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# Transient Analysis on Switching Capacitor Bank Using Power Factor Regulator

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## Abstract
This study discusses the analysis of transients that occur in capacitor bank switching using a power factor regulator (PFR). Electric power systems use capacitor banks to offset reactive power, enhance power factors, and minimize energy losses. However, the switching process in capacitor banks can cause significant voltage and current spikes, known as transient phenomena, which can damage equipment and disrupt system stability. This study conducts simulations and analyzes the impact of transients that occur during the capacitor bank switching process on the electric power system. The simulation is carried out using software that models the behavior of the electric power system, focusing on how the power factor regulator regulates the switching process and its impact on the resulting transients. The simulation results show that the use of PFR can reduce the negative impact of transients, but improper settings can still cause disturbances that have the potential to damage the system. These findings provide important insights for system engineers in designing and operating more reliable power systems, considering the importance of proper settings on the power factor regulator to minimize the effects of transients on capacitor bank switching. This study also recommends several mitigation strategies to reduce the impact of transients and improve overall system stability.
**Keywords:** Transient, Switching Capacitor Bank, Power Factor Regulator, Electric Power System

## Introduction
In power systems, capacitor banks play an important role in improving efficiency and stability by compensating reactive power, which in turn improves the power factor and reduces energy losses(Soma, 2021). Capacitor banks are often used in distribution and industrial networks to optimize system performance, reduce operating costs, and improve power quality(Rofandy et al., 2022). However, the sudden switching or operation of capacitor banks can cause undesirable transient phenomena, such as voltage and current surges(Roza et al., 2023). These transient phenomena, although short-lived, can have a significant impact on electrical equipment and overall system stability(Xue & Popov, 2014).

Transients that occur during the capacitor bank switching process are often caused by sudden changes in reactive power flow, which can produce voltage and current oscillations(Ali, 2011). These effects can affect electrical equipment, cause operational disruptions, and in severe cases, damage power system components(Xue & Popov, 2014). Therefore, understanding and controlling transient phenomena is important to maintain the reliability and efficiency of the power system(Benidris et al., 2016).

Power Factor Regulator (PFR) is a device used to control the power factor in an electric power system by regulating the capacitor bank switching process(Umamaheswari & Sukumar, 2018). The PFR functions to ensure that the capacitor bank is operated at the right time, so as to minimize the negative impact of transients(Mohammad et al., 2019). However, improper or suboptimal settings on the PFR can cause adverse transient effects, even though the goal is to optimize the power factor(Martins et al., 2021). Therefore, the analysis of transients that occur during capacitor bank switching using a Power Factor Regulator becomes very important. This study aims to understand the characteristics of these transients and how the PFR can affect these phenomena. With proper analysis, it is expected that solutions can be found to minimize the negative impacts of transients and improve the reliability and efficiency of the electric power system.

## Literature Review
1. Capacitor Banks in Power Systems

A capacitor bank is a collection of capacitors used in power systems to compensate for reactive power(Bisanovic et al., 2014). The use of capacitor banks can improve the power factor, reduce energy losses, and improve the voltage quality in the distribution system(Rofandy et al., 2022). Capacitor banks are usually placed at various points in the electrical distribution system to improve the voltage profile and maintain system stability(Arlenny et al., 2019).

2. Transients in Power Systems

Transients are phenomena that occur when there is a sudden change in the condition of the electrical power system, such as switching capacitor banks, load changes, or other disturbances(Shafiee et al., 2021). Transients can cause voltage and current spikes that last for a very short time but with significant amplitude(Yang et al., 2021). Uncontrolled transients can cause damage to electrical equipment, disruption to system operation, and decreased power quality(Akpoyibo & Ezechukwu, 2020).

3. Transient Mechanism in Capacitor Bank Switching

When a capacitor bank is connected or disconnected from the system, there is a sudden change in the flow of reactive power(Coury et al., 2003). This change can cause oscillations that produce voltage and current transients(Kanálik et al., 2020). This mechanism is influenced by factors such as the size of the capacitor, the impedance of the system, and the timing of the switching itself(Prah & Attachie, 2022). In addition, resonance between the capacitor bank and the inductive elements in the system can worsen the transient effect(Lennerhag & Bollen, 2018).

4. Power Factor Regulator (PFR)

A Power Factor Regulator (PFR) is a device used to regulate the power factor in an electric power system(Coman et al., 2020). The PFR controls the switching of the capacitor bank based on the reactive power requirements in the system, with the aim of maintaining the power factor close to the desired value (usually close to 1)(Ayaz et al., 2023). By optimizing switching, the PFR can help reduce energy losses and maintain voltage stability(Sultana & Roy, 2014). However, if the PFR is not set properly, the switching process can cause detrimental transients.

