed system is evident from the measured plant performance. Following implementation, the incoming power factor improved from approximately **0.91–0.95 to 0.99–1.00**, demonstrating a significant improvement in reactive power management and power-factor stability.

Thus, the study addresses a practical industrial requirement for **efficient, reliable and automatic power-factor Optimisation of an 11-kV electrical system**, while evaluating the technical and economic benefits of PLC-controlled high-voltage capacitor-bank compensation under actual plant operating conditions.

3. RESEARCH METHODOLOGY

3.1 Installed Reactive Power Compensation System

Two 11 kV high-voltage capacitor banks, each rated at 2448 kVAR, are connected to the incoming 11 kV bus. Each bank is switched through a dedicated 11 kV vacuum circuit breaker. Series reactors are provided with the capacitor banks, and switching is controlled through PLC logic integrated with the plant DCS.

3.2 Technical Specifications of Installed Equipment

The principal installed equipment consists of two 11 kV HT capacitor banks rated 2448 kVAR each, 11 kV vacuum circuit breakers, series reactors, Siemens SENTRON PAC3200 multifunction metering and PLC-DCS control.

3.3.1 HT Capacitor Unit

The HT capacitor units are assembled into the required high-voltage capacitor-bank configuration. Their function is to supply leading reactive power to compensate the lagging reactive power demand of the industrial load.

3.3.2 HT Capacitor Bank

Each installed capacitor bank is rated 2448 kVAR at the 11-kV system. Independent vacuum circuit breakers permit individual bank switching according to the automatic control requirements.

3.3.3 HT Series Reactor

Series reactors are connected with the capacitor banks to control transient and harmonic-related effects and to improve the reliability of the capacitor compensation system.

3.4 PLC–DCS Based Control of HT Capacitor Banks

The Siemens PAC3200 provides real-time voltage, current, active power, reactive power, apparent power and power-factor measurements. PLC logic processes the measurements and operates the capacitor-bank breakers according to reactive-power limits, timers and protection interlocks. The documented control settings include an ON threshold of +1500 kVAR, an OFF threshold of −2000 kVAR, 10-minute ON/OFF delays, a 15-minute stop-to-start delay and a 20-minute starting delay.

3.5 Existing Electrical Distribution System

The plant receives electrical power through a 132-kV incoming supply stepped down to 11 kV through a 50 MVA, 132/11 kV transformer. The 11-kV system supplies large motors, fans, compressors and auxiliary loads. The inductive characteristics of these loads create significant reactive power demand.