5. Effect of Power Factor Regulator on Transients

The use of PFR in regulating the switching of capacitor banks can affect the nature and magnitude of the transients that occur(Coury et al., 2003). The PFR, which works automatically, plays a role in determining the right moment to activate or deactivate the capacitor bank, so that it can minimize or even avoid transients(Bisanovic et al., 2014). However, in some cases, especially when there is a setting error or unexpected external factors, the PFR can worsen transient conditions(Chen et al., 2020). Therefore, a deep understanding of the interaction between the PFR and transient phenomena is essential to optimize the performance of the electric power system(Barath C M K et al., 2024).

6. Power Quality and System Stability

Transients that occur during capacitor bank switching can affect power quality, which includes voltage, current, and frequency in the power system(Prah & Attachie, 2022). Poor power quality can cause equipment disruption and even damage(Ogheneovo Johnson, 2016). In addition, uncontrolled transients can disrupt system stability, which is the condition in which the power system is able to maintain its normal operation despite disturbances(Pavella et al., 2000).

## Methods

1. Research Design

This study uses a simulation approach to analyze transient phenomena that occur during capacitor bank switching using a Power Factor Regulator (PFR). The research design involves modeling the electric power system with various capacitor bank switching scenarios, both with and without PFR, to understand and evaluate the impact of transient phenomena.

2. System Modeling

a. Capacitor Bank and Power System Modeling:

1. The capacitor bank will be modeled as an energy storage component that has certain capacity characteristics.
2. The electric power system used in the simulation will include voltage sources, network impedances, loads, and transformers, as well as other relevant elements.

b. Power Factor Regulator (PFR) Modeling:

The PFR will be modeled to control the capacitor bank switching. This model will include the PFR control logic that regulates when and how the capacitor bank is turned on or off based on the reactive power requirements and system power factor.

3. Transient Simulation

a. Simulation Software:

The simulation will be carried out using electric power system simulation software such as MATLAB/Simulink. This software was chosen because of its ability to model transient phenomena with a high degree of accuracy.

b. Simulation Scenario:

Scenario with PFR: The capacitor bank is turned on and off using PFR, to observe how PFR affects the transients that occur.

c. Simulation Parameters:

1. The parameters to be analyzed include voltage and current at critical points after the transformer, as well as during and after the switching process.
2. The simulation period is determined in such a way as to capture the transient phenomenon completely, usually in the microsecond to millisecond time range.

4. Data Analysis

a. Time and Frequency Analysis:

1. The simulation data will be analyzed temporally to identify the duration and amplitude of the transient.
2. Frequency analysis will be carried out to understand the frequency components that appear during the transient and how this is affected by the switching of the capacitor bank and PFR.

## Results and Discussion

1. Simulation Results

In the analysis of the planning of the Electric Power Panel using Capacitor Bank to the equipment is taken based on the data to be designed. Based on the data, Active Power = 15 kW (Cos ϕ = 0.95), Reactive Power = 9.3 kVAR (Cos ϕ = 0.95), Apparent Power = 17.65 kVA (Cos ϕ = 0.95), Voltage = 400 V (3 phase), Target Cos ϕ = 0.95, Initial Cos ϕ = 0.85, load distance = 5 meters, Capacitor Current 4 kVAR = 22.8 A then (1 Capacitor = 5.7 A x 4), Then the capacitor (4 x 4 kVAR)

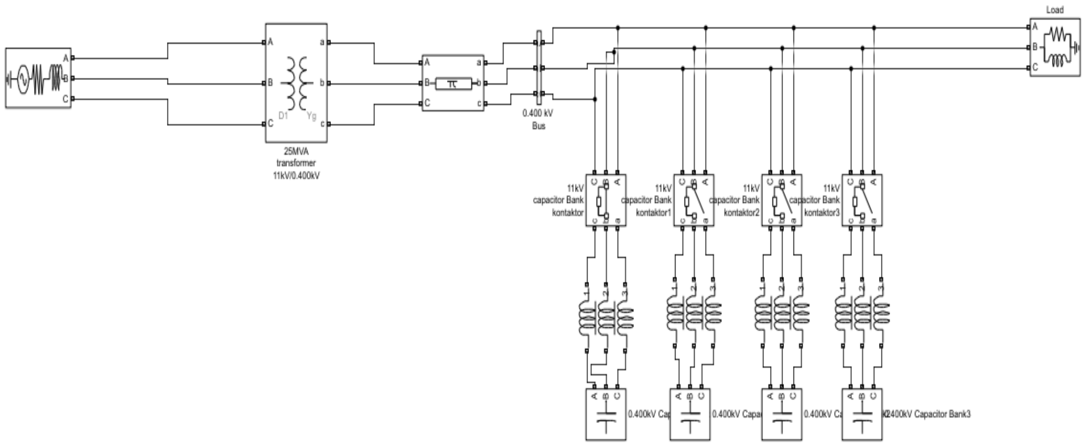


**Figure 1**. Transient Simulation on Switching Capacitor Bank Using Power Factor Regulator

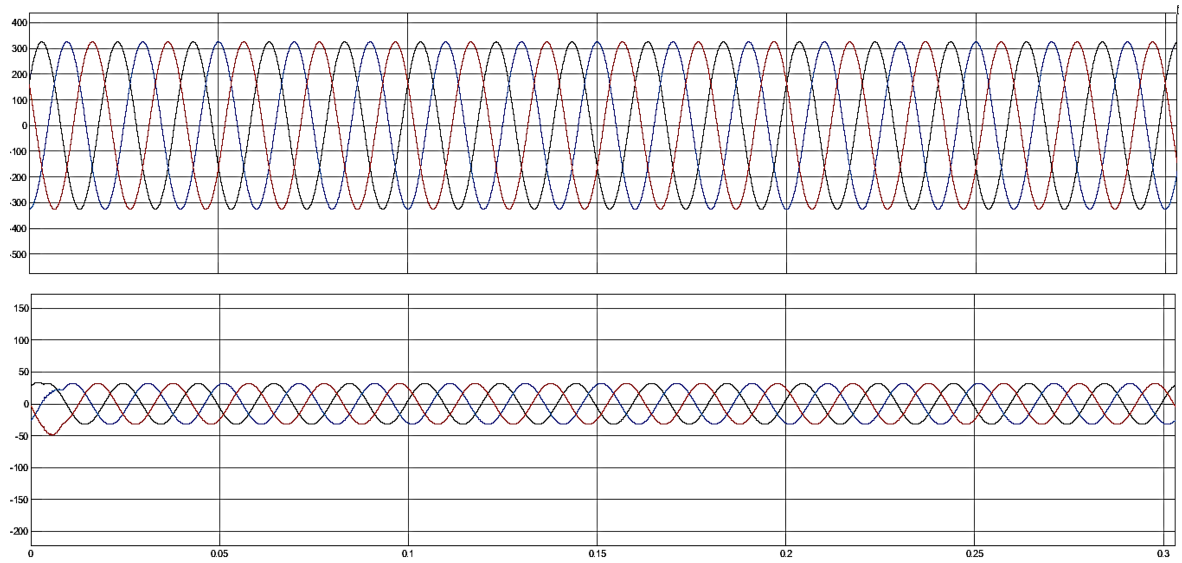

**Figure 2**. Operation Simulation Without Capacitor Bank

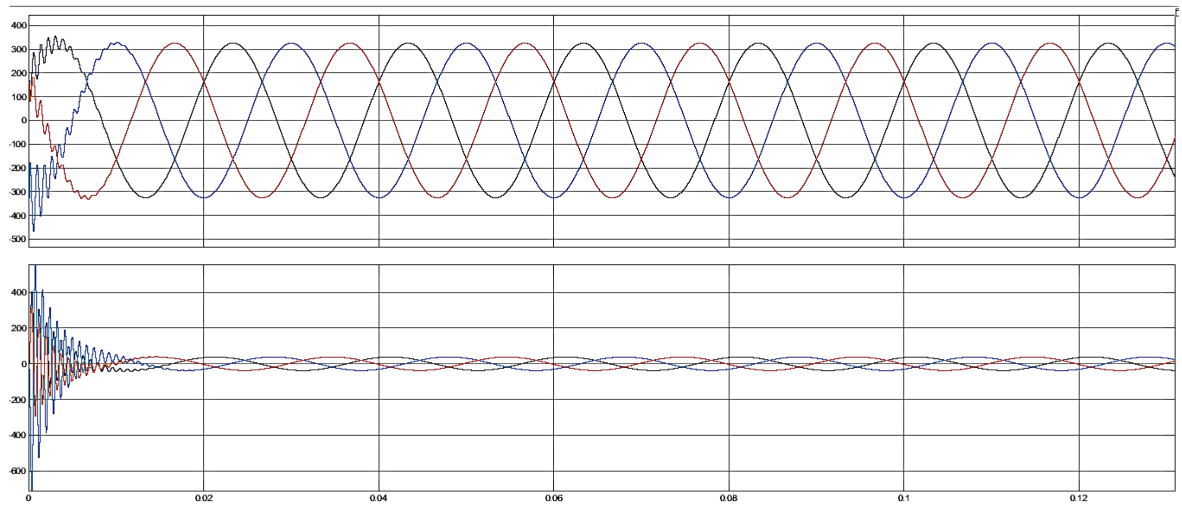

**Figure 3**. Capacitor Bank Simulation Results Cause Transient Switching on Power Factor Regulator

**Table 1**. The Impact of Transient Switching Power Factor Regulators on the Voltage and Current of Power Systems

| Capacitor bank | Max/Min Current $I_1$ (A) | Max/Min Current $I_2$ (A) | Max/Min Current $I_3$ (A) |
|---|---|---|---|
| Close capacitor bank-I | Max 400/Min580 | Max 200/Min 200 | Max 200/Min 200 |
| | Max Voltage R (V) | Max Voltage S (V) | Max Voltage T (V) |
| | Max 340 | Max 340 | Min 480 |
| | Steady State Current Is (A) | Duration of Transient T (ms) | Frequency of Transient F (Hz) |
| | 21,65 | 13 | 77 Hz |
| Close capacitor bank-II | Max 250/Min80 | Max 180/Min180 | Max 220/Min400 |
| | Max Voltage R (V) | Max Voltage S (V) | Max Voltage T (V) |
| | Max 340 | Min 340 | Min400 |
| | Steady State Current Is (A) | Duration of Transient T (ms) | Frequency of Transient F (Hz) |
| | 21,65 | 13 | 77 Hz |
| Close capacitor bank-III | Max 100/Min 80 | Max80/min 50 | Max100/Min 180 |
| | Max Voltage R (V) | Max Voltage S (V) | Max Voltage T (V) |
| | Max 340 | Max 340 | Min 380 |
| | Steady State Current Is (A) | Duration of Transient T (ms) | Frequency of Transient F (Hz) |
| | 21,65 | 13 | 77 Hz |
| Close capacitor bank-IV | Max 50/Min 50 | Max 50/Min 50 | Max 50/Min 50 |
| | Max Voltage R (V) | Max Voltage S (V) | Max Voltage T (V) |
| | Max 340 | Max 340 | Min 480 |
| | Steady State Current Is (A) | Duration of Transient T (ms) | Frequency of Transient F (Hz) |
| | 21,65 | 13 | 77 Hz |

From this table, it can be seen that each capacitor bank closure has a different effect on the power system current and voltage, both during transient and steady state conditions. The duration and frequency of transients remain consistent in all cases, but the current and voltage values show significant variations depending on the capacitor bank configuration used.

2. Scenario with Power Factor Regulator (PFR):

Reduced Surge: When PFR is used to control the switching of capacitor banks, the voltage and current surges are significantly reduced. The peak voltage is recorded to increase only up to 105% of the nominal value, while the transient current only increases by about 1.5 times the normal current.