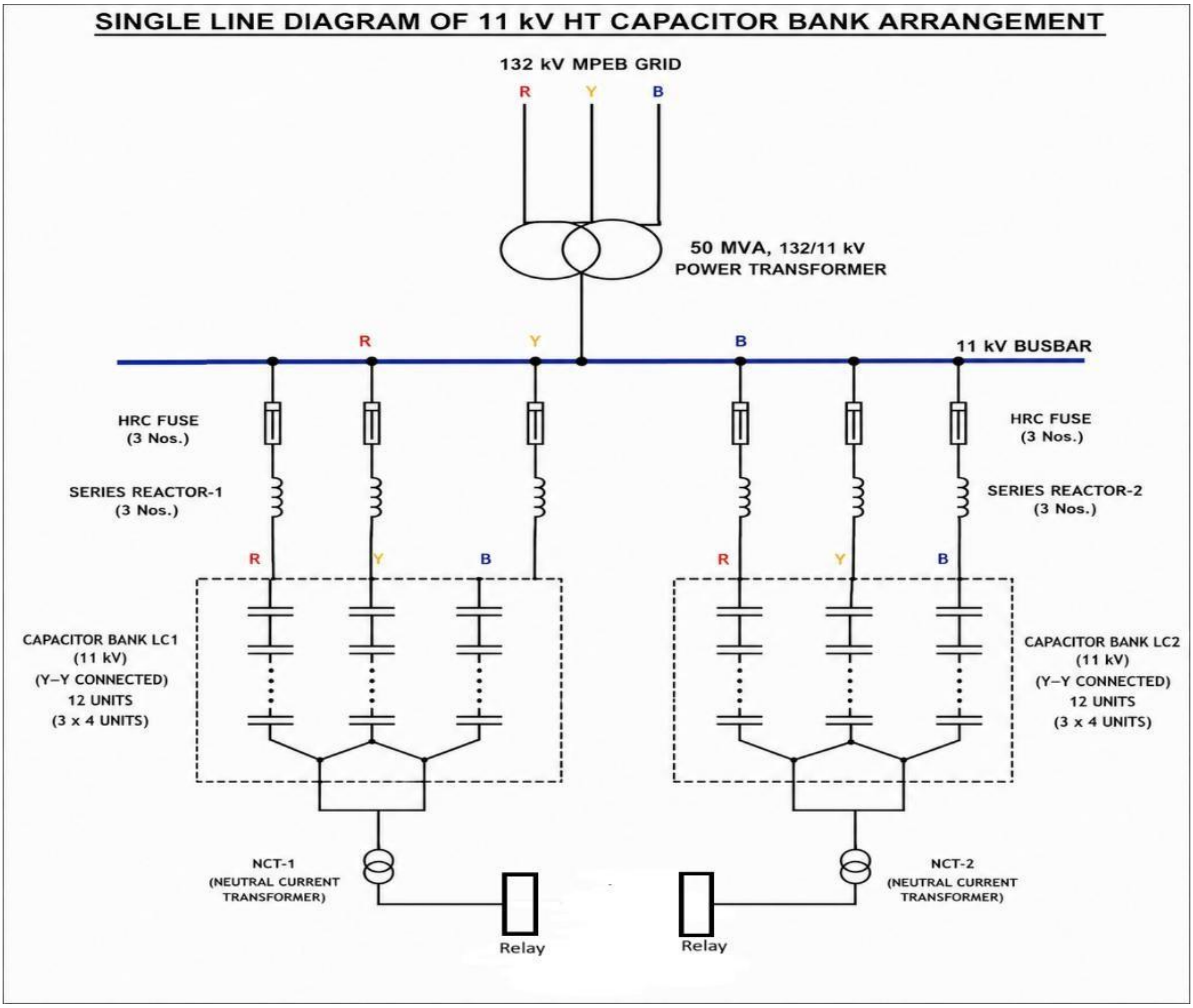

Fig. 2 Single line diagram of 11KV HT Capacitor bank

4. DATA COLLECTION, CALCULATIONS AND PERFORMANCE ANALYSIS

4.1 Pre-Implementation Performance Analysis

Table 4.1 presents the historical operating data recorded from the Siemens PAC3200 multifunction meter through the Distributed Control System (DCS) before the installation of the 11 kV HT capacitor bank. The data was collected on 15 December 2025 at different time intervals to evaluate the electrical performance of the incoming feeder under normal plant operating conditions.

The recorded values indicate that the active power demand varied between 11,620 kW and 16,710 kW, depending on the production load of the plant. Similarly, the reactive power demand fluctuated from 5,120 kVAR to 7,980 kVAR, reflecting the changing requirements of inductive equipment such as large motors, compressors, conveyors, and other electrical drives operating in the cement plant. The corresponding apparent power ranged from 12,720 kVA to 18,510 kVA throughout the day.

The measured power factor remained in the range of 0.91 to 0.93 (lagging), with an average value of 0.92. The highest power factor of 0.93 was observed at 12:00 hours, whereas the minimum value of 0.91 occurred during most of the remaining operating periods. Although the power factor remained relatively stable, it was below the desired utility target of 0.99, indicating that the plant was drawing a considerable amount of reactive power from the electrical grid.

The line voltage remained nearly constant throughout the observation period, varying only between 10.89 kV and 10.92 kV, with an average voltage of 10.90 kV. This confirms that the incoming supply voltage was stable and that voltage fluctuations had minimal influence on the observed power factor. The line current varied between 806 A and 1,095 A, with an average current of 947 A, corresponding to the changes in plant loading.