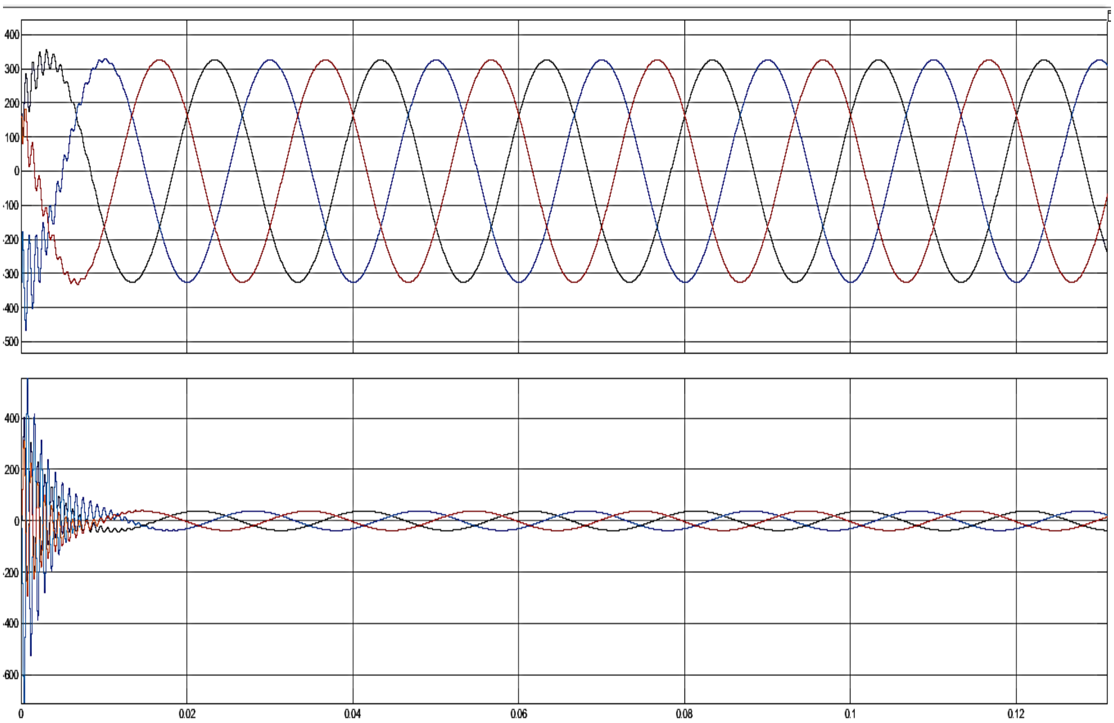

**Figure 4**. Transient Simulation Results using 1 Capacitor Bank

Surge Reduction: When PFR is used to control the switching of capacitor banks, the voltage and current surges that occur are significantly reduced. Peak voltages are recorded to increase only up to 105% of the nominal value, while transient currents only increase by about 1.5 times the normal current.

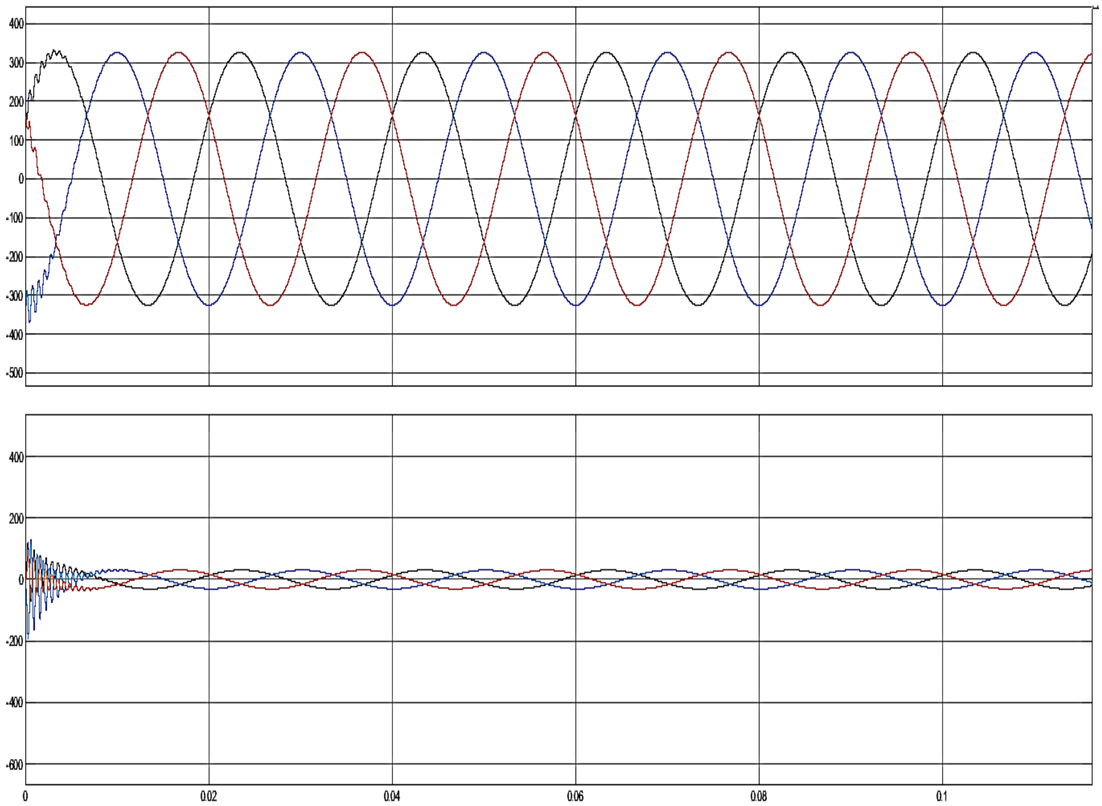


**Figure 5**. Transient Simulation Results using 4 Capacitor Banks in closed state on Power Factor Regulator

Improved Power Quality: The use of PFR also helps speed up the system recovery process to steady state, reduces the duration of voltage oscillations, and improves overall power quality. This shows that PFR is effective in dampening the impact of transients that occur during switching.

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**Table 2**. The results of calculating the condition of the capacitor bank Power Factor Regulator for the Electric Power System

| Status Condition | 3 phase voltage (Volt) | RMS (V) | RMS (I) | P (watt) | Q kVAR | Pf |
|---|---|---|---|---|---|---|
| Without capacitor bank | 400 | 230.4 | 26.85 | 1.498 | 1.097 | 0,8068 |
| | 400 | 230.4 | 26.85 | | | |
| | 400 | 230.4 | 26.85 | | | |
| Capacitor bank -I (Close) | 400 | 230.4 | 23.88 | 1.493 | 696.7 | 0,9063 |
| | 400 | 230.4 | 23.88 | | | |
| | 400 | 230.4 | 23.88 | | | |
| Capacitor bank-II (Close) | 400 | 230.3 | 22.05 | 1.494 | 299.1 | 0,9806 |
| | 400 | 230.3 | 22.05 | | | |
| | 400 | 230.3 | 22.05 | | | |
| Capacitor bank-III (Close) | 400 | 230.3 | 21.65 | 1.492 | 991.2 | 0,9978 |
| | 400 | 230.3 | 21.65 | | | |
| | 400 | 230.3 | 21.65 | | | |
| Capacitor bank-IV (Close) | 400 | 28.9 | 22.75 | 1.491 | 497 | 0,9487 |
| | 400 | 238.9 | 22.75 | | | |
| | 400 | 238.9 | 22.75 | | | |

The use of capacitor banks in the electric power system has an effect on reducing the current (RMS) and increasing the power factor (Pf) of the system. Larger capacitor banks (Capacitor Bank-III) are able to improve the power factor to approach the ideal value (1). However, each capacitor configuration has a different impact on the magnitude of reactive power (Q) and power factor, indicating that the adjustment of the use of capacitor banks must be adjusted to the reactive power requirements in the system.

3. Discussion
   a. Effectiveness of Power Factor Regulator (PFR):
      The results of the study indicate that PFR plays an important role in reducing the negative impact of transients during capacitor bank switching. By optimally setting the switching time and conditions, PFR is able to suppress voltage and current spikes, which are the main factors causing disturbances in the electric power system. This is in line with the literature stating that proper settings on PFR can improve system stability and maintain power quality.
   b. Implications for Power System Design:
      The use of PFR in the design and operation of electric power systems not only improves the power factor but also functions as a transient mitigation tool. The implication of this finding is that the integration of PFR in modern electric power systems is highly recommended to minimize the impact of capacitor bank switching which can cause equipment damage and decrease system efficiency.
   c. Research Limitations:
      This study is mainly focused on transient analysis under ideal conditions without considering various external factors such as uncertain load variations or disturbances originating from external sources. For further testing, field research on real systems with more complex variations is needed to validate the results of this simulation.

4. Recommendations for Implementation

Based on the results obtained, it is recommended that PFR be widely implemented in power systems that use capacitor banks. PFR settings should be properly calibrated to optimize switching and minimize transients. In addition, periodic monitoring and adjustment of PFR settings should be carried out to adapt to dynamic system operating conditions.

## Conclusions

The process of switching capacitor banks in the power system produces significant transient phenomena, including voltage and current spikes. Without proper regulation, these transients can negatively impact power quality and system stability, causing operational disruptions and potential damage to electrical equipment.

The use of Power Factor Regulator (PFR) has proven effective in reducing the negative impact of transients that occur during capacitor bank switching. PFR is able to significantly reduce the amplitude of voltage and current spikes, and accelerate the recovery of the system to a stable condition. This shows that PFR is an important tool in maintaining the stability and quality of power in the power system.

The implementation of PFR in the design and operation of the power system not only helps in regulating the power factor but also functions as a mitigation mechanism against transients. Therefore, the integration of PFR in systems that use capacitor banks is highly recommended to minimize the risk of transients and improve the efficiency of system operations.

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Finally, hopefully this research can be useful for the development of science and technology, especially in the field of electric power systems.

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