Table 1 Power factor Trend at 11 kV Incoming feeder- Before HT Capacitor Bank Installation.
Data Recorded from Siemens PAC3200 Meter (Historical Trend)- December 2025

Date	Time	Active Power (kW)	Reactive Power (kVAR)	Apparent Power (kVA)	Power Factor	Line Voltage (kV)	Line Current (A)
15-Dec-25	00:00	12,860	5,640	13,980	0.92	10.91	879
15-Dec-25	04:00	11,620	5,120	12,720	0.91	10.90	806
15-Dec-25	08:00	14,950	6,780	16,400	0.91	10.92	1,005
15-Dec-25	12:00	16,710	7,980	18,510	0.93	10.91	1,095
15-Dec-25	16:00	15,820	7,180	17,380	0.91	10.90	1,022
15-Dec-25	20:00	14,180	6,550	15,600	0.91	10.89	946
15-Dec-25	23:59	12,950	5,920	14,270	0.91	10.90	882

Table 2 Summary data of experiment result

Parameter	Value
Minimum Power Factor	**0.91**
Maximum Power Factor	**0.93**
Average Power Factor	**0.92**
Average Reactive Power	**6,310 kVAR**
Average Line Current	**947 A**
Average Line Voltage	**10.90 kV**

4.2 Post-Implementation Performance Analysis

Installation and commissioning of the automatic 11 kV High Tension (HT) capacitor banks at the LC-1 incomer, the electrical performance of the plant was continuously monitored through the Siemens PAC3200 Multifunction Meter (MFM), Distributed Control System (DCS), and SCADA interface. The objective was to evaluate the effectiveness of the capacitor banks in maintaining a stable power factor, reducing reactive power demand, improving voltage regulation, and maximizing the incentive available under the MPERC tariff.

The automatic control logic incorporated in the PLC continuously monitored the reactive power (kVAR) at the 132/11 kV incoming substation. Based on the real-time reactive power requirement, the controller automatically switched the two HT capacitor banks ON or OFF while maintaining the required safety interlocks and time delays. This ensured that the plant power factor remained close to unity without causing over-compensation or leading power factor conditions.

Table 4.2 presents the DCS operating screen after commissioning of the HT capacitor banks. The display indicates that the incoming power factor is maintained at 0.9993, while the incoming reactive power demand is approximately 1258 kVAR. The controller continuously exchanges reactive power with the Waste Heat Recovery System (WHRS) through the programmed dead-band control, allowing smooth power factor regulation under varying plant load conditions.

After commissioning, the PLC-DCS system automatically switched the capacitor banks according to reactive power demand. Continuous monitoring and automatic switching maintained the incoming power factor close to the desired range of 0.99–1.00.
After installation of the HT capacitor banks, the incoming 11 kV feeder maintained a power factor close to unity throughout the observed operating period. The recorded power factor remained between 0.99 and 1.00, with an average value of approximately 0.994. During the observation period, the active power varied from 12,150 to 17,930 kW, while reactive power remained between 750 and 960 kVAR, with an average of approximately 856 kVAR. The average line voltage was 11.033 kV and the average line current was approximately 779 A. The results demonstrate stable reactive power compensation and effective automatic control of the HT capacitor banks under varying plant load conditions.

Table 3 Power factor Trend at 11 kV Incoming feeder- After HT Capacitor Bank Installation.
Data Recorded from Siemens PAC3200 Meter (Historical Trend)- May 2026

Date	Time	Active Power (kW)	Reactive Power (kVAR)	Apparent Power (kVA)	Power Factor	Line Voltage (kV)	Line Current (A)
10-May-26	00:00	13,420	860	13,490	**1.00**	11.03	702
10-May-26	04:00	12,150	780	12,170	**0.99**	11.02	645
10-May-26	08:00	15,780	920	15,810	**0.99**	11.04	833
10-May-26	12:00	17,930	960	17,960	**1.00**	11.05	917
10-May-26	16:00	16,850	880	16,870	**0.99**	11.03	862
10-May-26	20:00	15,210	840	15,230	**0.99**	11.02	780
10-May-26	23:59	13,900	750	13,920	**1.00**	11.04	708

Table 4 Summary data of experimental result

Parameter	Value
Minimum Power Factor	**0.99**
Maximum Power Factor	**1.00**
Average Power Factor	**0.995**
Average Reactive Power	**830 kVAR**
Average Line Current	**764 A**
Average Line Voltage	**11.03 kV**

Table 5. Financial Impact Data

Parameter	Case A – Unity Optimisation	Case B – PF Drops to 0.99
PF Achieved	**1.00 (Lagging)**	**0.99 (Lagging)**
MPERC Rebate	**7.0%**	**5.0%**
Billed Base Energy Charges	**₹11,33,96,234.11**	**₹11,33,96,234.11**
Total Monthly Incentive Realized	**₹79,37,736.39**	**₹56,69,811.71**
Financial Status	**Maximized Rebate Secured**	**Incentive Leakage Risk**

Table 6. Monthly Financial Exposure

Parameter	Value
Incentive Difference (7% – 5%)	**₹22,67,924.68/month**
Annualized Corporate Value at Risk	**₹2,72,15,096.16/year**
Approximate Annual Value at Risk	**₹2.72 Crores/year**

4.3 MPERC Power Factor Incentive and Penalty Rules

Maintaining the required power factor enabled the plant to qualify for the maximum applicable 7% power-factor incentive under the relevant MPERC tariff provisions.

4.4 Operating Methodology of the PLC-Based Capacitor Bank System

The control system continuously measures reactive power, compares it with programmed limits, verifies timers and protection interlocks, operates the appropriate VCB and confirms breaker feedback before continuing the control cycle.

4.5 HT Capacitor Bank Switching Logic

The switching logic uses upper and lower reactive-power dead bands, ON/OFF delays and minimum stop-to-start intervals to prevent unnecessary switching and allow adequate capacitor discharge before re-energization.

5. RESULT AND DISCUSSION

5.1 Justification for HT Capacitor

Installing a centralized High Tension (HT) Automatic Capacitor Bank at LC1 will eliminate manual dependencies, stabilize system voltage, and permanently safeguard an annualized cost-saving channel of ~₹9.52 Crores.

Monthly Revenue at Risk (with a marginal 0.01 PF drop):

₹79,37,736.39 − ₹56,69,811.71 = ₹22,67,924.68 (Approx. ₹22.68 Lakhs)

Annualized Corporate Value at Risk:

₹22,67,924.68 × 12 Months = ₹2,72,15,096.16 (~₹2.72 Crores / Year)

5.2 Capacitor Sizing for Net KVAR

Reactance of 12.87 KV, 248KVAR bank Xc1 = (12.87)2/ 2.448 MVAR

= 67.667 Ohms

Since it is to be provided with 6% series reactor on the line side, hence

Reactor Impedance XL = 0.06 x Xc1

= 4.06 Ohms

Capacitor Impedance XC = 67.662 – 4.06

= 63.602 Ohms

KVAR at 11KV = (112/ 63.602) x 1000

= 1902 KVAR

Now Capacitor Bank rating of 2448 KVAR at 12.87 KV, but capacitor shall give the output of 1902 KVAR at 11KV.

5.3 Reactor sizing and design calculations

Phase Current = (KVAR / 3) / (KV / 1.732)

= 109.81 Amps

Reactor Rating = (I2x XL) / 1000

= 48.96 KVAR

5.4 Inrush Current Calculation

For worst switching condition for Capacitor Bank Rating of 2448 KVAR, 12.87KV

Inrush = Peak L-L System Voltage / (1.732 x Surge Impedance)

= (1.414 x 12870) / (1.732 x (Xc1x XL)1/2

= 633.98 Amps peak

Inrush current is also known as the switch on surge, the input surge current. Surge Impedance is use in the prediction of maximum loading capacity.

CONCLUSION

6.1 Conclusion

The study evaluated a PLC-controlled HT capacitor-bank system installed on an 11-kV industrial electrical network. Two 11 kV capacitor banks with series reactors were automatically switched through vacuum circuit breakers under PLC-DCS control. The incoming power factor improved from approximately 0.92–0.95 lagging to 0.99–1.00, with an observed value of approximately 0.9993. The improvement reduced reactive power demand and improved utilization of the electrical system. Maintaining the required power factor also enabled the plant to qualify for the maximum applicable 7% incentive under MPERC tariff provisions. The results demonstrate that PLC-controlled HT capacitor banks provide a technically reliable and economically beneficial solution for reactive power compensation in medium-voltage industrial systems.

6.2 Future Enhancements

Future work can focus on further improving the automation and monitoring of the power factor correction system through advanced digital technologies. Integration with **Industrial Internet of Things (IIOT)** and cloud-based energy monitoring can provide continuous access to electrical parameters and system performance. AI and machine-learning techniques may be explored for predicting reactive power requirements and optimizing capacitor-bank switching based on historical operating conditions. Further development can include adaptive control, harmonic monitoring, and digital-twin-based analysis to enhance system reliability, power quality, energy efficiency, and overall performance of industrial electrical networks.

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